2005

Energy efficient clustering and routing protocols for wireless sensor networks

Marziah Veyseh
San Jose State University

Follow this and additional works at: https://scholarworks.sjsu.edu/etd_theses

Recommended Citation

Veyseh, Marziah, "Energy efficient clustering and routing protocols for wireless sensor networks" (2005). *Master's Theses*. 2808.

DOI: <https://doi.org/10.31979/etd.aafs-g6qz>
https://scholarworks.sjsu.edu/etd_theses/2808

This Thesis is brought to you for free and open access by the Master's Theses and Graduate Research at SJSU ScholarWorks. It has been accepted for inclusion in Master's Theses by an authorized administrator of SJSU ScholarWorks. For more information, please contact scholarworks@sjsu.edu.

ENERGY EFFICIENT
CLUSTERING AND ROUTING
PROTOCOLS FOR WIRELESS SENSOR NETWORKS

A Thesis

Presented to

The Faculty of the Department of Electrical Engineering

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree of

Master of Science

by

Marziah Veyseh

May 2005

UMI Number: 1431290

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI[®]

UMI Microform 1431290

Copyright 2005 by ProQuest Information and Learning Company.

All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

© 2005
Marzieh Veyseh
ALL RIGHTS RESERVED

APPROVED FOR THE DEPARTMENT OF ELECTRICAL ENGINEERING

Nader F. Mir 5/26/05
Dr. Nader F. Mir

Belle Wei 5/26/05
Dr. Belle Wei

Melody Moh 5/31/05
Dr. Melody Moh

APPROVED FOR THE UNIVERSITY

Rhea I. Williamson 6/23/05

ABSTRACT

ENERGY EFFICIENT CLUSTERING AND ROUTING PROTOCOLS FOR WIRELESS SENSOR NETWORKS

By Marzieh Veyseh

This thesis presents a novel clustering protocol, Decentralized Energy Efficient cluster Propagation (DEEP), that is based on the idea of controlling the geographical dimensions of clusters and distribution of cluster heads in order to conserve energy and prolong network lifetime in wireless sensor networks. In addition, this thesis develops an inter-cluster energy conscious routing protocol that is compatible with the proposed clustering technique. The proposed clustering and routing protocols take advantage of the multi-rate capabilities of 802.11 a, b, g technologies by elevating the data rate to higher levels for shorter transmission ranges. This approach reduces the energy consumption by lowering the transmission time. Furthermore, due to the balanced load, protocol overhead caused by unnecessary frequent re-clustering is eradicated. Our simulation results demonstrate that DEEP substantially reduces total data communication and route setup energy consumption in sensor networks compared to an existing clustering scheme, LEACH.

ACKNOWLEDGMENT

To my loving parents

Who always instilled in me the importance of education, and never stopped dreaming about my success, and whose selfless love, devotion, and guidance kept me going.

To my wonderful husband

Who inspired and taught me to believe that nothing is impossible and without whose encouragement, patience, support, and sacrifices I couldn't have made it through this stage.

TABLE OF CONTENTS

LIST OF TABLES	viii
LIST OF FIGURES.....	ix
1. Introduction.....	1
1.1 Energy Demands for Promising Wireless Networks	1
1.2 Distributed Sensor Networks and Communication Protocols	2
1.2.1 Clustering Protocols.....	3
1.2.2 Energy-Aware Routing Protocols	4
1.3 Scope	5
2. Distributed wireless sensor networks.....	9
2.1 Introduction.....	9
2.2 Sensor Network Applications	9
2.2.1 Environmental Monitoring	10
2.2.2 Motion Monitoring	11
2.3 Microsensor Node Hardware	12
2.3.1 Examples of Microsensor Nodes	13
2.4 Operational Characteristic of Microsensor Networks.....	16
2.5 Energy Consumption Sources.....	17
2.5.1 Digital Processing Energy.....	17
2.5.2 Radio Transmission Energy	18
2.5.3 Protocol Overhead	19
3. Energy Efficient Clustering Protocols	20
3.1 Introduction.....	20
3.2 Energy Efficient Clustering Techniques	20
3.2.1 Centralized Clustering Techniques.....	22
3.2.2 Decentralized Clustering Techniques	23
3.3 Energy Adaptive Clustering Hierarchy (LEACH)	24
4. Energy Conscious Routing Protocols for Wireless Ad hoc Networks.....	27
4.1 Introduction.....	27
4.2 Energy Conscious Routing Protocols	27
4.2.1 Centralized Route Selection Protocols	28
4.2.2 Distributed Route Selection Protocols.....	29
4.3 Directed Diffusion	30
4.4 Energy Aware Routing (EAR).....	32
4.4.1 Setup Phase.....	33
4.4.2 Data Communication Phase.....	34
5. Communication Energy Model.....	36
5.1 Introduction.....	36
5.2 Wireless Communication Energy Model	36
5.3 Motivations for Multi-hop Communication	39
5.4 Multihop versus Direct Communication.....	41
5.4.1 Wireless Communication Standards.....	41

5.4.2 Energy of Real World Transceivers.....	42
5.4.3 Expected Data Rate of Different Wireless Standards	45
5.4.3 Multihop Communication Efficiency	48
5.5 Intra-Cluster Communication	52
5.5.1 Two-Dimensional Communication Spaces	52
5.5.2 Intra-Cluster Communication Energy Consumption	55
5.4.3 Intra-Cluster Direct Communication Advantages.....	57
6. Decentralized Energy Efficient Cluster Formation Protocol	60
6.1 Introduction.....	60
6.2 Decentralized Energy-Efficient Cluster Propagation (DEEP) Protocol.....	61
6.2.1 Protocol Details.....	62
6.2.2 Protocol Execution Steps.....	66
6.2.3 DEEP Advantages.....	67
6.3 Performance Evaluation.....	69
6.3.1 Re-clustering.....	74
6.3.2 Performance Comparison	77
7. Inter-Cluster Routing Protocol.....	81
7.1 Introduction.....	81
7.2 Inter-Cluster Energy Conscious Routing Protocol.....	81
7.2.1 Protocol Details.....	82
7.2.2 Comparison between ICR and EAR	86
7.3 Simulation Results	87
7.3.1 Total Energy Consumption in the Network versus Number of Sent Data Packets.....	88
7.3.2 Performance Comparison between DEEP and LEACH after the Execution of the Routing Protocol.....	90
7.3.3 Optimum Density of Cluster Heads.....	94
7.4 Application Specific Parameters.....	96
7.4.1 Data Aggregation in a Clustered Structure Sensor Network	99
7.4.2 Route Setup and Data Collection Period	103
Conclusion	108
Publication	111
Bibliography.....	114

LIST OF TABLES

Table 5.1: Energy consumption parameters for atheros2004 tri-mode chipset.....	44
Table 5.2: Expected data rate of 802.11g technology.	46
Table 5.3: Calculated wireless transmission energies for different transmission ranges @ 802.11g technology.....	54

LIST OF FIGURES

Figure 2.1: Microsensor node architecture.....	12
Figure 2.2: Berkeley PicoRadio testbed node [43]	14
Figure 2.3: Smart Dust “Laser Mote” [14]	15
Figure 3.1: Sensor network with clustered structure.....	21
Figure 3.2: Clustered structure achieved using LEACH protocol [9].....	25
Figure 4.1: Operation example for Directed Diffusion [27].	32
Figure 5.1: Energy model for communication between two sensor nodes.	37
Figure 5.2: Received signal strength based on the transmission range for different transmitted powers.	38
Figure 5.3: Transmission range division into smaller distances through the use of relay nodes.	40
Figure 5.4: “Data Aggregation” reduces the number of data bits injected into the network.	41
Figure 5.5 [35]: Expected data rate of different wireless technologies.....	45
Figure 5.6: Comparison between energy consumption for 802.11g @ 1Mbps and the same technology with multi-rate extensions.	47
Figure 5.7: Energy consumption of IEEE 802.11 technologies with constant data rate and multihop communication	49
Figure 5.8: Multihop energy consumption for 802.11a technology.....	50
Figure 5.9: Comparison of multihop energy consumption for different wireless technologies with maximum transmission range equal to 50 meters.....	51
Figure 5.10: Two-dimensional communication inside the cluster.....	52
Figure 5.11: Sensor nodes' distances form cluster head in 2-dimensional space.....	53
Figure 5.12: Communication cost versus distance form cluster head for 802.11a.	56
Figure 5.13: Communication cost versus distance form cluster head for 802.11g.	56
Figure 5.14: Cluster head positioned at the center of the cluster.	57
Figure 5.15: Cumulative communication cost between sensor nodes and the cluster head versus distance form the cluster head for both clusters with centered and cornered positioned cluster heads.	59
Figure 5.16: Communication cost between sensor nodes and the cluster head versus distance form the cluster head for both clusters with centered and cornered positioned cluster heads.	59
Figure 6.1: Initial cluster head starts the advertisement process, cluster head candidates send cluster head declaration signal within the range of d_r	64
Figure 6.2: If two cluster head candidates could hear the cluster head declaration signal of each other, one of them should be eliminated through negotiation.	64
Figure 6.3: Cluster head candidates send the cluster head exploration signal to find new cluster head candidates within the range of (e_{r1}, e_{r2})	65
Figure 6.4: DEEP algorithm pseudo-code.	68

Figure 6.5: Initial cluster head candidate, which is placed at the center of the sensor field, starts the simulation by advertising its candidacy. Cluster heads are gradually dispersed across the network. This picture shows the final generated clusters while nodes are directly connected to the associated cluster heads.	70
Figure 6.6: Number of cluster members for each generated clusters.....	71
Figure 6.7: Average distance between sensor nodes and the cluster head for each cluster.	72
Figure 6.8: Performance of DEEP protocol for different chosen protocol parameters.	73
Figure 6.9: Each round of re-clustering process in DEEP protocol generates a new set of cluster heads.	75
Figure 6.10: Accumulative percentage of the nodes that have been chosen as cluster head till the end of each round.	76
Figure 6.11: Number of generated cluster heads at the end of 27 rounds of re-clustering will dramatically drop.	76
Figure 6.12: DEEP generates well-distributed cluster heads across the network.	78
Figure 6.13: Energy (μ J) consumed by each cluster head to receive one bit of information from all of the sensor nodes in the cluster.....	79
Figure 6.14: Standard deviation among CHs' intra-cluster energy consumption for LEACH is always greater than the same parameter for DEEP.	79
Figure 7.1: Interest signal structure.....	83
Figure 7.2: Local base station starts the route discovery process by generating interest signals.	84
Figure 7.3: Total energy consumption in the network versus sent data packets to the base station for both protocols LEACH and proposed DEEP using 802.11g technology.....	89
Figure 7.4: Standard deviation among intra-cluster communication energy consumption associated with cluster heads.....	91
Figure 7.5: Maximum range of transmission for the interest signals.....	92
Figure 7.6: Total energy consumption inside clusters and among cluster heads.	93
Figure 7.7: Total data communication energy consumption in the network along with energy consumption associated with interest flooding.	94
Figure 7.8: Standard Deviation among intra-cluster, inter-cluster and route setup communication energy consumption in cluster heads.	96
Figure 7.9: State transition diagram for a sensor node operating in a network with event-driven applications.	98
Figure 7.10: State transition diagram for a sensor node operating in a network with periodic data collection applications.....	99
Figure 7.11: "Data Aggregation" reduces the number of data bits injected into the network.	100
Figure 7.12: "Data Aggregation"; timing and operation delay associated with a relay cluster head.	102
Figure 7.13: Energy consumption in a cluster head as a function of time.	104
Figure 7.14: Route setup period as a function of data collection period.....	107

CHAPTER 1

INTRODUCTION

1.1 Energy Demands for Promising Wireless Networks

While digital signal processing, Radio Frequency (RF) circuit design, and sensor technologies are moving toward building low-cost low-power microscopic sensor nodes, networking hundreds or thousands of these unattended sensor nodes is receiving a lot of interests in the research community. Densely deployed wireless networks of tiny, ubiquitous sensor nodes should be able to gather comprehensive information about a large hostile geographical area or movement of an object for surveillance purposes.

Target tracking, security, environmental monitoring, system control, and chemical/biological detection are some of the most important applications of sensor networks. These networks form a new kind of ad-hoc networks with their own characteristics and challenges. Less mobility, dense deployment, and serious energy consumption considerations are some of the exclusive characteristic of microsensor networks. Random distribution of the sensor nodes caused by easy deployment methods such as spreading sensors by helicopters over forests and deserts, or by ships over lakes and seas makes the battery recharge or exchange an impossible fact. Dense deployment and small size of the sensor nodes also create some serious energy consumption considerations. High density implies that periodic battery replacement will be tremendously inconvenient or more likely, impossible, and small size of the nodes

implies limited physical space for batteries. Therefore sensor nodes operate as long as their battery is not depleted.

1.2 Distributed Sensor Networks and Communication Protocols

Energy-aware Medium Access Control (MAC) and routing protocols have become an increasingly popular research topic within the networking community. In general, energy-conscious communication protocols attempt to conserve the sensor nodes' energy by introducing data management protocols that consume the smallest amount of energy while maintaining network connectivity. We can classify these protocols into three main categories:

- Energy-aware MAC protocols,
- Energy-aware routing protocols, and
- Clustering protocols.

Most of the proposed energy-aware MAC protocols aim to use one of the two methods for communication energy reduction: adjusting the transmission power and keeping the transceiver off as long as possible.

Since output power of the sensor nodes' radio should increase by transmission range, adjusting the power for smaller ranges could save energy compared to keeping it in a constant level. This popular approach has been used in many sensor network designs such as [6] and [9]. Also [19] utilizes a control channel for per-packet negotiation of transmit power.

Inspired by the Time Division Multiplexing algorithm, shutting down the radio, when it's not sending data bits, is a popular approach to conserve energy in sensor network. Authors of [20] propose an approach that dynamically set routes and arbitrate medium access to minimize energy consumption using TDMA based MAC. Different operation modes for radio's hardware also use the same strategy to conserve energy. "Sleep mode," introduced in 802.11 IEEE standard groups, is a mode that keeps the radio off until it receives a "wake up" signal from the source. Extensive use of this method can be seen in [21]. Energy-aware routing and clustering protocols also attempt to reduce energy consumption and maximize the network lifetime by controlling communication methodology across the network.

1.2.1 Clustering Protocols

For a large sensor network, clustering can simplify the multihop route discovery process compared to a flat, non-clustered network. Clustering is a process of dividing a network into non-overlapping groups of sensor nodes. Each cluster is managed by a chosen Cluster-Head (CH). Cluster members send data packets to the cluster head, and cluster heads communicate with each other and send the aggregated packet to the Local Base Station. Although formation and maintenance of clusters introduce additional cost of the control messages, clustered structure of the network limits the number of transmissions for multihop routing. Since every node in a clustered network is connected to a cluster head, the route discovery process among cluster heads is sufficient to establish a feasible route in the network.

A robust clustering algorithm should attempt to generate clusters with well-positioned cluster heads and minimize the communication cost inside and outside the clusters. Therefore, geographical position of sensor nodes in the field is one of the most important factors in the cluster formation process. A Global Positioning System (GPS) uses at least four known satellites to find the coordinates of the installed receiver [29]. Since GPS might not be practical in terms of cost and power, several positioning algorithms have been proposed that reduce the necessary number of nodes with self location finder capabilities. APS [29] is a distributed, hop by hop positioning algorithm that extends both distance vector routing and GPS positioning to provide the approximate location of the nodes. A method of accurate localization that intends to find the position using Time-of-Arrival (TOA) and Received Signal Strength (RSS) is proposed in [30]. Bergamo in [31] came up with the simple scheme of using some fixed beacons on the corners of the field, whose signals are used by sensors to compute their relative position. Localization algorithms also introduce additional cost of the control messages and researchers' concern is to reduce its overhead as much as possible.

1.2.2 Energy-Aware Routing Protocols

Due to the exclusive characteristics of wireless sensor network, which is high number of sensor nodes, vast deployment area, and short communication range, sensors' data can not reach to the base station unless some sensor nodes act as relay nodes. Assuming that all sensors can act as a relay node, there could be a large number of possible routes from one data source to the sink. While energy conservation is the most

important consideration for such a network, proper route selection becomes a vital network management decision.

In a clustered network, routing protocol is essential both inside and outside of the cluster. Intra-cluster and inter-cluster routing protocols have been recently considered and studied as one of the most important realm in sensor networks.

1.3 Scope

The central goal of this thesis is to design and evaluate a novel energy efficient clustering protocol and develop a routing protocol for a sensor network with environmental monitoring applications. The proposed Decentralized Energy-Efficient Cluster Propagation (DEEP) aims to establish clusters with uniformly distributed cluster heads. This protocol manages to balance the load among cluster heads by keeping the clusters' circular radius fairly equal. This protocol is completely decentralized, and there is no need for any location finder device or hardware. We also propose an inter-cluster routing protocol compatible with the clustering algorithm that set the most efficient route among cluster heads. Moreover, an accurate, comprehensive communication energy model is crucial and necessary to design a low-energy routing or clustering protocol.

Chapter 2 of this thesis introduces distributed microsensor networks as a newly progressed technology and accentuates some of the most important applications associated with these networks. Furthermore, this chapter reviews some of the on-going projects such as PicoRadio, Smart Dust, and Adaptive Multi-domain Power-Aware Sensors (μ AMPS) as examples for wireless sensor networks. Operational characteristics

and energy consumption sources in wireless sensor networks are other important factors that this chapter examines.

Chapter 3 of this thesis surveys some of the most important clustering techniques and examines their advantages and deficiencies. In addition, centralized and decentralized clustering protocols are described and reviewed. Also, Chapter 3 introduces Low Energy Adaptive Clustering Hierarchy (LEACH) [9] protocol and explains the methodology and execution of this protocol in detail.

Chapter 4 investigates energy efficient routing protocols for ad hoc networks as well as wireless sensor networks. This chapter explains the details of centralized and distributed routing protocols along with reactive and proactive routing. Motivated by on-demand routing protocols, another group of reactive routing protocols that have been proposed to address the exclusive issues of wireless sensor networks such as SPIN [28], directed diffusion [27] and Energy Aware Routing (EAR) [38] are described and compared in this chapter.

In Chapter 5, the specific hardware parameters associated with wireless transmission is explored in depth, and a comprehensive energy model for wireless communication is obtained. While we chose 802.11 standard groups as our preferable wireless technology for this design, multi-rate capabilities associated with these technologies is exploited and utilized. We took advantage of the multi-rate methodology for wireless communication by means of switching to higher data rates for shorter transmission ranges. This approach reduces the energy consumption by lowering the

actual time of data transmission and keeping the transceiver on or awake for a shorter period of time.

Chapter 6 proposes the novel clustering technique, Decentralized Energy-Efficient Cluster Propagation (DEEP) that is based on the idea of starting with a predefined initial cluster head and spreading new cluster head candidates gradually across the network. To optimize energy consumption in terms of intra-cluster and inter-cluster communication, DEEP controls circular radius of each cluster and the relative distance between a pair of adjacent cluster heads. Because of the balanced load among cluster heads, there is no need for frequent re-clustering, but after current cluster heads are out of energy, protocol can rotate the cluster head position among all the sensor nodes. Also identical distance between a pair of neighboring cluster heads lead to the ease of route setup deployment.

Chapter 6 compares the performance of the proposed DEEP protocol with the performance of the protocol LEACH in terms of intra-cluster communication energy consumption and distribution of cluster heads.

Chapter 7 of this thesis introduces the proposed inter-cluster routing protocol and evaluates and compares the overall performance of the proposed protocol while comparing it with a generalized version of LEACH [9] protocol. The proposed Inter-Cluster energy conscious Routing (ICR) protocol establishes energy efficient multihop routes among the chosen cluster heads. This protocol uses interest flooding to establish routes between the base station and cluster heads and employs number of hops and residual energy of the cluster heads as substantial elements of the communication cost for each path. Clustering and routing simulation results, in this chapter, evaluates the

performance of the proposed protocols and compare the proposed DEEP protocol with a generalized version of LEACH.

CHAPTER 2

DISTRIBUTED WIRELESS SENSOR NETWORKS

2.1 Introduction

This chapter introduces distributed microsensor networks as a newly progressed technology and accentuates some of the most important applications associated with these networks. Furthermore, this chapter reviews some of the on-going projects such as PicoRadio, Smart Dust, and Adaptive Multi-domain Power-Aware Sensors (μ AMPS) as examples for wireless sensor networks. Operational characteristics and energy consumption sources in wireless sensor networks are other important factors that this chapter examines.

2.2 Sensor Network Applications

Dense deployment and small size of the sensor nodes gives wireless sensor network a new kind of scope that can be applied to a wide range of uses.

These applications can be divided into three categories [39], [41], and [42]:

- Monitoring spaces,
- Monitoring things, and
- Monitoring the interaction of things with each other and the surrounding space.

The first category includes environmental and habitat monitoring, agricultural applications, indoor climate control, surveillance, and intelligent alarms. The second includes structural monitoring, eco-physiology, equipment maintenance, medical diagnostics, and urban land mapping. The most spectacular applications involve monitoring complicated interactions, including wildlife habitats, disaster management, fire detection, emergency response, ubiquitous computing environments, asset tracking, healthcare, and manufacturing process flow.

2.2.1 Environmental Monitoring

Many initial wireless sensor networks have been deployed for environmental monitoring, which involves collecting organized readings over time across a large space. Researchers are using wireless sensor networks to monitor nesting seabird habitats and microclimate chaparral transects and to conduct analogous studies of contaminant propagation, building comfort, and intrusion detection. One example, monitoring the microclimate throughout the volume of redwood trees, helps form a sample of entire forests.

Another application to consider is monitoring reservoir waters in terms of pollutions, toxins, and other contaminations that might have been dropped to or entered the water for any possible reason. Also other factors such as temperature and pH level of the water along with other chemical and biological characteristics can be monitored and measured using wireless sensor networks. While protecting water from chemical and

other types of toxins is an inevitable must, controlling pH level of the drinking and agricultural water can elevate the quality of the provided water.

For this application, sensor nodes are scattered and distributed randomly over the reservoir or the lake using helicopters or boats. It is predicted that for toxic detections, sensors should be placed in average no more than 10m away from each other. This means that for the lake with dimensions of 1 mile x 1 mile, around $\frac{1610 \times 1610}{100} = 25,921$ sensor nodes should be distributed in order to cover the entire lake. Therefore, in order to make the communication possible, we consider deployment of some nodes with no energy constraint as Local Base Stations (LBS). These LBS's are responsible for controlling and collecting the information from a fraction of these huge numbers of nodes and directly sending the information to the base station that is located far from the reservoir.

2.2.2 Motion Monitoring

Monitoring objects presents different challenges and opportunities. Many applications can be viewed as a form of condition-based maintenance. A physical structure, such as a machine, motor, airplane wing, bridge, or building has typical modes of vibration, acoustic emissions, and responses. Wireless sensor networks offer a particular approach: performing local processing at each device and transporting the data continuously to operations staff. Sampling rates are much higher than with

environmental monitoring—typically about 100 Hz for vibration analysis and several kilohertz for acoustic analysis.

This requires more energetic sampling activity and greater care in how the network performs sampling. Buffering the data requires greater amounts of storage, and the system potentially performs more extensive local processing on data chunks sampled intermittently.

2.3 Microsensor Node Hardware

Figure 2.1 presents a generalized architecture for a microsensor node. Observations about the environment are gathered using some sensing subsystem consisting of sensors connected to an analog-to-digital (A/D) converter.

Figure 2.1: Microsensor node architecture.

The processing subsystem of the node can digitally process the data after it is provided by the sensor unit. Processing subsystem includes microprocessor, RAM, and ROM for data and program storage. ROM memory is used to store relevant data processing algorithms and communication protocols code. In order to deliver data or control messages to the neighboring nodes, data is passed to the node's radio subsystem. Finally, power for the node is provided by the battery subsystem including DC-DC converter to provide the voltages required by the mentioned components.

2.3.1 Examples of Microsensor Nodes

The PicoRadio project [13] aims to create an ultra low power wireless sensor network with tiny sensor nodes that don't weight more than 100 grams. The cost for this node shouldn't be more than a dollar and they are facilitated by an integrated radio with an energy dissipation of less than 5 nJ per communicated bit and an average power dissipation of 100 μ W, while a Bluetooth radio consumes more than 100 milliwatts. These aggressive energy and power targets are to be achieved through system-on-chip integration and event-driven operation. Figure 2.2 illustrates a prototype of PicoRadio testbed node developed with off the-shelf components.

Smart Dust [14] is an ongoing research project whose main goal is to integrate sensor hardware along with a complete communication system into a cubic millimeter autonomous sensor device. The Smart Dust project sacrifices some degree of functionality for small size. Smart dust *moten* (many, tiny nodes), easily the smallest microsensor prototypes in development, are targeted for ubiquitous applications.

Particularly, the choice of optical communication using lasers and micromirrors is noteworthy. These optical communication structures require substantially less energy and physical space than radio communication due to high antenna gain from the focused laser beam.

Figure 2.2: Berkeley PicoRadio testbed node [43].

Optical communication systems can consume well under 150 milliwatt of energy while demonstrating about 21km communication ranges—over thousand times longer than RF-based systems. Figure 2.3 shows the laser Mote developed to sense temperature, light, pressure, and humidity while communicates by reflecting an incident laser from a base station.

The Adaptive Multi-domain Power-Aware Sensors (μ AMPS) [45] project at MIT is designing a series of microsensor nodes that highlight power aware system design techniques. While the eventual goal of μ AMPS is a sensing system-on-chip, the first prototypes have been built with off-the-shelf components for rapid demonstrations of power aware design techniques.

Figure 2.3: Smart Dust “Laser Mote” [14].

The μ AMPS-1 node, a recent prototype node for the μ AMPS project, is composed of an acoustic sensor, StrongARM SA-1110 processor, low-power static and non-volatile memory, and a 2.4 GHz transceiver.

2.4 Operational Characteristic of Microsensor Networks

Dense deployment and small size of the sensor nodes create some serious energy consumption considerations. High density implies that periodic battery replacement will be tremendously inconvenient—and more likely, impossible, and small size of the nodes implies limited physical space for batteries. State-of-the-art lithium battery offers an energy density of about 2 kilojoules per cm^3 [15]. Assuming that 1 cm^3 is available within the node for the battery, the resulting battery capacity for the node is 2 kJ. This amount of energy would allow for the transmission of 8600,000 ten-kilobit packets (26 minutes of transmission) over a commercial 802.11g transceiver with 54 Mbit/sec speed [16]. Considering the fact that sensor network lifetime is defined to be at least more than a year, energy conservation strategies are essential for achieving the lifetimes necessary for feasible applications.

Microsensor networks' operational characteristic, unlike any other current paradigm in wireless communication, highly depends on its specific applications. Consider applications such as monitoring chemical/biological conditions of reservoir water or forest fire detection. These applications require at least 10 meter distance between sensor nodes so that the entire area of interest is covered by the sensors. While communication transmission range is less than 100m in IEEE standards like 802.11b and 802.11g and less than 50m in 802.11a, direct communication from nodes to the “Base Station” or “Command Node” is practically impossible.

2.5 Energy Consumption Sources

2.5.1 Digital Processing Energy

In order to implement the communication protocols and algorithms and also process the raw data from the sensors, digital processing circuitry is a necessary part in sensor node's architecture. Energy consumed by digital circuits consists of dynamic and static energy consumption. Dynamic energy is defined as [46]:

$$E_{Dynamic} = CV_{DD}^2 \quad 2.1$$

Where C is the switching capacitance and V_{DD} is the power supply. Static energy is defined as [46]:

$$E_{Static} = tV_{DD}I_0e^{\frac{V_{DD}}{nV_T}} \quad 2.2$$

The static dissipation term, originating from the undesirable leakage of current from power to ground at all times, is set by the thermal voltage V_T , and constants I_0 and n that can be measured for a given process technology.

For the ARM7TDMI processor, the cost for each instruction line is around 1 pJ [17]. The main goal for researchers and designers in smart dust project is to lower the microcontroller energy consumptions to less than 0.1pJ/instruction/bit and less than 10nW leakage energy in 1-100kHz operation frequency [18]. These operating goals will

be achieved through novel microcontroller architecture, reconfigurable data path components, data-driven operation, and element-level power cycling.

2.5.2 Radio Transmission Energy

The energy consumption of the radio consists of power consumed by the analog electronics (like VCO, PLL...), and the radiated RF energy used by the power amplifier. The radiated RF energy depends on the transmission range to power of 2, 3, or 4 based on the environmental conditions. The average power consumption of a microsensor radio can be described by:

$$E_{on} = (E_{tx} \cdot t_{on} + E_{tx} \cdot t_{st}) + (\eta_{amp} \cdot P_{out} \cdot t_{on}) + (E_{rx} \cdot t_{on} + E_{rx} \cdot t_{st}) \quad 2.3$$

where E_{tx} is the energy consumed by the transmitter circuitry, and E_{rx} is the energy consumed by the receiver circuitry (Watt). P_{out} is the output transmit power, t_{on} is the time that the transceiver spend to send or receive the data bits, while t_{st} is the start up time for the analog circuits.

Basically t_{on} is equal to $\frac{N_{bits}}{DataRate}$, more Number of bites means more

transmission time while higher data rates speed up the transmission and reduce the t_{on} .

t_{st} is the time that internal Phase Locked Loop (PLL) of the transceiver needs to lock in to the desired carrier frequency, and it heavily depends on the performance of the PLL.

The effect of the transceiver startup time t_{st} will greatly rely on the type of MAC protocol used. To minimize power consumption, it is desired to have the transceiver in a sleep

mode as much as possible however constantly turning on and off the transceiver also consumes energy since each time the t_{on} is needed before the radio can even start the transmission/reception.

2.5.3 Protocol Overhead

Communication protocols specifically media access and routing protocols introduce additional overhead to wireless communication. Due to the dense deployment and short communication range of the sensor nodes, strong MAC and routing protocols are needed to avoid collision and find the proper path for data packets to move forward through out the network.

MAC protocols usually perform channel reservation by sending periodic control packets. Routing protocols, on the other hand, use control signals to find, establish, or maintain a desired communication path. Also nodes' information such as energy level or geographical position might be obtained from the control signals. While these are often necessary and useful functions, each packet that does not carry application data contributes to protocol energy overhead. Finally, the energy overhead of packet headers sometimes can be significant. Protocols with long packet headers produce an identical inefficiency since a lot of energy will be spent to send and receive the header bits while the actual data doesn't need that much of power. Therefore designing a suitable packet format and communication protocol that doesn't contribute tremendously to the energy overhead is crucial.

CHAPTER 3

ENERGY EFFICIENT CLUSTERING PROTOCOLS

3.1 Introduction

This chapter surveys some of the most important clustering techniques and examines their advantages and deficiencies. In addition, centralized and decentralized clustering protocols are described and reviewed. Also, this chapter introduces Low Energy Adaptive Clustering Hierarchy (LEACH) [9] protocol and explains the methodology and execution of this protocol in detail.

3.2 Energy Efficient Clustering Techniques

In large networks, usually including thousand of nodes, clustering techniques can enable scalability, resource allocation, data aggregation, and energy conservation. While for sensor nodes that are far away from the Local Base Station (LBS), direct communication is not possible, multihop communication can put a lot of burden on the nodes that are closer to the LBS because they have to act as relays for the rest of the network. Also bandwidth allocation would be extremely difficult if all of the sensors try to send data packets.

Clustering is a technique that divides a network into non-overlapping groups of sensor nodes. Each cluster is managed by a chosen Cluster-Head (CH). Cluster members send the data packets to the cluster head, and cluster heads communicate with each other

and send the aggregated packet to the Local Base Station. Periodic re-clustering can select nodes with higher residual energy to act as cluster heads. Network lifetime is prolonged through (i) reducing the number of nodes contending for channel access, (ii) summarizing network state information and updates at the cluster heads through intra-cluster coordination, and (iii) routing through an overlay among cluster heads, which has a relatively small network diameter.

TDMA can be a chosen medium access method inside the cluster, and cluster heads can manage the time slots among the sensor nodes. Many clustering algorithms in various contexts have been proposed in the past [1-10], but to our knowledge, they either neglect the energy consumption considerations or make assumptions that are not practical to apply in terms of network geometry and dimensions.

Figure 3.1: Sensor network with clustered structure.

Clustering techniques can be divided into two major categories:

- Centralized clustering

- Decentralized clustering

3.2.1 Centralized Clustering Techniques

Centralized clustering protocols require the sensor nodes to send their individual information such as energy level and geographical position to the central base station. Base station then calculates the optimum number of members for each cluster, number of cluster heads, and cluster heads' position based on the predefined algorithm and informs each node about their newly assigned duty.

Reference [1] presents two different methods to solve this problem: Subtractive clustering and Fuzzy C-mean. Subtractive clustering assumes that each node can act as a cluster head and based on the density of the network calculates the measure of the likelihood for each node to be assigned as a new cluster head. However, Fuzzy C-mean is a data clustering algorithm that defines a membership grade for data points. In [2] authors try to solve the problem of finding N nodes among A available nodes for the cluster head title by equalizing the number of nodes in each cluster. K-clustering is a centralized method that attempts to balance the load among clusters by defining clusters that have equal number of members [3],[4],[5]. Considering the initial assumption that sensor network consists of thousands of nodes, its practically impossible for base station to collect information about every single node in the network and calculate the optimum cluster head geographical position prior to the cluster setup phase. Therefore centralized clustering is not an option for the large sensor networks.

3.2.2 Decentralized Clustering Techniques

Decentralized clustering techniques attempt to force the sensor nodes to collaborate with each other and create clusters without the help of any centralized base station. These clusters should be formed in a way that energy consumption inside the clusters and among the cluster heads is minimized. The authors in [6] present an energy efficient hierarchical clustering algorithm wherein each sensor nodes become a cluster head with probability p and advertises its candidacy to nodes that are no more than k hop away from the cluster head. In order to find the optimum value of k and p , authors uses ωd^n as a substantial energy model for the transceiver power consumption while we will prove in Chapter 4 that wireless communication energy model could not follow the ωd^n rule due to the dominating distance independent term and *multi-rate* communication. On the other hand, hierarchical clustering is not practical because wireless technologies have a limited transmission range, and as level of hierarchy grows, cluster heads get further from each other and can not reach the upper layer leader. Max-Min d-Clustering [7] [8] creates d-hop clusters, but there is no energy optimization associated with the algorithm.

Low Energy Adaptive Clustering Hierarchy (LEACH) is another decentralized clustering algorithm [9]. In this protocol, nodes elect themselves as cluster heads randomly and broadcast their candidacy to other nodes. Nodes that can hear the broadcast message of more than one cluster head candidates will choose the one with higher received signal energy. Although number of cluster heads can be controlled through the choice of algorithm parameter, there is no guarantee about the cluster head's position and

distribution. As a result, no optimization in terms of energy can be achieved with this algorithm. LEACH-C is the author's solution in order to fix the problem of energy conservation. They suggest turning the algorithm into a centralized clustering protocol that form the clusters and optimizes energy consumption. But still the problem of collecting the energy level and geographical position of all the sensor nodes exists.

To summarize, a robust clustering technique should attempt to reduce the energy consumption, balance the load among sensor nodes, and prolong network lifetime.

3.3 Energy Adaptive Clustering Hierarchy (LEACH)

LEACH [9] is an application-specific protocol architecture that aims to prolong the network lifetime by periodic re-clustering and change of the network topology. The operation is divided into *rounds*, which consists of clustering phase and steady-state phase for data collection.

At the start of each round, sensor nodes randomly choose a number between 0 and 1. Then compare this number with a calculated threshold called $T(n)$. If $T(n)$ is larger than the chosen number, the node becomes a cluster head for the current round. $T(n)$ is calculated using the following formula:

$$T(n) = \begin{cases} \frac{p}{1 - p \times (r \bmod (1/p))} & \text{If } n \in G \\ 0 & \text{Otherwise} \end{cases} \quad 3.1$$

Where p is the percentage of the cluster heads and r is the number of round. G is a set of nodes that haven't been chosen as cluster head for the last $1/p$ rounds. For the first round($r=0$), $T(n)$ is equal p and nodes have equal chances of becoming cluster heads. After that, as r gets closer to $1/p$, $T(n)$ increases and nodes that haven't been chosen as cluster head in the last $1/p$ rounds will have more chance to become a cluster head. After $1/p - 1$ rounds $T(n)$ will be equal to one, this means that remaining nodes will certainly be chosen as cluster head. So after $1/p$ rounds all the nodes have had a chance to become a cluster head once. Since being the cluster head puts a lot of burden on the sensor nodes, this ensures that there is no overly-loaded node in the network that runs out of energy way sooner than the others.

Figure 3.2: Clustered structure achieved using LEACH protocol [9].

After cluster heads are self-elected, they start to advertise their candidacy to the other sensor nodes. All cluster head candidates use the same level of output power energy for the advertisement phase. When a sensor node receives advertisement from more than one cluster head candidates, it starts to make a decision about its corresponding cluster head.

Each node will listen to the advertisement signals and chooses the candidate whose associated signal is received with higher power; this ensures that each sensor node chooses the closest candidate as cluster head.

The above implementation of LEACH algorithm is distributed because it can be accomplished by local computation and communication at each node, rather than the transmission of all the nodes' energy level and geographical position to a centralized point. However, cluster heads will be chosen randomly and there is no optimization in terms of energy consumption for intra-cluster or inter-cluster communications.

CHAPTER 4

ENERGY CONSCIOUS ROUTING PROTOCOLS FOR WIRELESS AD HOC NETWORKS

4.1 Introduction

In this chapter we investigate energy efficient routing protocols for ad hoc networks as well as wireless sensor networks. This chapter explains the details of centralized and distributed routing protocols along with reactive and proactive routing. Motivated by on-demand routing protocols, another group of reactive routing protocols that have been proposed to address the exclusive issues of wireless sensor networks such as SPIN [28], directed diffusion [27] and Energy Aware Routing (EAR) [38] are described and compared in this chapter.

4.2 Energy Conscious Routing Protocols

In general, wireless networks that operate without the need of a fixed infrastructure are called ad hoc networks. Traditional proactive routing protocols are not efficient for such networks because of the unnecessary route discovery phases that waste limited energy resources. Due to the exclusive characteristics of wireless sensor networks, which is high number of sensor nodes, vast deployment area, and short communication range, sensors' data can not reach to the base station unless some sensor nodes act as relay nodes. Assuming that all sensors can act as a relay node, there could be a large number of possible routes from one data source to a sink. While energy

conservation is the most important consideration for such a network, proper route selection becomes a vital network management decision.

To distinguish among all of these possible routes, cost function defines a value or weight for each route based on the parameters such as distance, number of hops, connection set up, and delay. Authors of [22] have introduced a comprehensive cost function for a specific communication path in the network. To find the proper path, two major approaches can be used:

- Centralized route selection protocols, and
- Distributed route selection protocols, which is classified into two main category:
 - Proactive routing, and
 - Reactive routing.

4.2.1 Centralized Route Selection Protocols

Centralized route selection algorithms aim to choose the appropriate next neighbor for each node using a central command node. This command node collects the information about direct paths' cost and geographical position of the nodes and finds the least cost path using shortest path algorithms such as Dijkstra [23]. CSEAR is a protocol proposed in [24] that chooses TDMA along with centralized routing to minimize energy consumption.

4.2.2 Distributed Route Selection Protocols

On the other hand, wireless networks that perform distributed routing leave the route selection decision to the sensor nodes by themselves. Nodes with proactive route selection algorithms such as link state routing and Distance Vector Routing (DSDV) [23] keep a routing table that contains next hop information to every single node in the network, however, periodic routing table updates might not be efficient since not every node in sensor network needs to communicate to every reachable destination. Also link-state protocols are not operating well in sensor network environment due to the same reason.

On the other hand, reactive routing protocols set the route to the desirable destination only when it's needed. Both data-source and data- destination can initiate the route request and establish a path or spanning tree. For ad-hoc wireless networks, Dynamic Source Routing (DSR) and Ad-Hoc On-Demand Vector Routing (AODV) are the examples of reactive routing [26]. DSR [36] uses source routing which means that each packet includes a complete ordered list of the nodes that it has to pass to reach the destination. Therefore the intermediate nodes don't have to look for the next hop in their memory; the next hop address is already in the header. However, source node should perform a route discovery stage before sending the packet. To do so, the source node floods the network with the ROUTE REQUEST packet. Each node that knows the path to the requested destination replies with a ROUTE REPLY packet that includes the entire path carried by the request packet.

AODV [37] is also an on-demand routing protocol, however its based on the idea of hop-by-hop routing rather than source routing. It means that when a node wishes to establish a route to a destination, it broadcasts a ROUTE REQUEST message to its neighbors. Each node that receives a ROUTE REQUEST packet creates a *reverse route* and saves the address of the nodes that has sent the packet. Then it broadcasts the request packet until it reaches the destination or a node that knows the path to the destination. This node replies to the request message with a ROUTE REPLY packet and all intermediate nodes create a *forward route* by saving the address of the neighbor that has sent the packet. Although these protocols perform efficiently in ad hoc mobile networks, they are not specifically designed to fit within sensor networks exclusive conditions and its crucial energy consumption consideration.

Motivated by on-demand routing protocols, another group of on-demand reactive routing protocols have been proposed to address the exclusive issues of wireless sensor network. SPIN [28] and directed diffusion [27] introduce a concept of “interest” propagation whenever a node wants to send data or a source needs to ask for it. Flooding the network with interest signals will establish a path from a sink to every possible source (spanning tree). While directed diffusion reinforces the paths with higher data rate, SPIN concentrates exclusively on the path set up via negotiation.

4.3 Directed Diffusion

Directed Diffusion [27] is a data-centric on-demand routing protocol that performs data aggregation to conserve energy and reduce number of transmissions. It's a

destination-initiated protocol, which means that sink starts to flood the network with *interest* signal whenever any *type* of data is required from the sensors (Figure 4.1a).

Interest signal includes a specified *rect* (geographical area of interest) and duration for the requested data. It also includes an *interval* parameter that specifies the requested data rate from the neighbor. A direction that *interest* signals come from is called *gradient*. When a node receives an interest signal, it checks to see if the same interest signal exists in the memory. If no, it makes an entry for the message and saves the address of the neighbor who has sent the signal as a *gradient* (Figure 4.1b). Then the node starts to broadcast the interest to its neighbors, and the same process continues until interest reaches to the specific area that was originally intended by the sink. At this point, due to the flooding of the interest message, more than one path is established between destination and source.

When a sensor node in that *rect* detects a target, it searches in its memory for the matching interest. After that, it computes the highest requested data rate and sends the data through the corresponding gradients. Every node in the path that receives the data packet performs the same procedure until the sink receives the data. In the *Reinforcement for path establishment* stage, sink sends positive reinforcement to specific paths by decreasing the interval field or increasing the requested data rate. Using this method, sensor nodes are forced to use a path with higher data rate (Figure 4.1c). Also this method could be used to negatively reinforce a path by decreasing the data rate while a better path exists.

Figure 4.1: Operation example for Directed Diffusion [27].

Although Directed Diffusion introduces a novel approach for sensor networks routing, path selection method does not consider the wireless communication cost or weight of each path. Therefore energy conservation is not a primary concern in the design of this protocol.

4.4 Energy Aware Routing (EAR)

EAR [38] is a similar approach to directed diffusion. It's an on-demand destination-oriented scheme and has three distinct phases:

- Setup phase or interest propagation,
- Data Communication phase, and
- Route maintenance.

4.4.1 Setup Phase

In this phase, sink or destination propagates an interest signal to find all the possible paths from sink to different sources. However, EAR included a cost field that represents the communication cost or energy of that specific path. Sink initiates the set up phase by setting the cost field to zero. Each intermediate node that receives the interest signal only propagates the request to the nodes that are further away from the sink and closer to the source. Therefore localization is an important factor in this protocol. Each node should have a broad view of the network to realize the relative distance between neighbors and the source or the sink. After receiving the request, if node i has sent the signal to node j , node j calculates the total cost of the path as:

$$C_{ij} = Cost(ij) + C_i \quad 4.1$$

Where C_i is the total cost of the path up to node i , and can be found in the cost field of the interest signal. $Cost(ij)$ is the defined cost of the path between node i and node j .

At this point, any interest entry that has a cost field less than some threshold number will be saved in the node's memory. Only the ones that have a very high cost field will be discarded.

Now, node j assigns a probability to every interest entry as while k is the number of interest messages received with the same *type* and *rect* field but different sender's address, i.e. they represent different communication paths in the network:

$$P_{ij} = \frac{\frac{1}{C_{ij}}}{\sum_k \frac{1}{C_{kj}}} \quad 4.2$$

This probability is inversely proportional to the cost of that specific path. After calculating the probabilities, node j can find the average cost of all possible paths to destination as:

$$C_j = \sum_k P_{kj} \times C_{kj} \quad 4.3$$

where node j sets the cost field of the outgoing interest signal to C_j . The problem with this phase of this protocol is the fact that each node has to wait for all the interest signals to come and then calculate the average cost between oneself and the destination. Also it does not put a limit on interest flooding since In the EAR protocol, sensor nodes save and propagate most of the incoming interest signals and only eliminate the ones with very high cost field.

4.4.2 Data Communication Phase

When an interest signal reaches a source node, and the source is ready to send the requested data, it randomly chooses one of the neighbors based on their associated probabilities saved in the memory, and sends the data packet to that neighbor. Each intermediate node that receives the data packet also randomly chooses a neighbor from the saved interest entries in the memory to send the packet to. This procedure continues until the data packet reaches the destination. Using this method, EAR tries to prevent

over-utilization of one optimal path. It means that not every time the data packet moves in the same route and depletes the nodes along that path. For the route maintenance phase, EAR performs localized flooding between sink and source to ensure paths are alive.

Energy metric or cost function is a very important component of the protocol. It could be chosen based on the residual energy of the nodes to increase the cost of the paths with low energy nodes, or it could be proportional to the wireless communication energy consumption of that specific path to avoid paths with high energy consumption.

CHAPTER 5

COMMUNICATION ENERGY MODEL

5.1 Introduction

In this chapter, the specific hardware parameters associated with wireless transmission is explored in depth, and a comprehensive energy model for wireless communication is obtained. While we chose 802.11 standard groups as our preferable wireless technology for this design, multi-rate capabilities associated with these technologies is exploited and utilized. We took advantage of the multi-rate methodology for wireless communication by means of switching to higher data rates for shorter transmission ranges. This approach reduces the energy consumption by lowering the actual time of data transmission and keeping the transceiver on or awake for a shorter period of time.

5.2 Wireless Communication Energy Model

Wireless communication energy model consists of five major blocks: transmitter's digital physical layer (PHY) and Medium Access Control (MAC) functions, transmitter's RF circuitry including Phase Locked Loop and Voltage Control Oscillator (VCO), power amplifier, receiver's RF circuitry, and receiver's digital functions. Figure 5.1 illustrates the energy model for communication between two sensor nodes.

Figure 5.1: Energy model for communication between two sensor nodes.

The most basic model of radio wave propagation is called "free space" radio wave propagation. In this model, radio waves emanate from a point source, travel in all directions in a straight line, and fill the entire spherical volume of space with radio energy that reduces in strength with $\frac{1}{d^n}$ ($2 < n < 4$), or 20 dB decrease in energy per decade increase in range. With d being the distance between the transmitter and the receiver, the received power is expressed as [32]:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, d > 0 \quad 5.1$$

While P_t is the transmitted power, G_t is the transmitter gain, G_r is the receiver gain, λ is the operation wavelength, and L is the additional losses in the system such as filter losses and antenna losses that is not related to the propagation losses [32]. We can express the free space loss as:

$$L_{free} = -20 \log_{10} \left(\frac{\lambda}{4\pi d} \right) dB \quad 5.2$$

But in the real world the power loss follows an exponent of a higher order, and it can be shown as:

$$P_{loss} = \omega d^n \quad 5.3$$

where n could be a number between 2 and 4 based on the environmental conditions, and ω models the free space path loss. For the receiver to be able to capture the signal and process it properly, the signal power level should be at some threshold point which is called “receiver sensitivity”.

Figure 5.2: Received signal strength based on the transmission range for different transmitted powers.

Therefore the transmitter amplifier should amplify the signal more than the anticipated path loss so that the signal could be detected without error. In general, we can summarize the sum of all transceiver energy components as:

$$E = \theta + \eta_{amp} \times \omega d^n \quad 5.4$$

where θ is a distance-independent term that accounts for overheads of the radio electronics and digital processing, and ωd^n models the attenuation of a transmission path. n could be a number between 2 and 4 based on the environmental conditions, and η_{amp} stands for the amplifier inefficiency factor and shows the inefficiency of the transmitter in order to generate ωd^n power at the output of the antenna.

5.3 Motivations for Multi-hop Communication

As it's shown previously, energy consumption of wireless transceiver changes with exponents of 2 or higher of the communication range, therefore it seems logical to assume that if we divide the long transmission distance into shorter transmission ranges, we will be able to reduce the total energy consumption:

$$E = \theta + \eta_{amp} \times \omega d^n \quad 5.5$$

In this case d is divided by number of hops (m), and total energy consumption is multiplied by m :

$$E = m \times \left[\theta + \eta_{amp} \times \omega \left(\frac{d}{m} \right)^n \right] \quad 5.6$$

In wireless sensor networks, long transmission ranges and limited power supply yield to the introduction of relay nodes (Figure 5.3). These nodes not only sense the environment and send their own data to the Local Base Station (LBS), they also act as a relay for nodes that can not reach the LBS directly by means of passing their data packets to the next neighbor (one step closer to the LBS).

Figure 5.3: Transmission range division into smaller distances through the use of relay nodes.

Another important advantage of the relay nodes is “Data Aggregation” [33]. Because of the high density of sensor networks, nodes that are geographically closer to each other might sense the same event or try to send the similar environmental information (Figure 5.4). In order to reduce the diffusion of spare data bits in to the network, relay nodes can receive the data packets, each of length L , from N nodes and aggregate them into one single packet of length L . This will reduce the number of data bits forwarded by the relay node from NL to L .

Figure 5.4: “Data Aggregation” reduces the number of data bits injected into the network.

5.4 Multihop versus Direct Communication

In order to compare the performance of multihop communication versus direct communication, two important issues should be considered: real world wireless transceiver’s power consumption parameters, and multi-rate wireless communication.

5.4.1 Wireless Communication Standards

Today’s popular IEEE 802.11 for wireless local area networks (WLANs) has changed the face of networking. This group of standards provides high speed data transmission and tremendous flexibility for mobile users. The enhancements in data rates and functionality of 802.11 technologies are leading to rapid progression of the WLAN market. For instance, the new 802.11g standard provides the widest possible range of both OFDM data rates of 54, 48, 36, 24, 18, 12, 9, and 6 Mbps, and the CCK rates of 11, 5.5, 2, and 1 Mbps.

Meanwhile, IEEE 802.15 for Wireless Personal Area Networks offers short range, low data rate, and low power communication for small networks. Applications in personal space networking such as office, room, briefcase, pocket, and car are the inherent results of this technology. IEEE 802.15.4 [40], however, is a new technology with very low complexity and cost-efficient solutions. Sensor networks along with interactive toys, smart badges, remote controls, and home automation have been considered as some of the potential applications of this new standard.

Low complexity associated with 802.15.4 leads to lower energy consumption in terms of Joule/sec. However, low data rates (around 250Kbps) elevate the transmission time of the actual data bits and keep the sensor node active for a longer time leading to more energy consumption. Therefore, there is an inherent trade off between the energy consumption regarding the actual data transmission and the energy consumption associated with the time that sensor nodes spend in sleep mode.

For this thesis, we chose 802.11 standards as our preferable wireless technology since multi-rate capabilities associated with these technologies give us the flexibility to lower the energy consumption by means of switching to higher data rates for shorter transmission ranges.

5.4.2 Energy of Real World Transceivers

The effects of distance dependent term in the total energy consumption depends on the real world transceiver parameters, θ , η_{amp} , and the path attenuation ωd^n . If the

value of θ is overshadowing the $\eta_{amp} \times \omega d^n$, reduction in the transmission distance through the use of multihop communication wouldn't be effective [25].

To determine the value of the distance dependent and independent parameters, it's essential to find the total power consumption in watt from the manufacturer data sheet. Then we can subtract the maximum output power multiplied by amplifier inefficiency factor, $\eta_{amp} \times \omega d^n$, and estimate the θ (W). Atheros2004 tri-mode chipset [16] has been chosen to observe the real values for the radio hardware. Theoretically, the maximum efficiency associated with power amplifier is 48.4%. However, in practical implementations power amplifier efficiency is less than 40% [34]. Therefore θ is calculated using the assumption $\eta_{amp} = (\frac{1}{0.4} = 2.5)$. To observe the amount of power consumption in joule per bit, all the parameters should be divided by the transmission data rate $\frac{joule}{Sec} \div \frac{bit}{Sec} = \frac{joule}{bit}$. Using this approach, Table 5.1 shows the values for θ and $\eta_{amp} \times \omega d^n$ calculated for the chosen chipset. The values shown in the table are calculated using the following method:

$$\theta = (\theta_{TX} + P_{RX}) = (P_{TX} - \eta_{amp} \times \omega d^n) + P_{RX} = (1.85 - 2.5 \times 0.0251) + 1.20 = 2.987_{Watt} \quad 5.7$$

Table 5.1: Energy consumption parameters for atheros2004 tri-mode chipset.

Mode	Sensitivity (dBm)	Maximum Output Power (dBm) ωd^n [16]	Total Power Consumption(W) [16]	α (Watt)	$\eta_{amp} \times \beta d^n$ (Watt)
802.11a	-72	+14	1.85(P _{TX}), 1.20(P _{RX})	2.987	0.0625
802.11b	-89	+21	1.75(P _{TX}), 1.29(P _{RX})	2.727	0.3125
802.11g	-70	+14	1.82(P _{TX}), 1.40(P _{RX})	3.157	0.0625

Despite the fact that the path attenuation energy increases exponentially by the transmission distance, Table 5.1 shows that the static power consumption of the radio hardware, θ , is dominating the path loss and therefore causing the total power consumption to remain constant as transmission distance increases (Figure 5.5). On the other hand, one of the current developments in ad hoc wireless communication is enabling devices to operate using different transmission data rates. 802.11a, 802.11b, and 802.11g are some of the wireless networking standards that have multi-rate capabilities [35].

Although sensor nodes, in general, generate data in low rates, they can transmit the information using wireless high-speed modulation and techniques. While this technique has never been proposed for sensor networks, multi-rate communication can decrease the transmission energy for smaller distances by switching to higher data rates and keeping the transceiver on for a shorter period of time.

5.4.3 Expected Data Rate of Different Wireless Standards

Physical properties of communication channels cause an inherent tradeoff between obtaining the highest possible data rate while trying to minimize the number of communication errors. In order to maintain connectivity and increase the quality of wireless channel, as transmission distance increases multi-rate wireless technologies provide reduced data rates.

Wireless consumers demand both high speed and long range communication, therefore introducing multi-rate transmission will give them the flexibility to choose among a wide variety of tradeoff points. Figure 5.5 shows the multi-rate capabilities of different wireless technologies. As transmission distance increases the provided data rate will decrease.

Figure 5.5: Expected data rate of different wireless technologies [35].

Table 5.2: Expected data rate of 802.11g technology.

Rate (Mbps)	Max. Range	Rate (Mbps)	Max. Range
1	100m	18	51m
2	76.5m	24	41.25m
6	64.5m	36	36m
9	57m	48	23.1m
12	54m	54	18.75m

The 802.11g standard has the same propagation characteristic as 802.11b, because it transmits in the identical 2.4-GHz frequency band. Because 802.11b and 802.11g products share the same propagation characteristics, implementations provide roughly the same maximum range at the same data rate. Because 5-GHz radio signals do not propagate as well as 2.4-GHz radio signals, the 802.11a product range is limited (50 meter) compared to the 802.11b or 802.11g product range (100m).

Lower data rates would keep the transceiver on for a longer period of time (lower speed) and lead to more energy consumption compared to higher data rates. But there is a strong tradeoff between speed and transmission range that should be taken in to account. Multi-rate communication would also necessitate the presence of a robust rate selection protocol.

As discussed previously, exploiting the multi-rate capabilities of wireless technologies would lead to the reduction of communication energy consumption for smaller distances by switching to the higher data rates and keeping the transceiver on for

a shorter period of time. In this case, as Figure 4.5 illustrates, energy in terms of Joule/bit scales discretely as transmission distance increases.

$$E_{Joule/bit} = \frac{(\theta + \eta_{amp} \times \omega d^n)_{Joule/sec}}{(Rate)_{bit/sec}} \quad 5.8$$

Figure 5.6 shows the energy consumption of atheros2004 radio for 802.11g technology at the constant rate of 1Mbps and the same technology with the multi-rate extension. Due to the large value of θ compared to maximum output power, single rate communication energy remains constant as transmission distance increases while multi-rate communication energy decreases for shorter transmission ranges.

Figure 5.6: Comparison between energy consumption for 802.11g @ 1Mbps and the same technology with multi-rate extensions.

5.4.3 Multihop Communication Efficiency

The pervious discussion considered the real-world radio parameters along with multi-rate capabilities of wireless technologies. This section analyses the efficiency of multi-hop communication from the perspective of both real-world radio parameters and multi-rate transmission.

Examining multihop communication without utilizing multi-rate transmission, we chose the constant rate of 6 for 802.11a, 1 for 802.11b, and 6 for 802.11g and maximum transmission range of 50m while varying number of hops from 1 to 6 within the chosen range. Figure 5.6 illustrates the energy consumption associated with the mentioned technologies. As seen in the figure, constant transmission data rate would lead to the higher energies for higher number of hops because of the fact that although transmission range for intermediate nodes is reduced, energy consumption has not changed. All the intermediate nodes should turn their transceivers on and spend a lot of energy to forward the packet, therefore 4 hop transmissions would consume nearly 4 times as direct communication:

$$E_{watt} = m \cdot (\theta + \eta_{amp} \times \omega (d/m)^n) = m \cdot (\theta + \eta_{amp} \times \omega d^n / m^n) = m (\theta + \eta_{amp} \times P_{out} / m^n) \quad 5.9$$

Therefore, multihop communication does not seem to be efficient while using constant speed or data rate for transmission of data. Also Figure 5.6 demonstrates that due to the lower data rates, 802.11b technologies spend more energy compared to 802.11a and 802.11g in terms of Joule/bit.

Figure 5.7: Energy consumption of IEEE 802.11 technologies with constant data rate and multihop communication.

Therefore 802.11b technologies aren't the best choice for the purpose of this design. But the important issue to consider is the effects of multi-rate communication on energy consumption, which will guide us to a very interesting result for wireless sensor networks.

Considering the fact that with multihop communication, maximum range of transmission would be divided by number of hops and transmission speed would be elevated as a result (5.3), it can be seen in Figure 5.8 that when multi-rate capabilities of 802.11a standard is utilized, direct communication is not efficient after transmission range exceeds 23 meters.

$$E_{Joule/bit} = \frac{m \left[\theta + \frac{\eta_{amp} \times P_{out}}{m^n} \right]}{Rate} \quad 5.10$$

Figure 5.8: Multihop energy consumption for 802.11a technology.

Between 23 and 45 meters maximum range of transmission, 2-hop communication seems to be the least cost method of communication, however, for maximum range of 50 meters, 4-hops appears to be the most efficient one. Comparing the performance of three different wireless technologies 802.11a, 802.11b, and 802.11g, Figure 5.9 shows the optimum point of operation for a one-dimensional wireless network.

Because of the lower speeds associated with 802.11b, the energy consumption is linearly increasing as number of hops rises from 1 to 6.

Figure 5.9: Comparison of multihop energy consumption for different wireless technologies with maximum transmission range equal to 50 meters.

While 802.11a and 802.11g standards are introducing lower energies for higher number of hops, energy consumption will start to increase after 4 hops because of the small transmission distance and constant data rate.

5.5 Intra-Cluster Communication

5.5.1 Two-Dimensional Communication Spaces

So far, we have considered one-dimensional communication spaces, while in the real world we are dealing with 2 or even 3 dimensional spaces.

$$E(d) > E(d_1) + E(d_2) + \dots E(d_n)$$

Figure 5.10: Two-dimensional communication inside the cluster.

In one-dimensional spaces, maximum distance d can be divided into n smaller distances each being equal to d/n , but in two or three dimensional spaces, several multihop paths can be established based on the density of the sensor nodes, therefore, the efficiency of multihop heavily depends on the dimensions and the density of the network.

To investigate the efficiency of multihop communication more thoroughly, Figure 5.11 shows an organization where sensor nodes are placed d meters away from each other, and they tend to send their data packet to the Cluster-Head (CH). Assuming that 802.11g technology is being used in this environment, wireless transmission energies are shown in

Table 5.2. d is an application dependent parameter and can be chosen based on the sensor's characteristics. For toxin detection applications, sensors should be placed in average no more than 10m away from each other.

Figure 5.11: Sensor nodes' distances form cluster head in 2-dimensional space.

With the choice of 10 for d , if node B tries to use node A as a relay node and send the data to the cluster head, total energy of the chosen 2-hop path will be larger than the direct transmission energy:

$$E(\sqrt{2}d) = 0.0517 < E(d) + E(d) = 0.1034 \quad 5.11$$

Table 5.3: Calculated wireless transmission energies for different transmission ranges @ 802.11g technology.

Min-d (m)	Max-d (m)	Energy Consumption (μ Joule/bit)
0	18.7	0.0517
18.7	23.1	0.0581
23.1	36	0.0775
36	41.2	0.1162
41.2	51	0.1789
51	54	0.2683
54	57	0.3578
57	64.5	0.5367
64.5	76.5	1.6100
76.5	100	3.22

Also for node C and D, there is no multihop path that can lead to a better energy consumption value than the direct communication path:

$$E(\sqrt{5}d) = 0.0581 < E(\sqrt{2}d) + E(d) = 0.1034 \quad 5.12$$

$$E(\sqrt{10}d) = 0.0775 < E(\sqrt{5}d) + E(d) = 0.1098 \quad 5.13$$

But if node E first sends the data to the intermediate node D, the total energy consumption will be less than a direct communication path:

$$E(\sqrt{17}d) = E(41.23) = 0.1789 > E(\sqrt{10}d) + E(d) = 0.1292 \quad 5.14$$

5.5.2 Intra-Cluster Communication Energy Consumption

The pervious discussion analytically concluded that direct communication was no more the best possible communication method for nodes that are more than 41.23m away from the cluster head. In order to compare the energy consumption of direct and multihop communication inside the cluster, we set up an environment representing one cluster. The dimension of the field is 50m×50m, and nodes are randomly dispersed over the field. At this point, we assume that the cluster head is chosen randomly among the sensors; later details of cluster head selection algorithm will be explained.

Figure 5.12 shows the energy consumption of direct, minimum energy 2-hop, and minimum energy 3-hop path based on the distance between sensor nodes in the cluster and the cluster head for a chosen 802.11a technology. Figure 5.12 shows that for nodes that are approximately more than 23.4 m away from the cluster head direct communication or 1-hop transmission is no more the best efficient way for data transmission. Figure 5.13 shows the power consumption for direct, minimum energy 2-hop, and minimum energy 3-hop communication paths for a chosen 802.11g technology. For this technology, direct transmission is the optimum choice for ranges less than 37m, which is almost as same as the result from analytical calculations (41m).

Figure 5.12: Communication cost versus distance form cluster head for 802.11a.

Figure 5.13: Communication cost versus distance form cluster head for 802.11g.

Because of the higher data rates associated with 802.11g technologies, they present lower energies and higher optimum ranges for direct transmission. Therefore, from now on, 802.11g is a chosen technology for this specific design.

5.4.3 Intra-Cluster Direct Communication Advantages

As we discussed earlier, MAC and routing protocol control signals can cause unnecessary energy consumption and put a lot of load on the sensor nodes. Routing protocol's control signals includes path set up, maintenance, and signals that carry the individual nodes characteristic such as energy level and geographical position. This information is necessary for the network to make a decision about the optimum multihop path.

Inside the cluster, every single member only needs to transmit its data packet to the Cluster-Head (CH).

Figure 5.14: Cluster head positioned at the center of the cluster.

If we assume that 802.11g is a chosen wireless technology for this sensor network, nodes that are more than 36m away from the cluster head should choose a minimum 2-hop or 3-hop path for communication in order to maintain the energy consumption optimality. Note that maximum wireless transmission range for 802.11g is about 100m. That means that direct communication is a real option for nodes within the range of 36-100m from the cluster head. Finding the optimum 2-hop or 3-hop transmission path requires a strong path selection algorithm that put a lot of weight on the cluster. In order to avoid the frequent control signal transmission and extra power consumption associated with that, cluster head could be placed in the center of the cluster with sensor nodes being placed closer than 37m around it(Figure 5.14.)

In this case, cluster members can send the data packets directly to the cluster head and there is no need for any route set up protocol while optimality is already achieved through the choice of cluster shape and cluster size.

Figure 5.15 compares two different clusters with the same dimensions. *A* is a cluster with the CH being positioned at the center, and *B* is a cluster with the chosen CH at the corner. As this figure shows, the cumulative energy consumption that the centered positioned cluster head should spend to receive one bit of information from all the members is significantly lower than the cumulative energy in cornered positioned cluster head. Also, in cluster *A*, communication energy consumption is distributed more evenly among cluster members than in cluster *B*. As a result, a robust clustering technique is essential in order to configure clusters with almost the same radius and cluster heads that are positioned in the center of clusters.

Figure 5.15: Cumulative communication cost between sensor nodes and the cluster head versus distance form the cluster head for both clusters with centered and cornered positioned cluster heads.

Figure 5.16: Communication cost between sensor nodes and the cluster head versus distance form the cluster head for both clusters with centered and cornered positioned cluster heads.

CHAPTER 6

DECENTRALIZED ENERGY EFFICIENT CLUSTER FORMATION PROTOCOL

6.1 Introduction

The previous chapter has discussed the importance of the cluster head location in the cluster and its effects on the total energy consumption. A robust clustering technique is essential in order to configure clusters with almost the same radius and cluster heads that are positioned in the center of clusters.

Microsensor networks can be rapidly deployed by dropping nodes by air or spraying nodes from a moving vehicle. Since these nodes begin without any knowledge about their location relative to the base station, distributed clustering algorithm should be able to form the clusters without the help of the base station and knowledge of network member's position. Although location finder devices and protocols could be deployed, they are either costly or put too much overhead on the network.

This chapter proposes a Decentralized Energy-Efficient Cluster Propagation (DEEP) Algorithm that aims to establish clusters with uniformly distributed cluster heads across the sensor field. This protocol manages to balance the load among all the cluster heads by keeping the cluster's radius fairly equal. Sensor nodes can implement the protocol without the help of any central base station, and there is no need for any location finder device or algorithm.

The DEEP protocol can be applied to all standards including the 802.15.4 and the 802.11x. Since the 802.15.4 standard was developed specifically to address issues associated with low-rate personal area networks, it utilizes power control for a change of power from 0 to -25 dBm. This reduction of output power results in a decrease in energy consumption by a factor of approximately 4. Because reducing output power decreases the range for received signal detection, controlling the mandatory transmission range between sensor nodes can minimize the energy consumption. As for the 802.11x standard, the popular approach of adjusting the transmission power for shorter transmission ranges in order to reduce energy consumption is not effective due to the high-energy consumption associated with digital circuitry and electronics. This chapter also compares the performance of the proposed DEEP protocol with the performance of the protocol LEACH in terms of intra-cluster communication energy consumption and distribution of cluster heads.

6.2 Decentralized Energy-Efficient Cluster Propagation (DEEP) Protocol

DEEP is based on the idea of starting with an initial cluster head and spreading new cluster head candidates gradually by controlling relative distance between a pair of adjacent cluster heads and circular radius of each cluster. Due to the balanced weight among cluster heads, periodic re-clustering is not necessary and therefore operational expenses caused by frequent re-clustering is eliminated. For the occasional inevitable re-clustering, small shift in the initial cluster head candidate can generate a completely new set of cluster heads without over-utilizing the previously chosen ones.

6.2.1 Protocol Details

In order to explain the details of this protocol, first we introduce control signals and protocol parameters:

- Control signals:
 1. Cluster head declaration signal
 2. Cluster head exploration signal
 3. Membership search signal
- Control Parameters:
 1. Declaration range (d_r).
 2. Exploration range (e_{r1}, e_{r2}).
 3. Minimum number of members (m).
 4. Fixed output power of CH exploration signal (P_{out}).

Protocol control parameters are application specific choices and can be defined prior to the network deployment. Protocol DEEP forms clusters by starting with an initial cluster head candidate that can be chosen prior to the network deployment. This initial cluster head candidate starts the cluster set up phase by propagating cluster head declaration signal within the range of d_r . This means that cluster head candidate chooses the appropriate data rate and signal output power so that it can reach nodes that are less than d_r away from the sender. At this point, sensor nodes that receive the declaration signal accept the corresponding cluster head as a leader. They can estimate their relative distance to the candidate by looking at the received signal energy level. Once they know

the relative distance to the cluster head candidate, they can conserve energy by adjusting the transmission speed to the appropriate value and switching to the sleep mode. Now initial cluster head candidate propagates the cluster head exploration signal within the range of e_{r2} (Figure 6.1). All the sensor nodes that are in this range can listen to the exploration signal but only nodes that have never played the role of cluster head and can verify the following equality will be chosen as a new candidate:

$$E_r > E_{rc2} \ \& \ E_r < E_{rc1} \quad 6.1$$

E_r is the received signal energy and should be bigger than E_{rc1} and smaller than E_{rc2} so that the node can consider itself as a candidate. This ensures that new cluster head candidates are positioned between e_{r1} (m) and e_{r2} (m) away from the initial cluster head. E_{rc1} and E_{rc2} are fixed protocol parameters that can be determined using the following formula:

$$E_{rc1} = P_{out} - \omega(e_{r1})^n \quad 6.2$$

$$E_{rc2} = P_{out} - \omega(e_{r2})^n \quad 6.3$$

P_{out} is the constant output power of the cluster head exploration signal, and ω and n are parameters that can be determined based on the environmental conditions of the deployment area. After new cluster head candidates are assigned, each candidate sends a declaration signal within the range of d_r to find new cluster members.

Figure 6.1: Initial cluster head starts the advertisement process, cluster head candidates send cluster head declaration signal within the range of d_r .

If two candidates could hear the declaration signal of each other, they are too close to each other to be considered both as cluster head candidates. Therefore one of them will be eliminated through negotiation because it shows that the presence of both of them is unnecessary. The negotiation process takes place as follow: whenever a cluster head receives a declaration signal, it informs the sender of the message using an acknowledgement message. The cluster head that receives the acknowledgment sends a dissolution message and informs all nodes within the range of d_r about its elimination.

Figure 6.2: If two cluster head candidates could hear the cluster head declaration signal of each other, one of them should be eliminated through negotiation.

If a node receives declaration signal from more than one candidate, it chooses the candidates whose associated signal is received with higher power. Then, confirmed cluster heads propagate exploration signal and search for new cluster head candidates.

Figure 6.3: Cluster head candidates send the cluster head exploration signal to find new cluster head candidates within the range of (e_{r1}, e_{r2}) .

Nodes that have already been chosen as cluster head or member ignore the cluster head exploration or declaration signals. This process will continue until all the nodes in the field belong to a cluster.

At this point, if there is a cluster that its total number of members is smaller than “Minimum number of members” (m), cluster will be dissolved and all the members including cluster head initiate a *Membership search signal*. Afterwards, they listen to the responds from the local cluster heads and choose the closest cluster head based on the received signal power. At the end, if $t = time_{out}$ and a sensor node hasn't received any

control signal, it sends a *membership search signal* and chooses the closest cluster head as a leader. Figure 6.4 shows the pseudo-code for the DEEP protocol.

6.2.2 Protocol Execution Steps

Protocol execution can be summarized as follow:

1. All nodes calculate $E_{rc1} = P_{out} - \omega(e_{r1})^n$ & $E_{rc2} = P_{out} - \omega(e_{r2})^n$
2. Initial cluster head finds cluster members by sending “cluster head declaration”.
3. Initial cluster head finds new cluster head candidates by sending “cluster head exploration signal”.
4. Cluster head candidates that are placed on the (e_{r1}, e_{r2}) ring find cluster members.
5. Nodes that receive more than one cluster head declaration choose the closest cluster head based on the received signal energy.
6. Cluster head candidates that receive cluster head declaration signal negotiate with the sender, and one of them gets eliminated.
7. Confirmed cluster heads send “cluster head exploration” to find new cluster head candidates (go to 4).
8. If number of members in a cluster is less than m , all the members find new clusters by sending *membership search signal*.

9. At the end, if a node has not received any control signal, it sends *membership search signal*.

6.2.3 DEEP Advantages

The protocol provided in section 6.2.1 has the following advantages:

- As it was discussed, DEEP is a completely decentralized protocol. A sensor node can either elect itself as a cluster head by receiving a cluster head exploration signal or join a cluster by receiving a cluster head declaration signal.
- After the execution of DEEP, all the sensor nodes are covered and belong to only one cluster.
- For the execution of DEEP, there is no need for any location finder hardware such as GPS (Global Positioning System), or a position estimation protocol that put extra overhead on the sensor nodes.
- DEEP can control the cluster head distribution across the sensor network through the protocol execution methodologies. These tactics include: cluster head candidates should receive the cluster head exploration signal with the certain amount of energy, and if they can hear the declaration signal of each other, one of the candidates will be eliminated.
- Communication cost is minimized via proper selection of protocol parameters (declaration range, and exploration range).

I. Initialize

1. Initial CH $\Rightarrow$ sends "CH declaration"
2. All nodes $\Rightarrow$ calculate $E_{rc1} = P_{out} - \omega(e_{r1})^n$
 $\& E_{rc2} = P_{out} - \omega(e_{r2})^n$
3. Initial CH $\Rightarrow$ send "CH exploration signal"

II. Repeat

1. If{received==CH exploration,
 If { $E_{rc1} < E_r < E_{rc2}$
 CH candidate = TRUE}}
2. If{ CH candidate==TRUE,
 send "CH declaration"
 wait
 send CH exploration}
3. If {CH candidate==TRUE,
 If {received==CH declaration,
 Negotiate}}
4. If {# received CH declaration signal ==1,
 Send acceptance}
5. If{# received CH declaration signal>1,
 If { $E_n > E_{\eta}$,
 Send acceptance to i}}
6. If {received==CH exploration,
 If {acceptance==sent or CH candidate==TRUE,
 Ignore}}

III. Finalize

1. If { # members<m,
 All members $\Rightarrow$ send "membership search"}
2. If { $t = time_{out}$ & no acceptance sent &
 CH candidate==FALSE,
 send "membership search signal"}

Figure 6.4: DEEP algorithm pseudo-code.

- Intra-cluster communication is controlled by cluster heads, and nodes transmit their data directly to the cluster heads. Therefore there is no additional control signal exchange associated with route selection and maintenance inside the cluster.
- Due to the uniform distribution of cluster heads, communication cost of a direct transmission path between a pair of cluster heads is almost identical across the sensor field. This is one of the most important characteristics of this protocol that contributes tremendously to the ease of deployment of the inter-cluster routing algorithm.

6.3 Performance Evaluation

In this section, the performance of the proposed DEEP algorithm is evaluated and compared with the famous clustering technique LEACH [9] using MATLAB.

In this scenario, 3000 sensor nodes are randomly distributed in a field of $550\text{m} \times 550\text{m}$, therefore sensors density is about 1 per $10\text{m} \times 10\text{m}$ area, which is the maximum detection range for the toxin sensors. 802.11g is the chosen wireless technology and the energy model for the wireless channel is based on the model described in Section 5.3.

We simulated the algorithm using different protocol parameters d_r , e_{r1} , e_{r2} and m while initial CH candidate is placed at the center of the field. Figure 6.5 shows the output of one of these simulations with parameters $d_r=30\text{m}$, $e_{r2}=80\text{m}$, $e_{r1}=78\text{m}$, $m=14$. Based on the results obtained from Section 2.1, 30m is an initial choice for d_r .

Figure 6.5: Initial cluster head candidate, which is placed at the center of the sensor field, starts the simulation by advertising its candidacy. Cluster heads are gradually dispersed across the network. This picture shows the final generated clusters while nodes are directly connected to the associated cluster heads.

In order to avoid overlapping between clusters, the value of e_{r_1} and e_{r_2} should be more than twice of the value of d_r . Since average distance between sensor nodes in this application is 10m, 80m is a fair choice for e_{r_2} . The width of the (e_{r_1}, e_{r_2}) ring should be large enough to accommodate new cluster head candidates and small enough to avoid cluster head candidates that are too close to each other. We chose 2m as an initial value for the ring width.

In order to balance the load among cluster heads, DEEP controls the cluster head distribution, rather than the number of cluster members. Figure 6.6 shows the distribution of the number of members for each cluster.

Figure 6.6: Number of cluster members for each generated clusters.

With this specific choice of protocol parameters average number of members is 24.3. Although number of members for some clusters is more than the other, communication cost is evenly balance among the cluster heads. Cluster heads that manage more number of members should execute more signal processing for the sake of data aggregation, but considering the fact that digital processing consume much less energy than wireless transmission, we can conclude that there wont be any over-utilized cluster head using this algorithm.

Figure 6.7: Average distance between sensor nodes and the cluster head for each cluster.

Average distance between sensor nodes in each cluster and the associated cluster head is plotted in Figure 6.7. None of the cluster heads in this simulated scenario forced to communicate with members that are in average more than 25 meters away from the cluster head. Figure 6.8 illustrates the performance of DEEP protocol using different algorithm parameters. As advertisement range for the cluster head declaration (d_r) increases, average distance between cluster members and the cluster head also increases. As size of the clusters grows, number of clusters in the scenario decreases. This affect can be seen in Figure 5.8b.

Figure 6.8: Performance of DEEP protocol for different chosen protocol parameters.

6.3.1 Re-clustering

In order to prevent over-utilization of some sensor nodes, clustering technique should ensure that the cluster head responsibility rotates among all the sensor nodes. This way, all the nodes will have the chance to become a cluster head and there won't be any energy depleted spot that blocks connectivity of the network. To achieve this, in LEACH [9], re-clustering is performed periodically, but every round of re-clustering requires several control signal exchanges among self-elected cluster heads and sensor nodes. Other proposals such as assigning a new cluster head for each clusters instead of changing the network topology based on the round-robin strategy[11], node connectivity or battery energy[12], push the cluster head to some other places in the cluster rather than the central point. This causes a dramatic change in the cluster head distribution and affects the inter-cluster communication, and also increases energy consumption associated with the nodes inside the cluster.

Re-clustering process in DEEP is based on one small shift in the initial cluster head. When the current period of cluster setting is finished, current CH candidate chooses the nearest node that has never been acted as an initial cluster head. This newly chosen initial cluster head starts the clustering process and creates a totally different cluster head constellation (Figure 6.9).

Figure 6.9: Each round of re-clustering process in DEEP protocol generates a new set of cluster heads.

We simulated the clustering process for 30 rounds. Figure 6.10 shows the accumulative percentage of the nodes that have become a cluster head at the end of each re-clustering round. No node becomes cluster head more than once during the network lifetime. With 3000 sensor nodes, if algorithm generates about 105 cluster heads at each round, after $3000/105 \cong 28$ rounds all the sensor nodes should have become a cluster head. Figure 6.11 shows that after 27 rounds of re-clustering, number of generated cluster heads will dramatically drop since most of the eligible nodes have been chosen as cluster head and have lost their energy.

For this scenario, DEEP can minimize energy consumption associated with re-clustering overheads by reducing the number of necessary rounds to 27 compared to hundreds or even thousands rounds of re-clustering associated with LEACH protocol.

Figure 6.10: Accumulative percentage of the nodes that have been chosen as cluster head till the end of each round.

Figure 6.11: Number of generated cluster heads at the end of 27 rounds of re-clustering will dramatically drop.

6.3.2 Performance Comparison

In this section, we implemented the proposed DEEP protocol in order to evaluate and compare the performance of the protocol with a generalized version of LEACH in three aspects:

- Cluster head constellation and distribution across the network,
- Intra-cluster energy consumption, and
- Standard Deviation among energy consumption associated with cluster heads' intra-cluster communications.

LEACH is implemented on the same scenario as presented in Chapter 3, and protocol parameter p is equal 0.0325. Figure 5.12 demonstrates the cluster head the random selection of cluster heads in LEACH, some of the cluster heads are too close to each other while others are way too far. This type of cluster head selection causes a lot of burden on some cluster heads and drains their battery very fast. Figure 5.13 shows the energy consumption in each cluster head in order to receive one bit of information from all the cluster members using 802.11g technology. Due to the inconsistent distribution of cluster heads (Figure 5.12), LEACH puts a lot of pressure on some of the cluster heads while DEEP share out the weight among all of them. The standard deviation (ESD) among cluster heads' intra-cluster energy consumption, in this scenario, is 7.7013 μ Joule/bit for LEACH, about 8 times larger than ESD among communication energy for DEEP while the average energy consumption per cluster head for LEACH is 5.476 μ J/b, about 2.3 times larger than the same parameter for DEEP.

(a) LEACH cluster head constellation

(b) DEEP cluster head constellation

Figure 6.12: DEEP generates well-distributed cluster heads across the network.

Figure 6.13: Energy (μ J) consumed by each cluster head to receive one bit of information from all of the sensor nodes in the cluster.

Figure 6.14: Standard deviation among CHs' intra-cluster energy consumption for LEACH is always greater than the same parameter for DEEP.

Executing both protocols for several rounds of re-clustering; we can see that the ESD among intra-cluster communication energy consumption associated with cluster heads is always greater in LEACH compared to DEEP. This can prove the fact that DEEP can perform well in terms of balancing the load among cluster heads compared to the existing protocol LEACH.

CHAPTER 7

INTER-CLUSTER ROUTING PROTOCOL

7.1 Introduction

This chapter introduces an inter-cluster routing protocol and evaluates and the overall performance of the proposed protocol. The proposed Inter-Cluster energy conscious Routing (ICR) protocol establishes energy efficient multihop routes among the chosen cluster heads. This protocol uses interest flooding to establish routes between the base station and cluster heads and employs number of hops and residual energy of the cluster heads as substantial elements of the communication cost for each path. Clustering and routing simulations, in this chapter, evaluates the performance of the proposed protocols and compare the proposed DEEP protocol with a generalized version of LEACH.

7.2 Inter-Cluster Energy Conscious Routing Protocol

After establishing well-distributed cluster heads and clusters in the network, energy conscious routing is essential in order to set communication routes among cluster heads in a two level hierarchical system. As we discussed in the Chapter 5, limited geographical dimensions of the clusters and centered positioned cluster heads would lead to the selection of direct transmission as the optimum and most efficient communication method inside the cluster. This way route setup control messages will be avoided and

energy consumption inside the cluster will reduce. However, due to the limited transmission range associated with low power wireless technologies, cluster heads' data packets can not reach the base station unless other cluster heads act as relay nodes. In this chapter, we propose an Inter-Cluster Energy Conscious Routing (ICR) protocol that is compatible with the proposed clustering algorithm. ICR uses interest flooding similar to directed diffusion [27] and Energy Aware Routing (EAR) [38] to establish routes between the base station and sensor nodes, but it differs from EAR and directed diffusion in some aspects. First we describe the ICR scheme and then accentuate the differences from EAR.

7.2.1 Protocol Details

The protocol ICR is a destination-initiated reactive routing protocol. This means that a destination, which we call Local Base Station (LBS), initiates an explicit route discovery phase. This initiation includes propagation of an *interest* signal that floods throughout the network and establishes energy efficient routes for the sake of data communication. Based on the application, which can be either periodic data collection or event driven, the *Interest* signal can include the *type* and the *period* of the desired data. For application that necessitates information from specific locations, interest signal also includes the position of the required information. If the LBS requires some periodic data collection phases, it set the *period* in which nodes send that specific *type* of information. Monitoring and surveillance application are examples for data collection paradigm. If the LBS requires sensor nodes to detect one specific event, it includes the *type* of the event in

the interest signal (Figure 7.1). Following to the route discover phase, sensor nodes switch to the sleep mode and wait for the specific event. In case of event detection, non-cluster head nodes send the data directly to the associated cluster head, and that cluster head uses the previously established route to send the information back to the LBS.

Type	Period	Exp.	Sender's address	Cost field
------	--------	------	------------------	------------

Figure 7.1: Interest signal structure.

Also *expiration* field is a counter that destroys the interest after timeout. We can explain the ICR execution in the following steps:

1. The LBS initiates the route discovery by sending an interest signal within the range of R_i . R_i Should be high enough to keep the cluster head network connected and low enough to prevent unnecessary energy consumption and interest generation. Due to the even distribution of cluster heads achieved by clustering algorithm, R_i can be chosen slightly bigger than the average distance between a pair of adjacent cluster heads. The LBS should adjust the output power and data rate of the interest signal to limit its transmission range to R_i (As discussed in Chapter 5). Also the cost field is set to zero before interest propagation starts.

2. Each intermediate cluster head that receives the interest signal saves the interest in its memory including the address of the nodes that has sent the message. Then the node should updates the cost field of the outgoing interest signal and sends it within the range of R_i . All the cluster heads that are placed within this range around the sender can hear the incoming signal.

Figure 7.2: Local base station starts the route discovery process by generating interest signals.

3. Since the distance between a pair of neighboring cluster heads is approximately the same across the network, communication energy consumption associated with two distinct adjacent cluster head is also the same. Therefore we can define the cost or weight of a multi-hop path only by the number of hops. Also remaining energy in the cluster heads along the path can affect the route selection decision. Therefore we define the total cost function as:

$$Cost = \alpha \cdot Hop_Number + \beta \cdot \sum_i \frac{B_M}{B_{ri}} \quad 7.1$$

In this equation, B_r represents the remaining energy in the battery of the node, B_M shows the maximum battery capacity of the sensor nodes, and α and β are normalization factors. Second part of the cost field favors the paths that include nodes with higher energy. To update the cost field, each intermediate cluster head calculates the inverse of its remaining battery power plus one (increment in the number of hop) and adds the outcome to the existing cost value.

4. If a cluster head receives an interest that currently exists in the memory i.e. the type, and period is the same, however the senders address is different, it compares the cost field of the received signal with the cost field of the previously saved message. If the incoming interest signal includes a cost field smaller than the previously saved message, the node replaces the old interest entry, updates the cost field, and propagates the packet since the new signal represents a shorter or more energy efficient path. If the new interest signal represents a path with higher number of hops, the node should destroy the packet. In case these two values are equal, the node creates another entry for the incoming interest and keeps that as an option for data communication.

5. After a cluster head collects the requested information from sensor nodes and compresses them into a packet with fixed length, it searches for the relay neighbor's address in the memory and sends the packet to that neighbor.
6. In order to reduce the diffusion of spare data bits in the network, relay nodes can receive the data packets each of length L , from N nodes and aggregate them in to one single packet of length L . This will reduce the number of data bits forwarded by the relay node from NL to L . To enable data aggregation during the data collection period, cluster heads that are closer to the base station, i.e. cost field of the saved interest message includes less number of hops, should wait for their neighbors to send their data packets. Then aggregate the incoming information along with their own data and send the packet with the fixed length to the relay neighbor.

7.2.2 Comparison between ICR and EAR

The proposed ICR protocol is different from the proposed protocol in [38] (EAR) in two aspects:

- In the EAR protocol, sensor nodes save and propagate most of the incoming interest signals and only eliminate the ones with very high cost field. However, in the ICR, every time that the cost field of the incoming interest message is higher than the previously saved one, the packet gets destroyed. This put a limit on the generation of the interest messages.

- In the EAR, in order to ensure that the optimal path does not get depleted and network degrades evenly, multiple paths are found between a source and a destination. Each node has to wait for all the interest signals to come and then calculates the average cost between oneself and the destination. Based on the average cost each path is assigned a probability of being chosen. Depending on the probability, each time one of the paths is chosen. The ICR assumes that data aggregation is executed among cluster heads, and no packet moves along the chosen path independently. This means that during the data collection period each cluster head aggregates the data from its N adjacent cluster heads and has to forward only one compressed packet rather than N distinct packets. Therefore only the least cost path or the optimum path is a final established route for each cluster head. This way the degradation of the optimal path for each packet is prevented.

After the execution of routing protocol a spanning tree is established that is rooted in the base station and connects all the cluster heads to the base station.

7.3 Simulation Results

We simulated the proposed ICR routing protocol in the network that has been clustered using the proposed DEEP protocol to evaluate the overall performance in three aspects:

- Total energy consumption in the network versus number of data packets sent from sensor nodes.
- Performance comparison between DEEP and LEACH after the execution of the routing protocol.
- Optimum density of cluster heads in terms of inter-cluster and intra-cluster communication energy consumption.

7.3.1 Total Energy Consumption in the Network versus Number of Sent Data Packets

Considering the results shown in [38] MAC layer abstraction would not degrade the accuracy of simulation results if designed MAC protocol assigns a unique channel for every node and prevent possible collisions. With this assumption, we extracted the MAC layer from our simulations and data packets were sent directly from network layer of one node to the network layer of the neighbor.

For the first scenario, 3000 sensor nodes are randomly distributed in a field of $550\text{m} \times 550\text{m}$, therefore sensors density is about 1 per $10\text{m} \times 10\text{m}$ area. Total energy consumption includes the energy that nodes spend to send data packets directly to the chosen cluster head and the energy that cluster heads spend to collect data packets from sensor nodes and send it back to the base station through multihop communication. For this scenario, cluster heads that are closer to the base station send their data packets first and then cluster heads that are further away from the base station start to send signals. Each cluster head sends the same amount of data, because they have the ability to compress the information received from sensor nodes. At the end of simulation,

information is collected from every sensor node in the field, and the area of interest is completely covered.

For the chosen 802.11g technology, as number of sent data packets increases, total energy consumption in the network also grows. But the slope of this upsurge is an important factor that determines the speed of energy consumption. Simulation results show that at the end of simulation, DEEP reduces the total energy consumption from 783 mJ/bit to 267 mJ/bit, over 65% reduction compared to LEACH. This is the case because in DEEP sensor nodes distance from cluster head and relative distance between two adjacent cluster heads is controlled through the clustering algorithm's methodology.

Figure 7.3: Total energy consumption in the network versus sent data packets to the base station for both protocols LEACH and proposed DEEP using 802.11g technology.

7.3.2 Performance Comparison between DEEP and LEACH after the Execution of the Routing Protocol

In order to compare the performance of the routing protocol on both DEEP and LEACH and find out the optimum density of cluster heads, we used a 1600-node network where nodes were randomly distributed in a field with area of $400 \times 400\text{m}$. In this scenario, sensor nodes send the information directly to their associated cluster head. Each cluster head compresses the data and waits for neighbor cluster heads' data packet. Then, the cluster head compresses all the received data packets into a packet with fixed length and sends it to the relay neighbor. In-network data aggregation performed by cluster heads as described above helps to reduce the amount of data dispersed in the network.

Our first experiment compares the ESD among cluster heads' intra-cluster energy consumption for protocols DEEP and LEACH while percentage of cluster heads in the network is changing. For the sake of fair comparison, we used the communication energy model described in Chapter 5 for both protocols. To achieve different densities for cluster heads in LEACH protocol, we changed the value of the protocol parameter p from 0.04 to 0.09. Figure 7.4 approves the fact that DEEP can substantially improve the distribution of the load among cluster heads regardless of the cluster head density. It also shows that increase in cluster head density can improve the intra-cluster load distribution for both protocols.

Next experiment compares intra-cluster and inter-cluster communication energy associated with both protocols. Figure 7.5 shows the maximum range of the interest signal (R_i) that establishes the routes among cluster heads. Since LEACH protocol

distributes the cluster heads randomly across the network (Figure 6.12), maximum range of R_i should be chosen high enough to make sure that all the cluster heads will be covered and network does not get partitioned.

Figure 7.4: Standard deviation among intra-cluster communication energy consumption associated with cluster heads.

But as density of cluster heads increases and they get closer to each other, R_i can decrease. Since we adjust the maximum range of the output signal by changing the transmission data rate, R_i maximum value should follow the values provided in Table 5.1 for 802.11g. Therefore, as Figure 7.5 shows, R_i changes from 100m to 76.5m, for LEACH, when cluster head density reaches 0.055 point and from 76.5m to 57m, for DEEP, when cluster head density passes 0.03 point.

Figure 7.5: Maximum range of transmission for the interest signals.

For a chosen cluster head density, R_i is higher for LEACH compared to DEEP because DEEP protocol distributes the cluster heads consistently. Higher values for R_i , in LEACH, lead to extra route setup overheads and faster network degradation. Figure 7.6 shows the total inter-cluster communication energy consumption compared to total intra-cluster energy consumption. The figure shows the reduction in inter-cluster energy when cluster head density varies from 0.03 to 0.05 for DEEP protocol.

Figure 7.6: Total energy consumption inside clusters and among cluster heads.

We can observe the cause of this effect in Figure 7.5. Since maximum range of interest signal (R_i) reduces from 76.5m to 57m, and cluster heads get closer to each other, energy consumption reduces. We can observe the same phenomena for LEACH protocol from point 0.05 to point 0.06. While R_i is remaining constant inter-cluster energy increases with cluster head density because more number of cluster head indicates more number of communications. We can observe the increase in inter-cluster energy consumption when cluster head density varies from 0.06 to 0.11. For lower cluster head percentage LEACH has significant consumption compared to DEEP because cluster heads get further away from each other and both inter-cluster and intra-cluster transmission energy increases.

7.3.3 Optimum Density of Cluster Heads

To investigate the optimum density of cluster heads in terms of energy consumption, Figure 7.7 shows the total energy consumption in the network to collect one bit of data from every sensor node.

Figure 7.7: Total data communication energy consumption in the network along with energy consumption associated with interest flooding.

Also Figure 7.7 shows the total overhead caused in the network by interest flooding and route setup for a network that has been clustered using DEEP and LEACH. Also we can observe the significant improvement in the network energy consumption using DEEP protocol. Considering the results from Figure 7.6 and inverse growth of inter-cluster and intra-cluster energy consumption for DEEP protocol, we can see that the summation of these two energies is almost constant while cluster head density is changing. Therefore, the optimum point for cluster head density can be determined based on the

route setup energy and distribution of the load. Total flooding overhead associated with LEACH is considerably higher than DEEP, because of the random distribution of cluster heads and mandatory high value for maximum transmission range of interest signals. Due to the reduction in the maximum range of interest signal (Figure 7.5)), route setup energy drops from 805 to 410 μ J, for LEACH protocol, when density passes the 0.055 point. At the same time, flooding overhead associated with DEEP drops from 89.6 to 40.1 μ J when density reaches the 0.05 point. Route setup energy increases as cluster head density grows more than 0.05 due to the generation of interest signals. From this experiment, the optimum point of operation is around 0.05 for cluster head density. However another important parameter to consider is distribution of load.

Figure 7.8 shows the standard deviation among cluster head inter-cluster and intra-cluster energy consumption along with the standard deviation among cluster head route setup energy consumption. From this figure, we can observe that optimum point for route setup and inter-cluster energy consumption is achieved when cluster head density is about 0.05.

However standard deviation among intra-cluster communication energy consumption associated with cluster heads declines as cluster head density increases. Since this reduction does not lead to a better optimum point, we conclude that 0.05 is the optimum point for cluster head density in terms of both load distribution and total energy consumption.

Figure 7.8: Standard Deviation among intra-cluster, inter-cluster and route setup communication energy consumption in cluster heads.

7.4 Application Specific Parameters

In order to investigate and calculate the proper period for both route setup and re-clustering phase, first we should classify different sensor network applications in terms of data collection behavior and paradigms. We can divide paradigms of data collection in sensor networks into two main categories:

- Periodic, and
- Event-driven

In the periodic data collection paradigm, all sensor nodes collect data all the time, and route the data generally through a tree. Scientific data collection is an example of

periodic data gathering. In event-driven data gathering, the interest of the end-user is in some specific information or an event. Toxin and chemical detection in lakes and reservoir water is an example of event-driven applications.

Figure 7.9 illustrates the state transition diagram for a sensor node operating in a network with event-driven applications. As we mentioned in previous chapters, sensor nodes stay in sleep mode and keep the transceiver off in order to conserve energy. During the sleep mode, the sensing hardware is active and monitors the target environment or object. However, when an event occurs, the node switches from sleep mode to active mode to inform the base station about the occurrence of the event. In Figure 7.9, S is the sensed parameter and Threshold is the upper limit allowed for the S . When S exceeds the threshold, the node changes to active/transmit state, turns the radio on, and starts transmitting the sensed phenomenon. In Figure 7.9, if the sensor node is a non-cluster head node, it should send the data packet directly to the associated cluster head. However, if the sensor node is a cluster head node, it should look in the memory and find the address of the neighboring cluster head that has been previously established through *interest* propagation.

Figure 7.9: State transition diagram for a sensor node operating in a network with event-driven applications.

After the transmission of data is complete, the node can immediately go to sleep. The transition from sleep mode to active/receive mode can happen when a sensor node receives a wake up call from a neighbor. In this case, the node turns the radio on and receives the sent data packet. In this figure, S_n is representing the sent data packet, and if the data packet is a solely control message, the node can process the data and go to sleep. However, if the message is a data packet that should be routed to the next cluster head, the node should go directly to active/transmit mode and start the transmission of data. Also, if a node receives a wake up call, while it is sending a packet, the node can go directly from active/transmit to active/receive after the transmission is completed. Figure 7.10 illustrates the state transmission diagram for a sensor node operating in a network with periodic data gathering applications. The difference between Figure 7.10 and Figure 7.9 is the condition that causes the node to go from sleep mode to active/transmit mode. In

periodic data collection applications, the network should be synchronized. A non-cluster head sensor node in such a network, go periodically from sleep to active/transmit and based on the application, sends the immediate or the average sensed parameters to the cluster head. Therefore, the node should wait for the right time to start the transmission. In order to obtain the proper value for the transmission period, first we should explain the data aggregation procedure in a clustered structure sensor network.

Figure 7.10: State transition diagram for a sensor node operating in a network with periodic data collection applications.

7.4.1 Data Aggregation in a Clustered Structure Sensor Network

In order to reduce the diffusion of spare data bits into the network, cluster heads that act as relay nodes can receive the L -bit-long data packets from N neighboring cluster heads and compress (aggregate) them into one single packet of length L . This will reduce

the number of data bits forwarded by the relay cluster head from NL to L . To enable data aggregation, as described above, during the data collection period, cluster heads that are closer to the base station, i.e. cost field of the saved interest message includes less number of hops, should wait for their neighbors to send their data packets. Then aggregate the incoming information along with their own data and send the packet with the fixed length to the next relay neighbor.

Figure 7.11: “Data Aggregation” reduces the number of data bits injected into the network.

Figure 7.12 illustrates the timing and operation delay associated with a relay cluster head. As we mentioned previously, a sensor node functioning in a network with periodic data gathering applications, stays in sleep mode and goes to active/transmit when a required time for data transmission is arrived. In Figure 7.12, energy consumption during the sleep mode and active mode is shown in terms of Joule/sec as a function of time. T is data collection period and r is the time that takes for a sensor node to send or receive a data packet of length L .

A non-cluster head sensor node in Figure 7.12 (a) sends the required information to its associated cluster head when the proper time has arrived. During that time, the cluster head receives the sent information from all cluster members since we assume that each cluster member is assigned a specific channel and all of them send the data simultaneously. After the reception of data is complete, the cluster head can start aggregation of the received information. However, at this time, the neighboring cluster heads should have finished the transmission of data packets so that the information is ready for the relay cluster head to aggregate. Therefore, the relay cluster head should receive the data packets of the neighboring cluster heads at the same time that the cluster members send their sensed information. As a result, the neighboring cluster heads should start the transmission of data r seconds sooner than the relay cluster head. Meanwhile cluster heads that are acting as neighbors for the neighboring cluster heads in this scenario should also start the transmission r seconds sooner. Therefore, there is an inherent delay associated with the data transmission in a network facilitated with data aggregation. To calculate the proper time of transmission, each sensor node should be informed about the relative distance of number of hops between oneself and the base station. This information is achieved through the route setup or interest propagation phase.

Figure 7.12: “Data Aggregation,” timing and operation delay associated with a relay cluster head.

The transmission time in each data collection period can be calculated as follow:

$$t = T + (N - n).r \quad (7.2)$$

where N is the maximum number of hops possible in a network between a cluster head and the base station and n is the associated distance in terms of number of hops between that specific cluster head and the base station. In a sensor network, N can be achieved prior to network deployment based on the network dimensions and density.

7.4.2 Route Setup and Data Collection Period

In order to find the relationship between data collection and route setup period, energy consumption in a cluster head as a function of time is shown in Figure 7.13. T is data collection period and T_c is the route setup and re-clustering period. We assume that a sensor node has the opportunity to be a cluster head only once during the network lifetime, and while the node is acting as cluster head, it can loose up to 75 percent of its total energy source. After that, the sensor node can use the 25 percent left energy to sense and send periodic information or special events. We also assume that at each clustering phase, route setup procedure and interest propagation is done only one time, and the established spanning tree can be used until the end of that clustering phase. In Figure 7.13, E_s is energy consumption during the sleep mode and is shown in terms of Joule/sec, and E_r is the energy consumption associated with route setup (interest flooding) and re-clustering overhead and is shown in terms of Joule. In this figure, E_d shows the amount of energy consumed in a cluster head in order to receive data packets from all cluster members and send the aggregated packet to the next neighbor.

Figure 7.13: Energy consumption in a cluster head as a function of time.

Total energy consumption during the data transmission in one clustering cycle is about $f \cdot E_d$ where f is equal $\frac{T_c}{T}$. Also to calculate the total energy consumption during the sleep mode, we should multiply the energy consumption in terms of Joule/sec by the total time that the node is sleep: $(T_c - f \cdot R) \cdot E_s$. Therefore, for a cluster head to spend no more than 75% of its total energy during one clustering cycle:

$$75\%E = E_r + f \cdot E_d + (T_c - f \cdot R) \cdot E_s \quad 7.3$$

If we replace f by $\frac{T_c}{T}$, and $75\%E$ by E_m :

$$E_m - E_r = \frac{T_c}{T} \cdot E_d + T_c \cdot E_s - \frac{T_c}{T} \cdot R \cdot E_s \quad 7.4$$

From this equation the value of T_c can be calculated in terms of T or data collection period:

$$T_c = \frac{T \cdot (E_m - E_r)}{(E_d + T \cdot E_s - R \cdot E_s)} \quad 7.5$$

To observe the effects of data collection period on the maximum allowed re-clustering or route setup period, real world parameters achieved from routing simulations and chosen wireless standard is considered and replaced in the obtained formula.

Maximum value for E_m is achieved by multiplying 0.75 by 2k Joule battery capacity obtained in Section 2.4. For 802.11 technologies, 10 mJ/sec energy consumption during the sleep mode is a reasonable choice based on the values provided in [47]. To calculate R, we need to know the minimum packet size or the mandatory header length associated with 802.11 standards. Based on [44], the mandatory header size for 802.11 technologies is about 38 bytes. Without considering the actual data bits or payload, the minimum size for a data packet is about 38 bytes. In this formula, R includes the wake up time along with the transmission and reception time. The value for R is calculated by considering wake up time equal to 6 micro second [47], and transmission time by dividing the packet size by the transmission speed of 24 Mbps (maximum transmission range of 41m).

Therefore R is equal to $6 + \frac{38 \times 8}{24 \times 10^6} \times 2 = 22.8 \mu \text{ sec}$. Based on the simulation results obtained in Section 7.3, the optimum point of operation in terms of cluster head density is about 0.05. At this point of operation, E_r or energy consumption associated with interest flooding is about $0.48 \mu \text{ J/bit}$. Since the length of interest signal or control signal is usually half of the length of typical data packet, we can calculate E_r in terms of Joule by multiplying 0.48 by 19×8 , which is equal to $68.4 \mu \text{ J}$. However, re-clustering overheads should also be considered in these manipulations. At this point, we assume that a cluster head should spent the same amount of energy to set the route and to carry out the re-

clustering communications. Therefore, the total value of E_r is $68.4 \times 2 = 0.136$ mJ. When cluster head density is 0.05, based on the simulation results from Section 7.3, total energy consumption associated with a cluster head regarding data communication inside and outside the cluster in average is about $15.06 \mu\text{J/bit}$. Considering the wake up energy consumption, the total data communication energy consumption for a cluster head is about 5.02m J. After replacing the parameters in Equation 7.5, route setup period can be written in terms of data collection period as follow:

$$T_c = \frac{T \cdot (1499.99)}{(5.02 \times 10^{-3} + 10 \times 10^{-3} \cdot T - 0.228 \times 10^{-6})} \quad 7.6$$

Investigation the above equation, we can observe that as T or data collection period increases, $(10^{-2} \cdot T)$ dominates the value of E_d or 5.02×10^{-3} J. Therefore, T_c converges to $\frac{E_m}{E_s}$ or in this case, $\frac{1499.99}{10 \times 10^{-3}} = 41.66$ hours. As its shown in Figure 7.14, the maximum value of T_c does not depend on T or data collection period, which is based on the application and its requirements.

Figure 7.14: Route setup period as a function of data collection period.

T_c or route setup period is inversely proportional to energy consumption during sleep mode and directly proportional to maximum capacity of the battery. This result is an interesting fact that confirms the dependency of lifetime on battery capacity and indecency of route setup and re-clustering period on the type and characteristics of application.

CHAPTER 8

CONCLUSION

Wireless networks of densely deployed, tiny, ubiquitous sensor nodes are a remarkable networking technology that is grasping more attention in the research community. The shrinking size and increasing density of next-generation wireless devices imply reduced battery capacities, meaning that emerging wireless systems must be more energy efficient than ever before. While wireless sensor network introduces challenging energy limitations, clustering protocols can reduce the amount of energy consumption by dividing the network into well-distributed clusters.

This thesis presented a novel clustering technique that is based on the idea of controlling the geographical dimensions of clusters and distribution of cluster heads and also developed an energy efficient routing protocol that is compatible with the proposed clustering technique.

In Chapter 5, the specific hardware parameters associated with wireless transmission was explored in depth, and a comprehensive energy model for wireless communication was obtained. While we chose 802.11 standard groups as our preferable wireless technology for this design, multi-rate capabilities associated with these technologies were exploited and utilized. We took advantage of the multi-rate methodology for wireless communication by means of switching to higher data rates for shorter transmission ranges. This approach reduces the energy consumption by lowering

the actual time of data transmission and keeping the transceiver on or awake for a shorter period of time.

Chapter 6 proposed the novel clustering technique, Decentralized Energy-Efficient Cluster Propagation (DEEP) that was based on the idea of starting with a predefined initial cluster head and spreading new cluster head candidates gradually across the network. To optimize energy consumption in terms of intra-cluster and inter-cluster communication, DEEP controlled circular radius of each cluster and the relative distance between a pair of adjacent cluster heads. Because of the balanced load among cluster heads, there were no need for frequent re-clustering, but after current cluster heads are out of energy, protocol can rotate the cluster head position among all the sensor nodes. Also identical distance between a pair of neighboring cluster heads lead to the ease of route setup deployment.

Chapter 6 also compared the performance of the proposed DEEP protocol with the performance of the protocol LEACH in terms of intra-cluster communication energy consumption and distribution of cluster heads.

Chapter 7 of this thesis introduced the inter-cluster energy conscious routing protocol and evaluated the overall performance of the proposed protocol. The proposed Inter-Cluster energy conscious Routing (ICR) protocol established energy efficient multihop routes among the chosen cluster heads. This protocol used interest flooding to establish routes between the base station and cluster heads and employed number of hops and residual energy of the cluster heads as substantial elements of the communication cost for each path. Clustering and routing simulations, in this chapter, evaluated the

performance of the proposed protocols and compared the proposed DEEP protocol with a generalized version of LEACH. Results from our experiments showed that DEEP could reduce the energy consumption and prolong network lifetime. Optimum point of operation in terms of cluster head density was about 0.05, and DEEP was able to distribute the load among sensor nodes more evenly than LEACH.

PUBLICATION

1. Marzieh Veyseh, Belle Wei, Nader Mir, "An Information Management Protocol to Control Clustering and Routing in Sensor Networks," Journal of Computing and Information Technology (CIT), Vol 13, No.1, March 2005.

ABSTRACT

This paper develops and analyzes a novel clustering protocol, the Decentralized Energy Efficient cluster Propagation (DEEP) protocol that manages the communication of data while minimizing energy consumption across sensor networks. The paper also presents an Inter-Cluster Routing protocol (ICR) that is compatible with the proposed clustering technique. The DEEP protocol takes advantage of the multi-rate capabilities of 802.11a, 802.11b, and 802.11g technologies by elevating the data rate to higher levels for shorter transmission ranges. This approach reduces the energy consumption by lowering the transmission time. In order to conserve energy and prolong network lifetime, the DEEP protocol starts with an initial cluster head and gradually forms clusters throughout the network by controlling the dimension of clusters and the geographical distribution of cluster heads. Because this model results in a balanced load among cluster heads, protocol overhead due to frequent re-clustering is eliminated. Simulation results demonstrate that the DEEP protocol distributes energy consumption approximately eight times better than the LEACH protocol-clustering scheme. In addition, the DEEP protocol

substantially reduces total data communication and route setup energy consumption in the network compared to the LEACH protocol.

2. Marzieh Veyseh, Belle Wei, Nader Mir, "A Decentralized Energy Efficient Cluster Formation Protocol for Wireless Sensor Networks," 10th IFIP International Conference on Personal Wireless Communications, August 2005.

ABSTRACT

This paper develops and analyzes a novel clustering protocol, the Decentralized Energy Efficient cluster Propagation (DEEP) protocol, which manages the communication of data while minimizing energy consumption across sensor networks. The paper also presents an Inter-Cluster Routing protocol (ICR) that is compatible with the proposed clustering technique. The proposed clustering protocol employs the unique technique of forming clusters using a pre-selected initial cluster head that starts the advertisement process and finds its cluster members as well as new cluster head candidates based on the relative distance between sensor nodes and their remaining energy level. Because this model results in a balanced load among cluster heads, protocol overhead due to the frequent reconfiguration of clusters is eliminated. Simulation results demonstrate that the DEEP protocol distributes energy consumption approximately eight times better than the existing clustering scheme, LEACH. In addition, the DEEP protocol

substantially reduces total data communication and route setup energy consumption in the network compared to the LEACH protocol.

BIBLIOGRAPHY

- [1] M. N. Halgamuge, et al., "Energy Efficient Cluster Formation in Wireless Sensor Networks," *IEEE 10th International Conference on Telecommunication*, vol. 2, pp. 1571 – 1576, March 2003.
- [2] J. Tillett, R. Rao, F. Sahin, "Cluster-Head Identification in Ad Hoc Sensor Networks Using Particle Swarm Optimization," *IEEE International Conference on Personal Wireless Communications*, pp. 201 – 205, Dec. 2002.
- [3] G. Gupta, M. Younis, "Fault-Tolerant Clustering of Wireless Sensor Networks," *IEEE Wireless Communication and Networking Conference*, vol. 3, pp. 1579 – 1584, March 2003.
- [4] G. Gupta, M. Younis, "Load-Balanced Clustering of Wireless Sensor Networks," *IEEE International Conference on Communication*, vol. 3, pp. 1848 – 1852, May 2003.
- [5] S. Ghiasi, et al., "Optimal Energy Aware Clustering in Sensor Networks," *MDPI* 2002.
- [6] S. Bandyopadhyay, E. J. Coyle, "An Energy Efficient Hierarchical Clustering Algorithm for Wireless Sensor Networks," *Twenty-Second Annual Joint Conference of the IEEE Computer and Communication, Soc.*, vol. 3, pp. 1713 – 1723, April 2003.
- [7] D. Amis, et al., "Max-Min D-Cluster Formation in Wireless Ad Hoc Networks," in *Proceedings of IEEE INFOCOM*, March 2000.
- [8] J. K. Taek, et al., "Efficient Flooding with Passive Clustering-an Overhead-Free Selective Forward Mechanism for Ad Hoc/Sensor Networks," *Proceedings of the IEEE*, vol. 91, Issue 8, pp. 1210 – 1220, Aug. 2003.
- [9] W. B. Heinzelman, A. P. Chandrakasan, H. Balakrishnan, "An Application-Specific Protocol Architecture for Wireless Microsensor Networks," *IEEE Transactions on Wireless Communications*, vol. 1, Issue 4, pp. 660 – 670, Oct. 2002.
- [10] O. Younis, S. Fahmy, "Distributed Clustering in Ad-hoc Sensor Networks: A Hybrid, Energy-Efficient Approach," *INFOCOME 2004*, unpublished.

- [11] W. Rabiner, et al, "Energy-Efficient Communication Protocols for Wireless Microsensor Networks," *Hawaii International Conference on System Sciences (HICSS '00)*, January 2000.
- [12] B. Chen, et al., "Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks", in the *Proc. of the 7th ACM Mobile Computing and Communication (MobiCom 2001)*, Rome, Italy, July 2001.
- [13] J. Rabaey et al., "PicoRadio for Wireless Sensor Networks: The Next Challenge in Ultra-Low Power Design," *Proc. ISSCC 2002*, pp. 200-201, February 2002.
- [14] UC Berkeley, *Smart Dust Specifications*,
<http://robotics.eecs.berkeley.edu/~pister/SmartDust/>.
- [15] R. Hahn and H. Reichl, "Batteries and Power Supplies for Wearable and Ubiquitous Computing," *3rd Int'l Symposium on Wearable Computers*, 1999, pp.168 -169.
- [16] S. Mehta, et al., "A CMOS Dual-band Tri-mode Chipset for IEEE 802.11a/b/g Wireless LAN," *2003 IEEE Radio Frequency Integrated Circuits (RFIC) Symposium*, pp. 427 – 430, June 2003.
- [17] Aristotle University of Thessaloniki, Department of Physics, *Instruction-level Energy Characterization of an ARM Processor*,
http://easy.intranet.gr/paper_36b.pdf.
- [18] UC Berkeley Presentation, *An Ultra Low-energy Microcontroller for Smart Dust for Wireless Sensor Networks*, http://www-bsac.eecs.berkeley.edu/archive/users/warneke-brett/pubs/17_4_slides4.pdf.
- [19] S. L. Wu, et al. "A Multi-Channel MAC Protocol with Power Control for Multi-Hop Mobile Ad Hoc Networks," *The Computer Journal (SCI)*, vol. 45, no. 1, 2002, pp. 101-110.
- [20] W. Ye, J. Heidemann, D. Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Networks," *Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. INFOCOM2002*, vol. 3, pp. 1567-1576, June 2002.
- [21] M. Singh and V. K. Prasanna, "Energy-Optimal and Energy-Balanced Sorting in a Single-Hop Sensor Network," *IEEE Conference on Pervasive Computing and Communications (PERCOM)*, March 2003.

- [22] P. Baldi, L. De Nardis, M; Di Benedetto, "Modeling and Optimization of UWB Communication Networks through a Flexible Cost Function," *IEEE Journal on Selected Areas in Communications*, vol. 20 , Issue 9 , pp. 1733 – 1744, Dec. 2002.
- [23] L. Peterson, B. S. Davie, *Computer Networks*, Morgan Kaufmann, San Francisco, 2003.
- [24] M. A. Youssef, et Al., "A Constrained Shortest-Path Energy-Aware Routing Algorithm for Wireless Sensor Networks," *IEEE Wireless Communication and Networking Conference*, pp. 794 – 799, March 2002.
- [25] Min, R., et Al., "Top Five Myths about the Energy Consumption of Wireless Communication," *Mobile Computing and Communication Review*, vol. 1, Num. 2, 2003.
- [26] C. E. Perkins, et Al., "Performance Comparison of Two On-Demand Routing Protocols for Ad Hoc Networks," *IEEE Personal Communications*, vol. 8, Issue 1, pp. 16 – 28, Feb. 2001.
- [27] C. Intanagonwiwat, et Al, "Directed Diffusion for Wireless Sensor Networking," *IEEE/ACM Transactions on Networking*, vol. 11, pp. 2 – 16, Feb. 2003.
- [28] E. Woodrow, W. Heinzelman, "SPIN-IT: a Data Centric Routing Protocol for Image Retrieval in Wireless Networks," *International Conference on Image Processing*, vol. 3, pp. 913 – 916, June 2002.
- [29] D. Niculescu, B. Nath, "Ad Hoc Positioning System (APS) using AOA," *Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies, INFOCOM 2003*, vol. 3 , pp. 1734 – 1743, April 2003.
- [30] N. Patwari, A. O. Hero, "Location Eestimation Accuracy in Wireless Sensor Networks," *Conference Record of the Thirty-Sixth Asilomar Conference on Signals, Systems and Computers*, vol. 2 , pp. 1523 – 1527, Nov. 2002.
- [31] P. Bergamo, G. Mazzini, "Localization in Sensor Networks with Fading and Mobility," *The 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 2 , pp. 750 – 754, Sept. 2002.
- [32] T. Rappaport. *Wireless communications: principles and practice*, Communications engineering and emerging technologies. Prentice Hall, 2nd edition, 2002.
- [33] D. Petrovic, R. C. Shah, k. Ramchandran, J. Rabaey, "Data Funneling: Routing with Aggregation and Compression for Wireless Sensor Networks," *IEEE International*

Workshop on Sensor Network Protocols and Applications, pp. 156 – 162, May 2003.

- [34] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*, Artech House Publishers, Boston, 1999.
- [35] Broadcom white paper, *The New Mainstream Wireless LAN Standard*, softcopy at <http://whitepapers.zdnet.co.uk/0,39025945,60072368p-39000522q,00.htm>.
- [36] J. Macker and S. Corson, *Mobile Ad Hoc Networks (MANET)*, IETF WG Charter, <http://www.ietf.org/html.charters/manet-charter.html>.
- [37] G. Holland and N. H. Vaidya, “Analysis of TCP Performance Over Mobile Ad Hoc Networks,” *Proc. IEEE/ACM MOBICOM '99*, Seattle, pp. 219–30, Aug. 1999.
- [38] R.C. Shah, J.M. Rabaey, “Energy Aware Routing for Low Energy Ad Hoc Sensor Networks,” *IEEE Wireless Communications and Networking Conference*, vol. 1, pp. 350 – 355, March 2002.
- [39] F. Akyildiz, et Al., “A Survey on Sensor Network,” *IEEE Communications Magazine*, Vol. 40, Issue. 8, Aug 2002.
- [40] J. Zheng, M. J. Lee, “Will IEEE 802.15.4 Make Ubiquitous Networking a Reality?: a Discussion on a Potential Low Power, Low Bit Rate Standard,” *IEEE Communications Magazine*, vol. 42, Issue 6, pp. 140-146, June 2004.
- [41] D. Culler, D. Estrin, M. Srivastava, “Guest Editors' Introduction: Overview of Sensor Networks,” *IEEE Computer Magazine*, vol. 37, pp. 41-49, Issue 8, Aug. 2004.
- [42] M. Tubaishat, S. Madria, “Sensor Networks: an Overview,” *IEEE Potentials*, vol. 22, Issue 2, pp. 20-23, April-May 2003.
- [43] UC Berkeley, *Pico Radio Testbed Photos*, http://bwrc.eecs.berkeley.edu/Research/Pico_Radio/Test_Bed/photos/Default_.html
- [44] Pablo Brenner, “A Technical Tutorial on the IEEE 802.11 Protocol”, BreezCome Wireless Communication, 1997.
- [45] MIT UAMPS Research, <http://www-mtl.mit.edu/research/icsystems/uamps/>.

- [46] R. Min, et Al., “Energy-Centric Enabling Technologies for Wireless Sensor Networks,” *IEEE [see also IEEE Personal Communications] Wireless Communications*, vol. 9, Issue 4, pp. 28-39, Aug. 2002.
- [47] MSI Computer, *MSI PC54G2 User Manual*,
http://www.msi.com.tw/program/products/communication/cmu/pro_cmu_detail.php?UID=584.