11-1-2005

Scalable Energy-efficient Location-Aided Routing (SELAR) Protocol for Wireless Sensor Networks

George Lukachan
University of South Florida

Scholar Commons Citation

Lukachan, George, "Scalable Energy-efficient Location-Aided Routing (SELAR) Protocol for Wireless Sensor Networks" (2005). *USF Tampa Graduate Theses and Dissertations.*
https://digitalcommons.usf.edu/etd/752

Scalable Energy-efficient Location-Aided Routing (SELAR) Protocol for Wireless Sensor Networks

by

George Lukachan

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Computer Science
Department of Computer Science and Engineering
College of Engineering
University of South Florida

Major Professor: Miguel Labrador, Ph.D.
Ken Christensen, Ph.D.
Adriana Iamnitchi, Ph.D.

Date of Approval:
November 1, 2005

Keywords: large scale, sensor node, multihop routing, network lifetime, power constraint

ACKNOWLEDGEMENTS

I take this opportunity to express my sincere thanks to Dr. Miguel Labrador, for giving me this wonderful opportunity of working on this project. I am also grateful to him for his extended support and guidance throughout the course of this work, and for making my study at USF a pleasant and exciting educational experience. My sincere thanks to Dr. Christensen and Dr. Iamnitchi, for being in my committee and for their valuable comments and suggestions.

It takes more than words to express my thanks to my family for their constant motivation and support, without which this work would not have been possible. I thank all my friends for their continuous encouragement and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SCALABLE ENERGY-EFFICIENT LOCATION-AIDED ROUTING (SELAR) PROTOCOL FOR WIRELESS SENSOR NETWORKS

George Lukachan

ABSTRACT

Large-scale wireless sensor networks consist of thousands of tiny and low cost nodes with very limited energy, computing power and communication capabilities. They have a myriad of possible applications. They can be used in hazardous and hostile environments to sense for deadly gases and high temperatures, in personal area networks to monitor vital signs, in military and civilian environments for intrusion detection and tracking, emergency operations, etc. In large scale wireless sensor networks the protocols need to be scalable and energy-efficient. Further, new strategies are needed to address the well-known energy depletion problem that nodes close to the sink node face.

In this thesis the Scalable Energy-efficient Location-Aided Routing (SELAR) protocol for wireless sensor networks is proposed to solve the above mentioned problems. In SELAR, nodes use location and energy information of the neighboring nodes to perform the routing function. Further, the sink node is moved during the network operation to increase the network lifetime. By means of simulations, the SELAR protocol is evaluated and compared with two very well-known protocols - LEACH (Low-Energy Adaptive-Clustering Hierarchy) and MTE (Minimum Transmission Energy). The results indicate that in realistic senarios, SELAR delivers upto 12 times more and upto 1.4 times more data packets to the base station than LEACH and MTE respectively. It was also seen from the results that for realistic scenarios, SELAR with moving base station has upto 5 times and upto 27 times more lifetime duration compared to MTE and LEACH respectively.

CHAPTER 1

INTRODUCTION

The advances in semiconductor technology has led to a given computing capacity becoming smaller and less expensive with each passing year. This has led to the creation of miniature radios and sensors which can sense forces in the physical world. These inexpensive radios and sensors are combined to create what is known as a sensor node. Wireless sensor networks consist of hundreds to thousands of tiny sensor nodes which are constrained in terms of energy, power and communication capabilities. Sensor nodes transmit the information they sense to a special node known as the base station. Base station, also known as a sink node, has significantly higher energy and computational capabilities compared to a sensor node. Base station can be recharged using external sources or be provided with, for e.g., a solar panel to recharge itself.

Wireless sensor networks have a myriad of possible applications. The applications of wireless sensor networks can be roughly classified into three categories [6]:

- *monitoring space*: This category of applications include environmental and habitat monitoring, precision agriculture, indoor climate control, surveillance, treaty verification and intelligent alarms.

- *monitoring things*: Structural monitoring, ecophysiology, condition-based equipment maintenance, medical diagnostics and urban terrain mapping are the applications of wireless sensor networks falling under this category.

- *monitoring the interaction of things with other things and the encompassing space*: Most of the dramatic applications of wireless sensor networks fall under this category which include applications like environmental monitoring, disaster management, emergency response, asset tracking and manufacturing process flow.

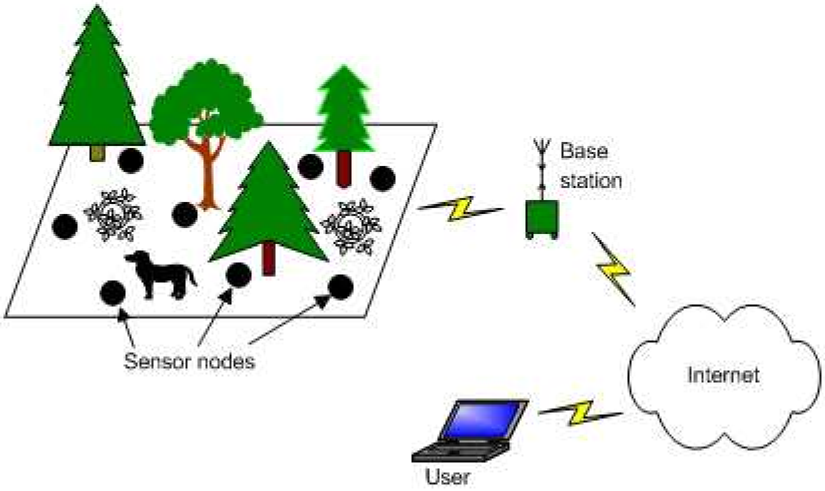

Figure 1.1 Environmental monitoring using sensor networks

Figure 1.1 depicts environmental monitoring using wireless sensor networks. Nodes scattered in different areas of the forest can be used to track various physical conditions like temperature, sunlight incidence, and so on. One example of environmental monitoring is monitoring the micro-climate throughout the volume of redwood trees to form a sample of entire forests [6]. Redwood trees are large enough to envelope an entire ecosystem. By placing wireless sensor nodes at various elevations of the tree we can measure incident light, radiant light, relative humidity, barometric pressure and temperature. Using the data recorded it can be seen how the weather front moves up and down the tree. Another application of wireless sensor networks, namely, motion monitoring can be used for condition-based maintenance [6]. Physical structures such as motors, airplane wings, and bridges have typical modes of vibration, acoustic emissions and response to stimuli. Mechanical changes to these physical structures will be reflected in their vibration modes, acoustic emissions, and response to stimuli. Tiny wireless sensor nodes can be placed on the physical structure to sense the vibrations, acoustic emissions and can transmit them to the monitoring station. Alternatively, the sensor nodes can continuously process the information it senses, if it finds any aberrations it can transmit the necessary data to the monitoring station.

Figure 1.2 graphically depicts the components of a sensor node. The four basic units of a sensor node are the *sensing unit*, *processing unit*, *transceiver*, and *power unit*. A Sensing unit consists

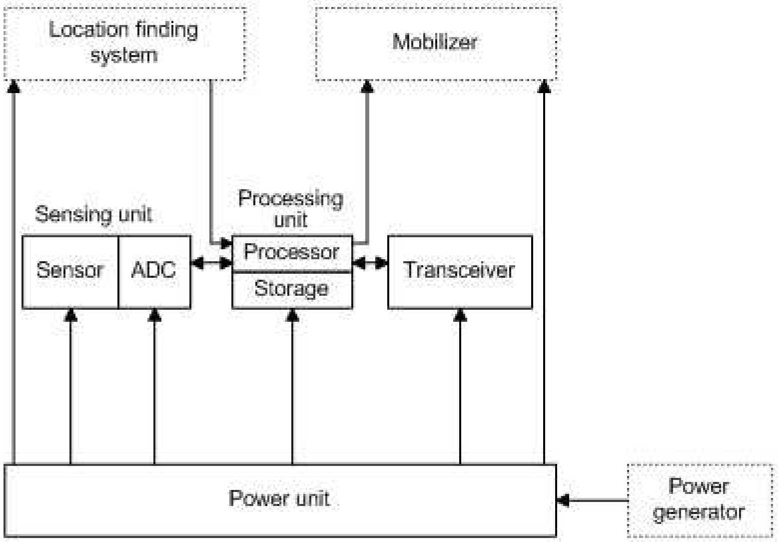

Figure 1.2 Components of a sensor node [2]

of sensors and analog-to-digital converters (ADCs). Sensors produce analog signals based on the physical phenomenon they observe. The analog signals produced by the sensors are converted to digital signals by the ADC. The processing unit receives signal from the ADC. The processing unit consists of a processor as well as storage. The processing unit contains procedures to collaborate with other nodes in the network. Every node is connected to the network via the transceiver. The power unit powers all other units in the sensor node to perform sensing, processing, transmission and reception of data. The sensor node can have additional units like power generators to supply power to the power unit. Sensor node can have a location finding system to calculate relative or absolute location of itself as well as that of other nodes. For certain applications the sensor node might require to be mobile and will have a mobilizer unit attached to it.

The protocol stack used in wireless sensor networks is shown in Figure 1.3. A brief description of each layer is as follows:

- *Physical layer*: It addresses the needs of robust modulation, transmission and receiving techniques.

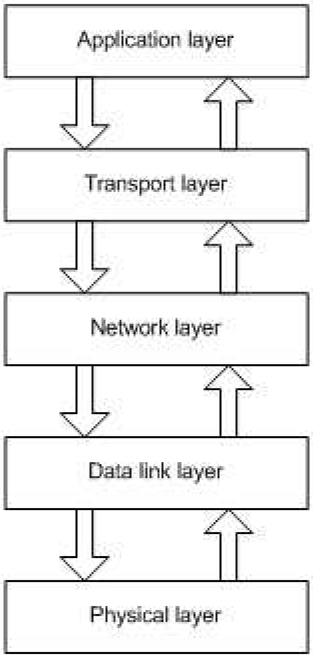

Figure 1.3 Sensor network protocol stack

- *Data link layer*: This layer should be power-aware and minimize collisions with neighboring broadcasts. It should also provide fair access to the media and high network utilization.
- *Network layer*: Energy-efficient routing is performed at this layer. Network layer should be simple with no high requirements in terms of storage, computations and communication overhead.
- *Transport layer*: This layer maintains the flow of data. Most of the time UDP protocol is utilized to send small amounts of data.
- *Application layer*: This layer can run application software depending on the type of sensing task.

This thesis focuses on the network layer, proposing a scalable and energy-efficient routing protocol for large-scale wireless sensor networks.

1.1 Routing in wireless sensor networks

The routing function in wireless sensor networks is challenging because of the power, storage and computational constraints of the nodes. In this section the design challenges posed by routing in wireless sensor networks and the solution provided by SELAR [7] are reviewed.

1.1.1 Design challenges for routing

The main challenges in designing a routing protocol for wireless sensor networks are as follows:

- *Fault Tolerance*: The ability to sustain sensor network functionalities without any interruption due to sensor node failures [8] [9]. Sensor nodes may fail due to physical damage or environmental interference. The failure of few nodes should not affect the overall productivity or functionality of the network. The routing function should be able to route around failures.
- *Scalability*: A sensor network is said to be scalable if an increase in sensor nodes increase the functionality of the network. The routing protocol should be designed in such a way that it is able to work with large number of nodes spread throughout large area.
- *Production Costs*: The production cost of a single sensor node should be such that the overall cost of deploying a wireless sensor network is significantly cheaper than deploying traditional sensors. For a large-scale sensor network to be feasible, the cost of a single sensor node should be much less than US$1 according to [2]. The routing function should be as simple as possible so that no high power, CPU and storage capabilities are needed.
- *Power/Energy Constraints*: Large scale wireless sensor nodes have extremely low amount of power and energy at their disposal. The routing protocol should be designed in such a way that each and every transmission and reception performed is justified. Rotuing overhead must be kept to a minimum.

1.1.2 Solution provided by SELAR

Scalable Energy-efficient Location Aided Routing protocol is meant to be a fault-tolerant, scalable and energy-efficient protocol. Every sensor node in a sensor network using SELAR maintains a state table containing the location and energy information of all its neighbor nodes. In SELAR, a sensor node forwards data packets to its neighbor node based on the energy left in the neighbor node. Hence, the energy of the network is used in a uniform manner. Further, the random failure of nodes in the network do not affect its overall functioning. The SELAR protocol is capable of handling a large number of sensor nodes as routing decisions are localized. Therefore, the addition of more nodes into the network do not degrade the performance of the network. SELAR does not use complex computations at the sensor nodes and routes packets in the network by being power aware leading to efficient utilization of node energies.

1.2 Contributions of this thesis

The contributions of this thesis are the following:

- Provides a comprehensive review of wireless sensor network routing protocols.
- Proposes an energy-efficient, fault-tolerant and scalable routing protocol for wireless sensor networks.
- Evaluates the proposed protocol by comparing it with existing protocols using standard performance metrics.
- Implements the protocol in the ns-2 simulator.

1.3 Document structure

This document begins with a discussion on wireless sensor networks and their routing protocols in particular. Chapter two provides an overview of the routing protocols in wireless sensor networks, well known routing protocols and work related to the design of the proposed protocol, SELAR. Chapter 3 describes the proposed protocol in detail. In Chapter 4, SELAR is implemented using ns-2 and compared with two other well known routing protocols - LEACH (Low-Energy Adaptive-Clustering Hierarchy) [10] [1] and MTE (Minimum Transmission Energy) [11] [12]. Finally, Chapter 5 provides conclusions and future works related to SELAR.

CHAPTER 2

RELATED WORK

In this chapter, the design considerations for wireless sensor network routing protocols are discussed. Then some of the well known wireless sensor network routing protocols are reviewed. The chapter concludes with a description of DREAM (Distance Routing Effect Algorithm for Mobility), ad hoc network routing protocol, which influenced the design of SELAR.

2.1 Design of wireless sensor network routing protocols

Routing is very important to the efficient performance of wireless sensor networks. A significant amount of research is being done to design efficient routing protocols for wireless sensor networks. Some of the desired features of wireless sensor network routing protocols are energy-efficiency, scalability, and fault-tolerance. In the subsections which follow, the design considerations for wireless sensor network routing protocols and their classification are discussed.

2.1.1 Overview of routing protocols

Routing protocols in wireless sensor networks can be broadly classified as follows [3] [4]:

- *Flat/Data-centric routing*: In this type of routing protocols, each node typically plays the same role and collaborates together to perform the sensing task. They use attribute based addressing because of the infeasibility of assigning global identifiers to every node in the network. In flat/data-centric routing, the sink node queries sensor nodes in a particular region and waits for data from the sensors located in that particular region. Examples of flat/data-centric routing protocols are SPIN (Sensor Protocols for Information via Negotiation)[13], Directed Diffusion [14], and Rumor Routing [15].

- *Hierarchical*: Hierarchical routing protocols are cluster-based. These type of routing protocols typically have good scalability and efficient communication. In hierarchical routing the nodes with higher energy can take care of aggregating/processing data and sending it to the base station while sensor nodes with lower energy can sense data and send it to the nearby higher energy node. Hierarchical routing tries to improve the overall energy-efficiency, lifetime, and scalability of the sensor network by creating clusters, clusterheads with special tasks assigned to them and by performing data fusion within the cluster. The main principle on which hierarchical routing is based on is that it takes more energy to send two packets than to send one packet with more data. Examples of hierarchical routing protocols are LEACH (Low-Energy Adaptive Clustering Hierarchy) [10], PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [16] and SMECN (Small Minimum Energy Communication Network) [17].

- *Location-based*: In location based routing protocols, location of the sensor node is used to address the node. Sensor nodes can use incoming signal strength to estimate the distance as well as the relative coordinates of the neighboring nodes. In some instances, GPS (Global Positioning System) may be used to find the location of the sensor nodes. Examples of location-based routing protocols are GAF (Geographic Adaptive Fidelity) [18], GEAR (Geographic and Energy Aware Routing) [19] and SPAN [20].

Figure 2.1 graphically depicts the classification of routing protocols for wireless sensor networks. Based on the protocol operation, the wireless sensor network routing protocols can be classified as *Multipath-based*, *Query-based*, *Negotiation-based*, *QoS-based* and *Coherent-based*. More information about this classification can be found in [3].

2.2 Review of wireless sensor network routing protocols

This section contains reviews of the following wireless sensor network routing protocols: Low-Energy Adaptive Clustering Hierarchy (LEACH)[10], Minimum Transmission Energy (MTE) [11] [12], Small Minimum Energy Communication Network (SMECN) [17], Flooding and Gossiping

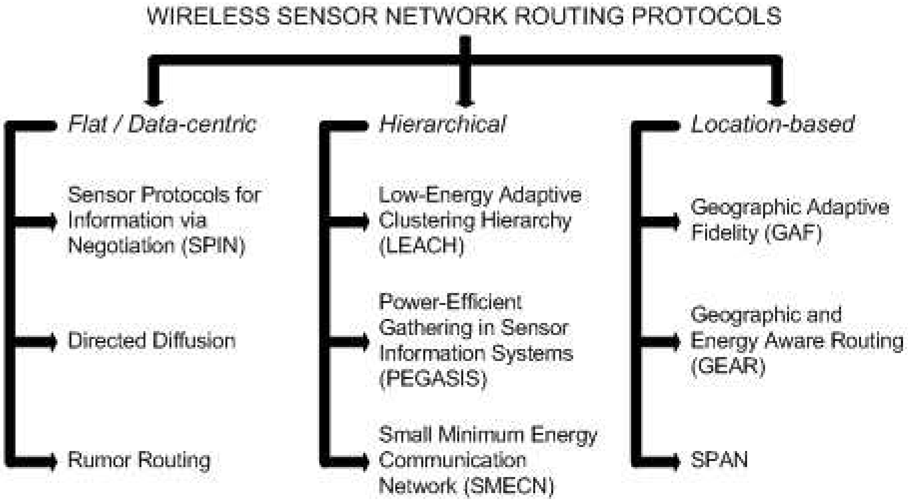

Figure 2.1 Classification of routing protocols [3][4]

[21], SPIN (Sensor Protocols for Information via Negotiation)[13], SAR (Sequential Assignment Routing) [22], Directed Diffusion [14], SPEED [23].

2.2.1 Low-Energy Adaptive Clustering Hierarchy (LEACH)

Low-Energy Adaptive Clustering Hierarchy (LEACH), a clustering based protocol for wireless sensor networks, is discussed in [10]. In LEACH, a set of nodes act as clusterheads and the rest of the nodes perform the sensing function. The nodes which act as clusterheads are changed randomly at regular intervals of time so that there is uniform dissipation of energy throughout the wireless sensor network. The operation of LEACH is divided into the setup phase and the steady phase. The duration of the steady phase is set to be longer than that of the setup phase so as to minimize overhead.

During the setup phase every sensor node chooses a random number between 0 and 1. If the random number chosen by the clusterhead is less than the threshold $T(n)$, then the sensor node becomes a clusterhead. The Threshold *T(n)* is determined using Equations 2.1 and 2.2.

$$T(n) = \frac{P}{1 \, - \, P \, \times \, [\, r \, mod \, (1/P) \,]}; \; if \; n \in \boldsymbol{G}, \tag{2.1}$$

$$T(n) = 0; \; if \; n \notin \boldsymbol{G} \tag{2.2}$$

where *P* is the desired percentage to become a clusterhead, *r* is the current round and *G* is the set of nodes that have not been clusterheads for the past $\frac{1}{P}$ rounds. Once the clusterheads are chosen, the new clusterheads broadcast the news throughout the whole wireless sensor network. Each sensor node receiving the advertisement from clusterheads, chooses the clusterhead it wants to belong to based on the signal strength of the advertisement. Each sensor node informs the clusterhead from which it receives the strongest signal that it will become a member of that clusterhead. Following this each clusterhead assigns a time slot to every sensor node in its cluster, during which the sensor node can send data to its respective clusterhead. A TDMA approach is used by the clusterheads to assign time slots to each sensor node in its cluster.

Once the steady phase begins, the sensor nodes sense and transmit data to their respective clusterheads. The clusterheads perform data fusion on the data received from the sensor nodes and sends the aggregated data to the base station. After a certain amount of time, the steady phase ends and a new setup phase begins followed by another steady phase. This process continues until all the sensor nodes in the wireless sensor network have no energy left. Data packet collisions in LEACH are minimal since it uses a TDMA mechanism within each cluster and a CDMA mechanism when clusterheads transmit data to the base station.

2.2.2 Minimum Transmission Energy (MTE)

Minimum Transmission Energy (MTE) protocol is a multihop routing protocol in which data packets are forwarded to intermediate nodes in the path to the base station such that transmission energy is minimized [11] [12]. In MTE, if a node needs to send a data packet to the base station, it selects intermediate nodes on its path to the base station such that the sum of the transmission energies dissipated is less than that required to send the data packet directly to the base station. If a sensor node A has a node B on its path to the base station C, then node A will transmit to the base station C through node B if and only if

$$d_{AB}{}^2 + d_{BC}{}^2 < d_{AC}{}^2. \tag{2.3}$$

2.2.3 Small Minimum Energy Communication Network (SMECN)

The Small Minimum Energy Communication Network (SMECN) is proposed in [17]. SMECN is an extension of Minimum Energy Communication Network (MECN) [24]. Given a network topology, MECN constructs energy-efficient subnetworks for every sensor node in the network. MECN finds global minimum power paths using localized search for each node without considering all the sensor nodes in the wireless sensor network. MECN assumes that every node can transmit to every other node in the network. SMECN considers the network to be fully connected but does not assume every node to be capable of transmitting to every other node in the network. The subnetwork constructed by SMECN is smaller than the one constructed by MECN if the broadcast region is circular around a broadcaster for a given power setting. SMECN creates subnetworks that assist in sending messages on minimum-energy paths by constructing a subnetwork where the minimum-energy path is guaranteed to exist. By creating smaller subnetworks than MECN, SMECN increases the probability that the path used is the one requiring minimum energy.

2.2.4 Flooding and gossiping

Flooding is one of the oldest routing techniques. In flooding, each node receiving a packet broadcasts that packet to every other node unless the packet has reached its destination or the maximum number of hops assigned to the packet has been reached. Flooding is a simple routing protocol which requires no topology maintenance or route discovery algorithms. Flooding protocol has the following drawbacks:

- *Implosion*: Duplicated packets are received by a sensor node.

- *Overlap*: Two nodes sharing the same observation region may sense a stimuli at the same time resulting in duplicated messages.

- *Resource blindness*: Flooding works without taking into account the availability of resources like energy.

Gossiping [21] is a derivation of flooding. In gossiping, a sensor node randomly selects a neighbor to forward a packet instead of broadcasting to all its neighbors. The neighbor node, on receiving the data packet, selects another sensor node randomly and forwards the packet. Gossiping avoids the implosion problem but it may take a long time to send the packet to its destination.

2.2.5 Sensor Protocols for Information via Negotiation (SPIN)

Sensor Protocols for Information via Negotiations (SPIN) [13] is designed to address the deficiencies of classic flooding. SPIN uses negotiation and resource adaptation as each node disseminates information to every other node in the network considering them to be potential base stations. SPIN is designed based on the idea that sensor nodes operate more efficiently and conserve energy by sending data that describe the sensor data instead of sending all the data. SPIN uses three types of messages:

- *ADV*: Data advertisement messages.

- *REQ*: Request for data messages.

- *DATA*: The data packet/message.

The working of SPIN is shown in Figure 2.2. Initially, a sensor node broadcasts an ADV message containing a description of the data it has. The neighbor nodes who are interested in the data sends a REQ message to the first sensor node. The sensor node holding the data then sends the DATA message to the nodes from which it received the REQ message. The neighbor nodes then repeat this process. Finally, all nodes in the network interested in the data will have a copy of the data. In SPIN topological changes are localized since each node needs to know only its single-hop neighbors.

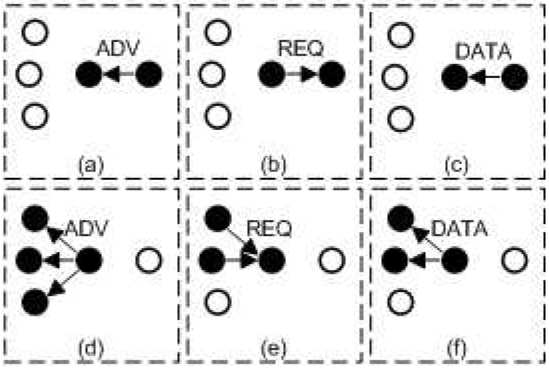

Figure 2.2 Working of SPIN protocol

2.2.6 Sequential Assignment Routing (SAR)

In Sequential Assignment Routing (SAR) [22], multiple trees are created with the root of each tree being a single-hop neighbor of the base station. Each tree grows away from the base station by including nodes with high QoS and energy reserves. Most of the sensor nodes in the network belong to different trees, enabling the sensor nodes to choose a tree to send data to the base station. The two parameters associated with each path in a tree are:

- Energy resources.
- Additive QoS metric.

Each node selects the path to the base station based on the energy resources, QoS metrics of that path and the packet's priority level. Single Winner Election (SWE) and Multi Winner Election (MWE) handle the necessary signaling and data transfer tasks during local cooperative information processing.

2.2.7 Directed diffusion

Directed diffusion is a data-centric protocol proposed in [14]. In directed diffusion the base station sends out a task description, which is also known as interest to all the sensor nodes in the network. The naming of task descriptors are done by assigning attribute-value pairs that describe the task. Each sensor node saves the interest in its memory. The interest entry consists of several gradient fields and a timestamp field. When a sensor node receiving the interest has data to send to the base station, it becomes the source node. The gradients from the source node back to the sink are setup as the interest is propagated throughout the sensor network. When the base station starts receiving data from the source node it should reinforce the interest.

2.2.8 SPEED

SPEED [23] uses geographic forwarding to find paths to the base station. In SPEED each sensor node is required to maintain information about its neighbors. SPEED uses a routing module called Stateless Non-deterministic Geographic Forwarding (SNGF). The SNGF module works with four other modules which are as follows:

- *Beacon Exchange*: This module collects information about nodes and their location.
- *Delay Estimation*: This module estimates the delay to each neighbor by calculating the elapsed time when an acknowledgement is received from a neighbor in response to a packet transmitted to it.
- *Neighborhood Feedback Loop*: This module provides the relay ratio which in turn is calculated by considering the miss ratios of the neighbors of a node.
- *Backpressure rerouting*: This module tries to work around congestion in the network. When a node fails to find out a next hop neighbor, it sends the packet back to the node it received the packet from so that a new route can be followed.

2.3 Distance Routing Effect Algorithm for Mobility (DREAM)

Distance Routing Effect Algorithm for Mobility (DREAM) is a routing protocol designed for wireless Ad hoc networks [25]. DREAM is included here because SELAR's design is partially influenced by this protocol. In DREAM each mobile node maintains a location table for all other nodes in the network. Each location table consists of the coordinates of the source node based on some reference system, the source node's speed and the time the location packet was transmitted by the source node. Each mobile node transmits location packets to nearby mobile nodes in the network at a given frequency and to faraway mobile nodes in the ad hoc network at a lower frequency. When a node S needs to send information to node D, it calculates a circle around the most recent location information of D using

$$R = V_{max} \times (t_1 - t_0) \tag{2.4}$$

where R is the radius of the circle, V_{max} is the known maximum speed of node D, t_1 is the current time and t_0 is the timestamp for this node's information from the location table. Then node S defines a forwarding zone whose vertex is at S and whose sides are tangent to the circle around D. S then sends a data packet to all its neighbors in the forwarding zone. The neighbor nodes in turn calculate their own forwarding zones to D and repeat the process. Mobile node D on receiving the data packet sends an acknowledgement packet (ACK) to S. The ACK packet is send to S in the same manner as the data packet was send to D. If node S does not receive an ACK packet it uses a recovery procedure. Flooding is a recovery procedure suggested in [25].

The forwarding zone concept in SELAR was influenced by DREAM. In SELAR, the destination D is always the base station. Furthermore, SELAR increases its forwarding angle as and when needed so that at least one sensor node is present in the forwarding zone. A detailed description of the SELAR protocol is given in Chapter 3.

CHAPTER 3

THE SCALABLE ENERGY-EFFICIENT LOCATION AIDED ROUTING (SELAR) PROTOCOL

The Scalable Energy-efficient Location-Aided Routing (SELAR) protocol for wireless sensor networks is a protocol that assumes that a location mechanism exists to provide the location to all nodes and therefore perform the routing function. Every node can know its location using GPS (Global Positioning System) or some distributed localization protocol [26][27][28]. One of the main considerations during the design of SELAR was to create a simple and scalable protocol with minimal computational overhead at the power-constrained sensor nodes and one that is capable of consuming the energy of the network evenly. SELAR needs every sensor node to know its own location as well as that of its neighbors and the base station. For this, SELAR can use any existing location mechanism. Once this is achieved, every sensor node which needs to send data to the base station, selects from amongst its neighbors in the forwarding zone, the node with the maximum energy. This process continues until the base station receives the data packet. Every sensor node has to be concerned only about forwarding the data packet to its immediate neighbor in the direction of the base station. This leads to sensor nodes nearer to the base station dissipating their energy faster. Since sensor nodes that have the base station nearer to them dissipate energy faster, this thesis proposes to move the base station to better utilize the remaining alive nodes. The base station could be attached to a robot, thus enabling it to move. The rest of this chapter discusses in detail the design considerations, working of the protocol and moving of the base station.

3.1 Design considerations

The main considerations during the design of the protocol were as follows:

- *Simplicity*: SELAR is designed to be a simple protocol which is easy to implement since it requires very low amount of computation at individual nodes. SELAR attempts to optimize the amount of calculations to be done by the individual sensor node. Each sensor node knows the energy and location information of itself as well as that of the nodes within its radio range. In addition, every node knows the location information of the base station. In SELAR, the nodes within the radio range of a particular sensor node form its neighbors. Each sensor node selects the neighbor node to which it forwards its packet, based on the location information of the base station as well as the location and energy information of its neighbors. As such, nodes in SELAR need to maintain a very small routing table and make just a few computations to forward the packets.

- *Scalability*: Scalability is an important issue in wireless sensor networks. SELAR is a scalable routing protocol because the routing function does not depend on the number of nodes in the network.

- *Energy-efficiency*: SELAR is an energy-efficient protocol. Every sensor node forwards data packet to its most energy-rich neighbor at that particular point in time. Every node periodically exchanges its available energy with its neighbors. Thus sensor nodes forward data packets based on most recent energy information about its neighbors. This ensures that sensor nodes have their energy drained uniformly. However, it is expected that sensor nodes closer to the base station will be used more and therefore will die first. Therefore, SELAR by itself does not guarantee a global even energy distribution. In order to solve this problem, this thesis proposes to move the base station.

3.2 Working of the protocol

In SELAR, every wireless sensor node has to know the following:

- The energy and location information about itself.
- The energy and location information about all its neighbors.
- The location information of the base station.

The location of every wireless sensor node can be found, as suggested in [29], by using GPS (Global Positioning System) or some distributed localization protocol. The base station can broadcast its location information to all the wireless sensor nodes. This should be possible for the base station since it is a high power node with superior capabilities than the sensor nodes. The wireless sensor network is considered to be relatively static. In SELAR sensor nodes transmit two types of packets - control and data.

Initially, during the control packet dissemination phase, every sensor node broadcasts its location and energy information to all its neighbors. Every sensor node maintains a table containing the location and energy of all its neighbors. This table is updated based on the information contained in the control packets received from its neighbors. In the simulations run in chapter four, data packets are transmitted by each sensor node at regular time intervals. The control packet dissemination phase can be triggered at regular intervals when significant amount of energy has been dissipated in the network. . During the control packet dissemination phase, every sensor node broadcasts its energy information to all its neighbors.

During the data packet dissemination phase, every sensor node forwards one packet each to the base station. Each sensor node forwards its packet to the neighbor with maximum energy in the direction of the base station. The subsections below discuss in detail the control packet dissemination model, the data packet dissemination model and the algorithm used to determine the neighbor nodes within a given forwarding zone.

3.2.1 Control packet dissemination phase

SELAR begins with a control packet dissemination phase. During the control packet dissemination phase, every sensor node broadcasts the energy and location information about itself to all its neighbors. Future control packet dissemination phases require sensor nodes to broadcast their available energy information alone. The control packet dissemination model is graphically depicted by Figure 3.1, where sensor node S broadcasts control information to its neighbors N1, N2 and N3. All other sensor nodes shown in Figure 3.1, being outside the radio range of node S, do not receive the control packet broadcasted by node S. Similar to node S, all other sensor nodes broadcast their energy information to their respective neighbors. The main purpose of the control packet dissemination phase is to increase the productive lifetime of the wireless sensor network. Each sensor node by knowing the energy and location information of its neighboring sensor nodes, can forward packets to the base station, by making use of sensor nodes with maximum amount of energy. Alternatively, each sensor node decide when to send control packets to neighbors. For example, each time a sensor node's energy level decreases by a certain amount, it can broadcast a control packet with its current energy level to all its neighbors. Each sensor node, on receiving a control packet from its neighbor node, updates the corresponding entry in its state table. The format of the state table maintained at each node is shown in Figure 3.2. The state table at each sensor node has the following fields:

- *Neighbor ID*: This field contains the identification for the corresponding neighbor node. This identification can either be one that is global in nature or generated locally.
- *Location*: This field contains the location information for the corresponding node. The location information can be absolute or relative.
- *Energy*: This field contains the available energy of the corresponding node. This field is updated whenever a control packet is received from the respective neighbor. Sensor nodes can be provided with the hardware and software capability to know its remaining energy.
- *Timestamp*: This field contains the time at which the last control packet was received from the corresponding node. If a certain amount of time has passed since the reception of control

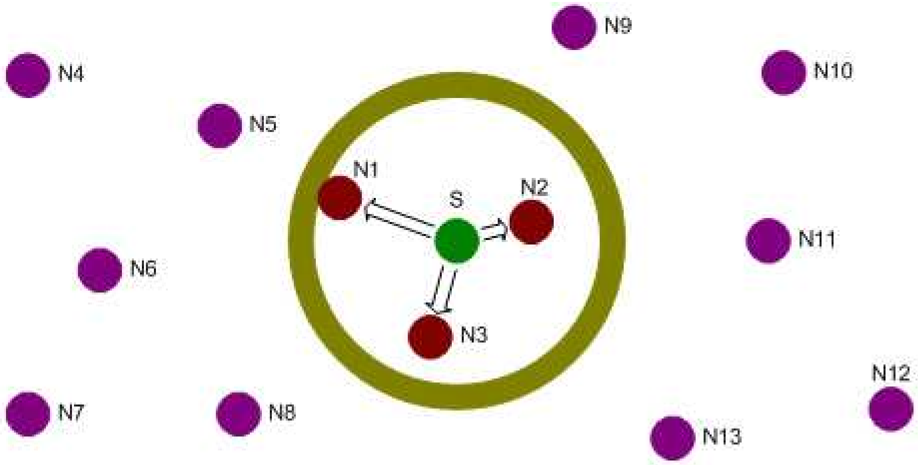

Figure 3.1 Control packet dissemination

Neighbor ID	Location	Energy	Timestamp

Figure 3.2 Format of the state table maintained at every sensor node

packet from a particular neighbor node, then the sensor node sets the energy field in the state table corresponding to that neighbor node to 0. This is done so as to avoid sending data packets to dead sensor nodes. The next time a control packet is received from that particular sensor node, the state table is updated accordingly.

3.2.2 Data packet dissemination phase

The data packet dissemination model in SELAR is very much similar to that used in [25]. Whenever a sensor node needs to send a data packet to the base station, it considers all the sensor nodes in the forwarding zone. Forwarding zone for a particular sensor node is the sector formed within the radio range of that sensor node, in the direction of the base station. The sensor node then forwards the data packet to the maximum energy sensor node in the forwarding zone. This process continues until a sensor node which has the base station in its radio range receives the forwarded packet. This sensor node then sends the data packet directly to the base station.

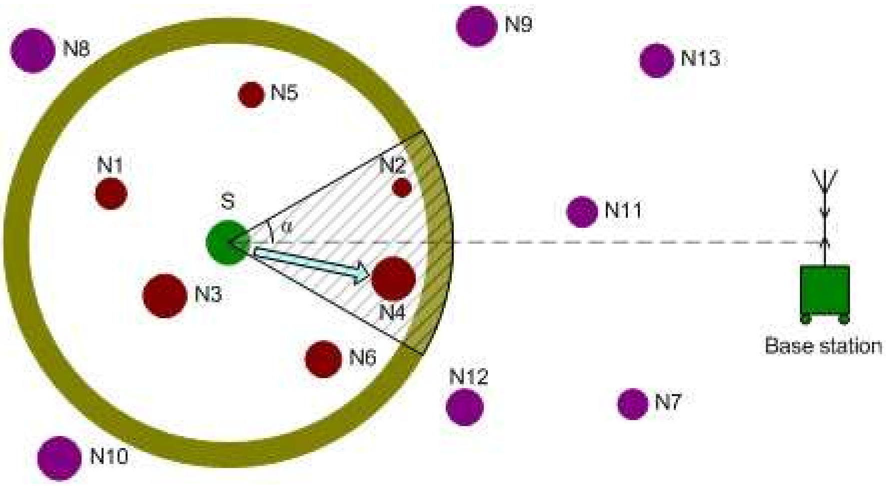

Figure 3.3 Data packet dissemination

A few important aspects of the data packet dissemination phase in SELAR are discussed below:

- Every sensor node maintains a state table. The format of the state table is shown in Figure 3.2. The state table contains the location and energy information of all the neighbors of the particular sensor node. Every node makes its data packet forwarding decision based on the information contained in the state stable.

- Initially, the forwarding zone angle α is set to 15°. The forwarding zone angle α is graphically depicted in 3.3. The angle subtended by the forwarding zone at the corresponding node will always be twice that of α (hence, initially 30°). If a sensor node does not find any alive neighbor node in its forwarding zone, it increases α by steps of 15° until at least one alive sensor node is present in its forwarding zone. The maximum value which can be taken by α is 180°. At this point, the forwarding zone of the particular sensor node is its whole radio range. If the sensor node is not able to find alive neighbor nodes with α set to 180°, it broadcasts the data packet within its radio range. This is done as a last resort, taking into account the possibility that a few neighbor nodes could still be alive but are not able to successfully send control packets. Alternatively, the sensor node can stop sending data packets when it is not able to find anymore alive neighbor nodes. In some applications, more sensor nodes are

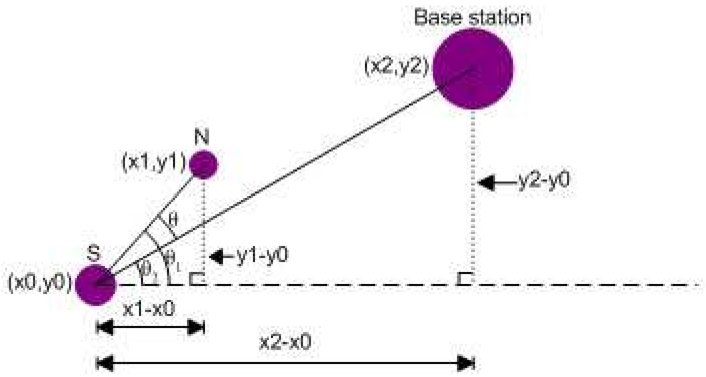

Figure 3.4 Determining whether a neighbor node is within the forwarding zone

dropped into the nearly dead network. When this happens, the nodes can resume sending data packets.

The data packet dissemination model is depicted graphically in Figure 3.3 where the diameter of the nodes represent the amount of energy they contain. Sensor node S has two neighbor nodes in its forwarding zone, nodes N2 and N4. Sensor node S forwards its data packet to node N4 since it has more energy than N2. In Figure 3.3 the shaded region within the sector is the forwarding zone of sensor node S. During the data packet dissemination phase every sensor node sends a single data packet to the base station. Similar to control packet dissemination, during data packet dissemination a random factor is introduced to the transmission start time of the packets so that all sensor nodes do not transmit at the same time.

3.2.3 Algorithm for determining neighbor nodes within the forwarding zone

The algorithm for determining the neighbor nodes within the given forwarding zone of a sensor node has been borrowed from the DREAM ns-2 code received from the authors of [30]. The algorithm is explained with the help of Figure 3.4. Consider the situation where sensor node S needs to determine whether its neighbor node N falls within the forwarding zone. This can be determined by performing the following:

- The angle (θ_1) which the line connecting node S (x0, y0) and node N (x1, y1) makes with respect to the x-coordinate is determined by atan($\frac{y1-y0}{x1-x0}$).

- The angle (θ_2) which the line connecting node S (x0, y0) and base station (x2, y2) makes with respect to the x-coordinate is determined by atan($\frac{y2-y0}{x2-x0}$).

- The angle which the base station and node N makes at node S can be found out as: θ = θ_1-θ_2.

- If θ is less than or equal to the forwarding angle then node N lies in the forwarding zone of node S else node N lies outside the forwarding zone of node S.

3.3 Moving the base station

In this thesis, the following method to deal with the energy depletion problem of the nodes closer to the base station is proposed. In order to increase the lifetime and productivity of the wireless sensor network, the base station is moved around the area. In SELAR, after a certain amount of time, it is found that the nodes farther away from the base station have more energy than those nearby. To take care of this, the base station is moved to an appropriate point, such that the nodes which have the base station in their radio range have sufficient amount of energy. The base station can be moved by attaching it to a robot which can be teleoperated remotely. An implementation of moving the base station is given in Section 4.3.1. Consider monitoring a habitat spread over a 400 m $\times$ 400 m area. We can predetermine points to which it is feasible to send the movable base station. We can move the base station to these points as and when required. Moving the base station is proposed in [31] too.

CHAPTER 4

SIMULATION AND RESULTS

This chapter describes the implementation of SELAR in the network simulator 2 (ns-2) [32]. SELAR is compared with two other protocols - Low-Energy Adaptive Clustering Hierarchy (LEACH) [10] and Minimum Transmission Energy (MTE) [11] [12]. Simulations were performed using the ns-2 code extensions obtained from MIT uAMPS project [5] which in turn is built on the CMU Wireless and Mobility platform [33] included in ns-2.1b5.

4.1 CMU wireless and mobility platform

The ns-2.1b5 release has the CMU Wireless and Mobility platform included with it. The following are the CMU additions to the baseline simulator:

- Mobility Model.
- MAC protocols.
- Channel propagation models [34].

Figure 4.1 shows the implementation of a mobile node. Data packets are created by the Application and then send to the Agent. The network and transport layer functions are performed by the Agent. The Agent then sends packets to CMUTrace which writes statistics about the packets to trace files. The Connector then receives these packets and sends them to the Link-Layer for data-link processing. After a small delay, the Queue receives the packets from the Link-Layer. The packets are queued at the Queue if there are packets waiting to be transmitted. The MAC runs media access protocols on the packets once it receives them from the Queue. The MAC sends the packets to the Network Interface, where the packets are sent through the Channel after adding the correct

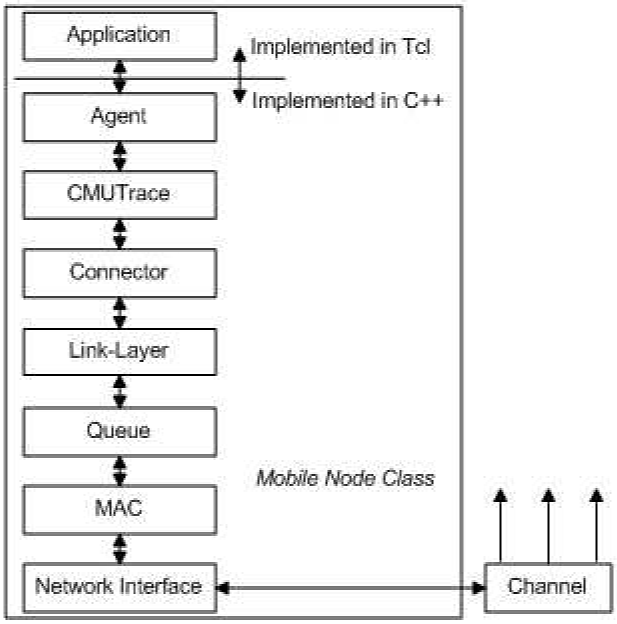

Figure 4.1 Block diagram of an ns-2 mobile node [5]

transmit power. A copy of the data packet is sent to each node connected to the Channel. Each node's Network Interface, on receiving the data packet, sends them up through the same functions but in the reverse model. The Agent receives the data and sends a notification to the Application.

4.2 MIT uAMPS ns-2 code extensions

The ns-2 code extensions from MIT uAMPS project add support for large-scale wireless sensor networks. MIT uAMPS ns-2 code extensions were done in ns-2.1b5 release atop the CMU Wireless and Mobility model.

4.2.1 Resource-adaptive node

The MIT uAMPS extensions to ns-2 added a Resource-Adaptive node [13]. The block diagram of the Resource-Adaptive node is shown in Figure 4.2. Resource-Adaptive nodes help in implementing Resource-Adaptive protocols. The two new features of Resource-Adaptive nodes are:

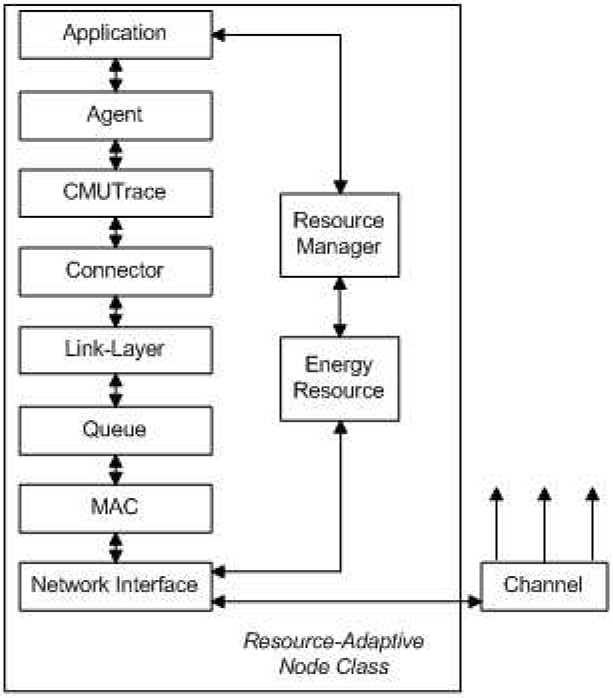

Figure 4.2 Block diagram of a resource-adaptive node [5]

- *Resource Manager*: Provides a common interface between Application and the individual resources.
- *Resources*: Anything that needs to be monitored (energy, node neighbors).

The following functions are used by Application to update the status of the node's resources through the Resource Manager:

- *add*: To add more of a resource to the node's supply.
- *remove*: To remove the specified amount of resource from the node's supply.
- *query*: To enquire about the amount of resource the node currently has.

These functions are used in the simulations to assign, decrement and advertise energy values of the nodes.

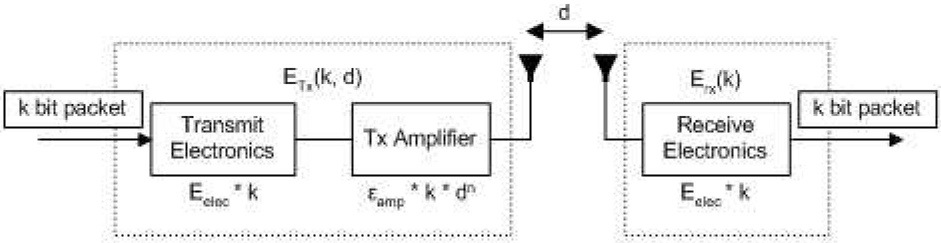

Figure 4.3 Radio energy dissipation model [1]

Table 4.1 Parameters used for radio model [1]

Parameter	Value
Electronics energy (E_{elec})	50 nJ/bit
Receiver power threshold ($P_{r-thresh}$)	6 nW
Radio energy parameter for Friss model ($\epsilon_{friss-amp}$)	100 pJ/bit/m^2
Radio energy parameter for Two-ray model ($\epsilon_{two-ray-amp}$)	0.013 pJ/bit/m^4
Radio bitrate (R_b)	1 Mbps

4.2.2 Radio model

The MIT uAMPS ns-2 code extension assume a simple radio energy model which is shown in Figure 4.3. The transmitter dissipates energy to run the radio electronics as well as the amplifier, whereas the receiver dissipates energy to run the radio electronics only. Table 4.1 lists the important parameters used by the radio model. These are typical values used in several investigations. Using the values in 4.1 and given a packet of size k bits, the energy consumed in the entire transmission and reception processes can be calculated and therefore adjusted. For more information about the radio energy model, please refer to Section 4.1.2 in [1]. The radio parameters in MIT uAMPS ns-2 code extensions are based on that of the available transceiver baseband chips [35].

4.2.3 Network interface

The physical layer functions are performed by the Network Interface. When the Network Interface is ready to transmit a packet, it removes the appropriate amount of energy to send the packet, based on the distance to the receiver. Once a node has used up all its energy it is removed from the channel. Packets sent to dead nodes, nodes that are removed from the channel, are thrown away.

A node can either be in the sleep state or awake state. If the node is in the sleep state while its Network Interface receives a packet, it drops the packet. Else, if the node is awake, the Network Interface calculates the received power of the packet. The following three scenarios could happen:

- If the received power of the packet is below a certain detection threshold, the packet is dropped.
- If the received power of the packet at the node is above the detection threshold but below the successful reception threshold, the packet is marked as erroneous and passed up the stack.
- If the received power of the packet is above the successful reception threshold, the packet is considered to have been received successfully and is passed up the stack to the MAC layer.

Depending on the distance between the transmitter and the receiver, the free space model or multipath fading model is used, as defined by the channel propagation model in ns-2 [34] [36]. The Friss free space model is used if the distance between the transmitter and receiver is less than the cross-over distance. Cross-over distance is the maximum distance upto which a packet can be transmitted successfully using the Friss free space model. The cross-over ($d_{crossover}$) distance is calculated [1] using

$$d_{crossover} = \frac{4\,\pi\,\sqrt{L}\,H_T\,H_R}{\lambda} \tag{4.1}$$

where L is the system loss factor not related to propagation, H_T and H_R are the heights of the transmitter and receiver antennae respectively. The Friss equation to estimate the received signal power [1] is given by

$$P_R = \frac{\lambda\,G_T\,G_R\,P_T}{(4\pi)^2\,d^2} \tag{4.2}$$

where, λ is the wavelength, P_R is the received signal power in Watts (or dBm), G_T is the transmitter gain, G_R is the gain at the receiver, P_T is the transmitted signal power in Watts (or dBm) and *d* is the distance between the receiver and transmitter antenna measured in meters. For a two-ray ground reflection model [36], the received signal power [1] is inversely propartional to d^4, and is estimated using

$$P_R = \frac{G_T\,G_R\,P_T\,({H_T}^2\,{H_R}^2)}{d^4\,L}. \tag{4.3}$$

For the experiments, an omnidirectional antenna having the following parameters is used: G_T = G_R = 1, H_T = H_R = 1.5 m, L = 1 (no system loss), 914 MHz radio, $\lambda = \frac{3\times10^8}{914\times10^6}$ = 0.328 m. From these values the cross-over distance is calculated as 86.2 m. These values have been taken from [5].

4.2.4 MAC implementation

The ns-2 code extensions of MIT uAMPS project has a new protocol called MacSensor. The MacSensor protocol consists of the following:

- *CSMA (Carrier-Sense Multiple Access)*: Implemented in the MacSensor class. The CSMA implemented is non-persistent. In non-persistent CSMA a node on detecting the channel to be busy, sets a random time interval and tries to transmit again after that time interval.
- *TDMA (Time-Division Multiple Access)*: This is implemented within the Application, by setting the Application to send data to the Agent during the specified TDMA time-slot. This implementation assumes the clocks of all nodes to be synchronized.
- *DS-SS (Direct-Sequence Spread Spectrum)*: A simple model of DS-SS is implemented jointly within the Application and the MacSensor class.

A node running the MacSensor protocol cannot receive a packet while transmitting. If a node receives a packet while it is transmitting, it marks it as erroneous and passes it up to the link layer, where the erroneous packet is dropped. If a node running the MacSensor protocol receives a packet while it is already receiving another packet, the following two scenarios can occur:

- If the packet which is already being received, has more than a certain amount of signal strength than the new packet which has arrived, the new packet is dropped.
- Otherwise if the signal strength of the first packet being received is not significantly more than that of the new packet which has arrived, both packets collide and are dropped.

4.2.5 Base station application

The base station is a very powerful node and has virtually no energy constraints. Every data packet generated has the base station as its ultimate destination. The base station application needs to keep track of every data packet it receives. The base station application helps us in determining the following:

- Estimate of the latency of different protocols.
- Quality information about the different protocols.

4.2.6 Implementation of LEACH and MTE

The implementation of LEACH [10] is done according to the description in Chapter 3 of [1]. LEACH is implemented as a subclass of ns-2's Application class.

MTE routing is implemented as described in [10] and [1]. In MTE routing, each node chooses the closest node that is in the direction of the base station as its next-hop neighbor. Initially, all nodes expend a certain amount of energy to find their next-hop neighbors. A node N's upstream neighbors are the set of nodes which have N as their next-hop neighbor. Consider node N1 is node N's next-hop neighbor. Whenever node N dies, its upstream neighbors become part of node N1's upstream neighbors. The following action takes place in MTE routing:

- Each node's transmit power is set to the minimum required to reach its next-hop neighbor.
- MTE routing uses non-persistent CSMA MAC protocol.
- Every node forwards data packets to the next-hop neighbor until the base station receives it.

Te data packet transmission rate in MTE is similar to that for SELAR (4.3). For LEACH the data packet transmission rates are much higher. The data packet transmission rate for LEACH can be obtained from [5].

4.3 Implementing SELAR using the MIT uAMPS ns-2 code extensions

SELAR has been implemented in ns-2.1b5 using MIT uAMPS ns-2 code extensions, as described in Chapter 3. Initially it is assumed that all nodes know their own locations as well as that of the base station. The protocol starts with a control packet dissemination phase during which all sensor nodes broadcast their location and energy information to their neighbor nodes. Every control packet dissemination phase is followed by two data packet dissemination phases. The algorithm to find the neighbor nodes within the forwarding angle was obtained from the ns-2 code for DREAM given by the authors of [30]. SELAR sends data packets continuously. The approximate data packet transmission rates used by SELAR are - 25 packets every 0.6 s for the 200 m × 200 m scenario, 50 packets every 1.7 s for the 283 m × 283 m scenario, 75 packets every 3.1 s for the 347 m × 347 m scenario, 100 packets every 4.8 s for the 400 m × 400 m scenario.

4.3.1 SELAR with moving base station

As mentioned in Section 3.3, SELAR with moving base station is implemented. Figure 4.4 graphically represents the implementation of SELAR with moving base station. Initially, the base station is placed at position 1. When the base station stops receiving data packets, it moves to position 2 and broadcasts to all sensor nodes about its new position. The sensor nodes change the information in their respective state tables accordingly and resets their forwarding angle to 15° in the direction of position 2. Again, when the base station stops receiving data packets at position 2, it moves to position 3 and the same sequence of steps as above are followed. Finally, when the base station stops receiving packets at position 3, it moves to position 4 and stays there till the end of the simulation. Cartesian reference system is used in the simulations. Positions 1, 2, 3 and 4 are midpoints along the four edges of the sensor network topology.

4.4 Restriction applied to radio range

The maximum radio range of sensor nodes used in simulating SELAR is restricted to the crossover distance (refer Section 4.2.3). For LEACH and MTE, as implemented by the MIT uAMPS ns-2

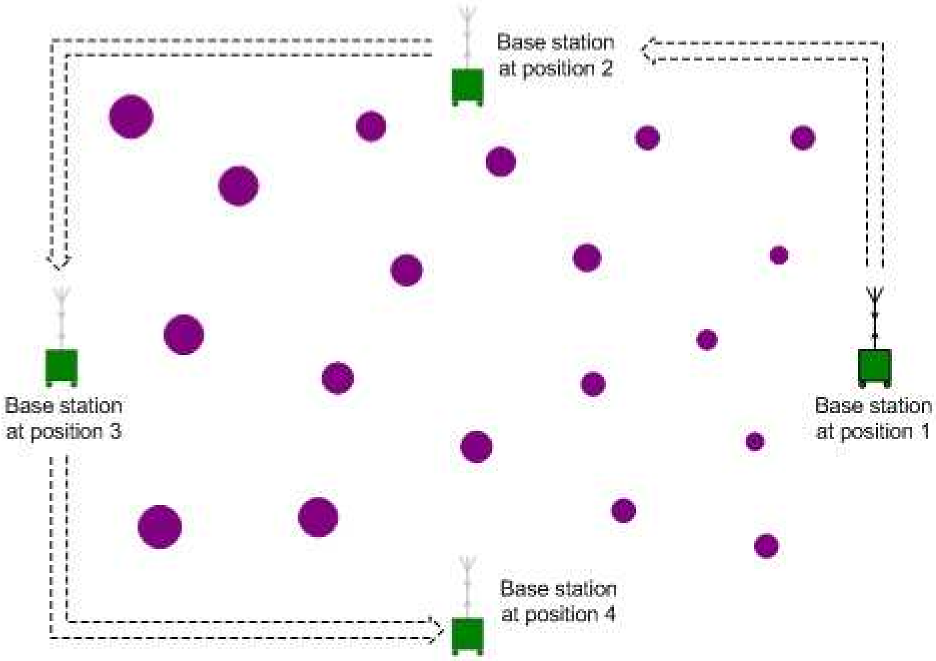

Figure 4.4 Moving the base station in SELAR

code extensions, no power restriction has been placed. This results in them being able to transmit to as much distance as they want, as long as they have the energy to perform the necessary power amplification. This unfortunately is not possible in reality. Most of the low cost sensor nodes work at radio ranges of few tens of meters indoors and nearly and order of magnitude higher outdoors [37] [38].

LEACH and MTE were run the way they were obtained from [5] i.e., without any maximum radio range restrictions. Then, the maximum range of sensor nodes running LEACH and MTE was restricted to the cross-over distance and simulations were rerun. The results obtained are described and discussed in the sections which follow.

4.5 Simulation scenario

Five different sensor node topologies each, for four different scenarios were created and LEACH, MTE, SELAR and their variations were run on these topologies. The topologies were created randomly. A random function which uses uniform distribution was used to place nodes within each topology. For example, if 100 nodes are to be placed in a 400 m × 400 m area, two random numbers are generated using uniform distribution such that the numbers lie between 0 and 400. The two numbers generated form the (x,y) coordinate of the sensor node. This is done 100 times to generate the 100 node positions. The scenarios were created in such a way that the node density is same for all. The performance of the various protocols with increasing number of sensor nodes had to be measured. The simulation tool, ns-2, restricts the maximum number of sensor nodes which can be simulated to 128. Based on these considerations, the four scenarios created are as follows:

- 200 m × 200 m scenario with 25 nodes.
- 283 m × 283 m scenario with 50 nodes.
- 347 m × 347 m scenario with 75 nodes.
- 400 m × 400 m scenario with 100 nodes.

The various protocols and their variations are run on the various topologies of the four scenarios are as follows:

- MTE.
- MTE with maximum radio range restricted to cross-over distance (86.2 m).
- LEACH.
- LEACH with maximum radio range restricted to cross-over distance (86.2 m).
- SELAR with stationary base station.
- SELAR with moving base station.

4.6 Results

This section discusses and analyzes the performance of SELAR routing protocol compared to that of LEACH and MTE.

4.6.1 Data packets

The average number of data packets received after running MTE, LEACH, SELAR with stationary base station (SST) and SELAR with moving base station (SMV) are shown in Table 4.2 and Figure 4.5. Figure 4.5 shows the 95% Confidence Interval for the mean values found using the t-distribution with 4 degrees of freedom. From Table 4.2 and Figure 4.5, it is observed that LEACH delivers the highest number of packets followed by MTE. SELAR with moving base station (SMV) is seen to deliver more data packets as the size of the network increases. SELAR with stationary base station is seen to deliver the least amount of data packets. This is because both the SELAR protocols have their maximum radio range restricted while MTE and LEACH operate under no such restrictions (which is not practical for large scale wireless sensor networks). Again the huge difference between the number of data packets delivered by LEACH compared to other protocols is because LEACH uses data fusion.

The average number of data packets received after running MTE and LEACH with restricted radio range, SELAR with stationary base station (SST) and SELAR with moving base station (SMV) are shown in Table 4.3 and Figure 4.6. In these set of simulations all the protocols have their maximum radio range set to cross-over distance (86.2 m). Figure 4.6 shows the 95% Confidence Interval for the mean values found using t-distribution with 4 degrees of freedom. From Table 4.3 and Figure 4.6, it is observed that SELAR with moving base station (SMV) delivers the highest number of packets followed by SELAR with stationary base station (SST). MTE and LEACH are shown to deliver significantly less number of data packets, when their data ranges are restricted like that for the SELAR protocols. For MTE this happens because as each node dies, the distance between the corresponding upstream neighbors and next-hop neighbor increases, eventually leading them to be out of each others range. For LEACH to work efficiently, every node should have every other node within its radio range. This is so that during the set-up phase in LEACH, every cluster-head can broadcast advertisement packets to all the sensor nodes in the wireless sensor network. With restricted radio range this is not possible, which results in some nodes forming part of non-optimal clusters and some other nodes not participating in data packet delivery. Also, in LEACH, cluster-heads transmit directly to the base station, so if they are out of range they cannot deliver data. It is

Table 4.2 Average number of data packets received at the base station

Protocol	Scenarios			
	200 × 200	283 × 283	347 × 347	400 × 400
MTE	7889	8981.4	9164.6	8371.4
95% CI for MTE	(6979.73 to 8798.27)	(8198.29 to 9764.51)	(8523.75 to 9805.45)	(7937.01 to 8805.79)
LEACH	8172.8	14392.2	17723.8	18865.2
95% CI for LEACH	(5727.49 to 10618.11)	(10956.74 to 17827.66)	(13823.16 to 21624.44)	(12257.93 to 25472.47)
SST	7044.6	7226.2	6494.6	6228.8
95% CI for SST	(6245.18 to 7844.02)	(6090.97 to 8361.43)	(5643.41 to 7345.79)	(5453.73 to 7003.87)
SMV	7650.4	8335.6	8491.8	9524.4
95% CI for SMV	(7032.49 to 8268.31)	(7496.33 to 9174.87)	(7395.97 to 9587.63)	(7835.15 to 11213.65)

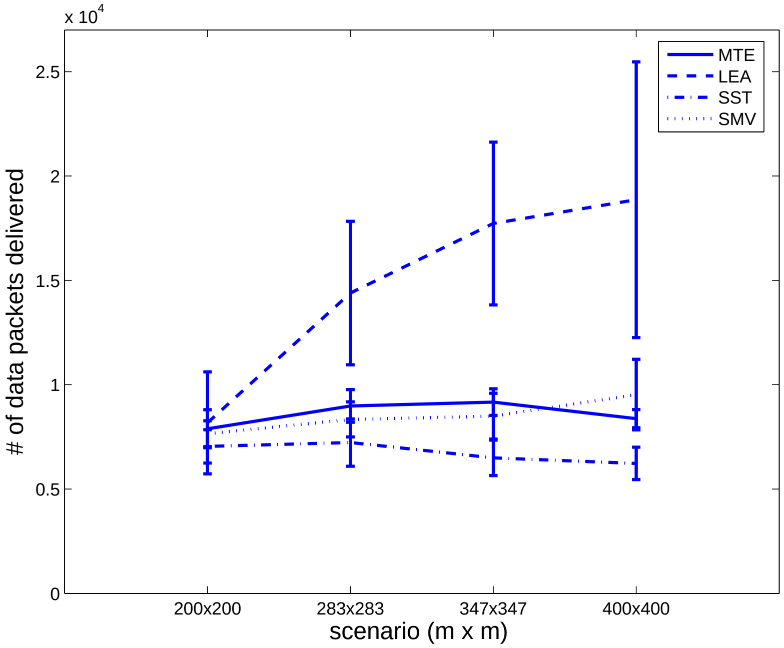

Figure 4.5 Average number of data packets received at the base station

observed that LEACH delivers the least amount of packets and the number of packets it delivers to the base station decreases with increase in scenario size. This experiment proves that the LEACH and MTE protocols are not scalable. On the other hand, SELAR is scalable but suffers from the

Table 4.3 Average number of data packets received at the base station after restricting the maximum radio range to cross-over distance (86.2 m)

Routing Protocol	Scenarios			
	200 × 200	283 × 283	347 × 347	400 × 400
MTE	4975.4	5920.2	5067	4997
95% CI for MTE	(4474.57 to 5476.23)	(4475.82 to 7364.58)	(4114.7 to 6019.3)	(4225.01 to 5768.99)
LEACH	1915	951.2	809.8	493
95% CI for LEACH	(1035.07 to 2794.93)	(465.76 to 1436.64)	(622.98 to 966.62)	(301.34 to 684.66)
SST	7044.6	7226.2	6494.6	6228.8
95% CI for SST	(6245.18 to 7844.02)	(6090.97 to 8361.43)	(5643.41 to 7345.79)	(5453.73 to 7003.87)
SMV	7650.4	8335.6	8491.8	9524.4
95%CI SMV	(7032.49 to 8268.31)	(7496.33 to 9174.87)	(7395.97 to 9587.63)	(7835.15 to 11213.65)

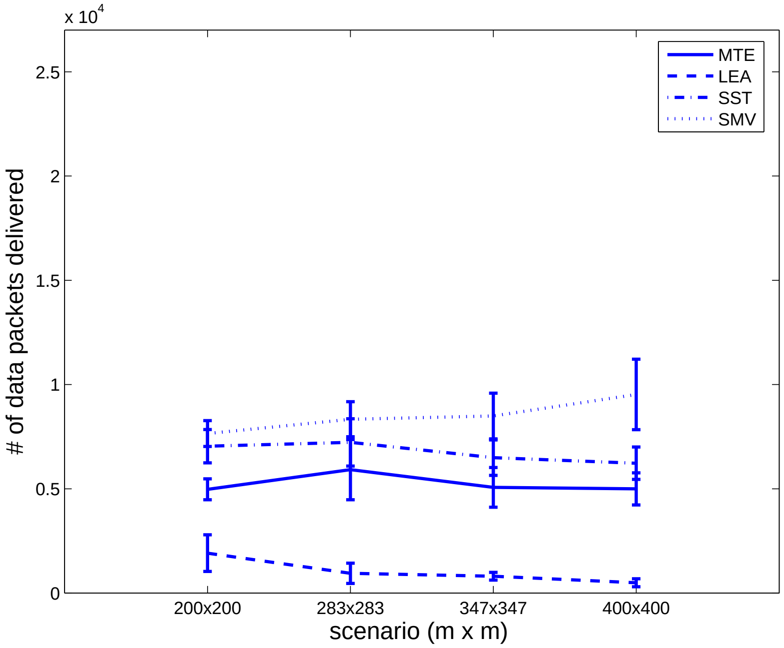

Figure 4.6 Average number of data packets received after restricting radio range to cross-over distance (86.2 m)

problem of energy depletion of nodes close to the base station. However, it was shown that the strategy of moving the sink around addresses this problem.

4.6.2 Network lifetime

For our simulations, network lifetime is defined as the time at which the last data packet is received at the base station. The average network lifetime after running MTE, LEACH, SELAR with stationary base station (SST) and SELAR with moving base station (SMV) are shown in Table 4.4 and Figure 4.7. Figure 4.7 shows the 95% Confidence Interval for the mean values in Table 4.4 found using t-distribution with 4 degrees of freedom. The average network lifetime after running MTE with maximum radio range restricted to cross-over distance (86.2 m), LEACH with maximum radio range restricted to cross-over distance (86.2 m), SELAR with stationary base station (SST) and SELAR with moving base station (SMV) are shown in Table 4.5 and Figure 4.8. Figure 4.8 shows the 95% Confidence Interval for the mean values in Table 4.5 found using t-distribution with 4 degrees of freedom.

The network lifetime for sensor nodes has been defined as the time at which the base station receives the last data packet from any sensor node. From Figures 4.7 and 4.8, it is observed that all protocols have somewhat similar lifetimes with restricted as well as unrestricted radio ranges. The SELAR protocols, in all cases, have their maximum radio ranges restricted to the cross-over distance (86.2 m). The lifetime of sensor network running MTE protocol drops when the maximum radio range is restricted. This can be seen from Tables 4.4 and 4.5. But, in both cases the network lifetime for MTE protocol is greater than that for SELAR with stationary base station (SST). This can be explained based on the working of both protocols and the definition of network lifetime. In SELAR, every node forwards data packets to its neighbor in the direction of the base station with maximum energy, while in MTE the next hop neighbor is fixed. Because of fixed next hop neighbors in MTE, certain nodes have fewer data to forward to the base station than others and hence, live longer. This can happen when the position of the node is such that initially, all its neighbors have better options than choosing the sensor node. This results in the base station receiving packets for longer amount of time (though few data packets are received) from these sensor nodes with lesser load, and this in turn increases the network lifetime. On the other hand, the lifetime of LEACH protocol is much lesser than other protocols because it sends data at a faster rate.

Table 4.4 Average network lifetime in simulation seconds

Routing Protocol	Scenarios			
	200 × 200	283 × 283	347 × 347	400 × 400
MTE	839.26	1414.04	2021.58	2087.14
95% CI for MTE	(563.07 to 1115.45)	(937.19 to 1890.89)	(1414.66 to 2628.5)	(1452.88 to 2721.4)
LEACH	150.34	218.28	288.06	351.28
95% CI for LEACH	(117.91 to 182.77)	(183.49 to 253.07)	(252.29 to 323.83)	(277.81 to 424.75)
SST	601.43	514	476	566
95% CI for SST	(222.67 to 980.19)	(151.88 to 876.12)	(223.61 to 728.39)	(98.13 to 1033.87)
SMV	809.57	1343.83	2469.05	7151.31
95% CI for SMV	(557.16 to 1061.98)	(795.12 to 1892.54)	(1469.41 to 3468.69)	(2418.37 to 11884.25)

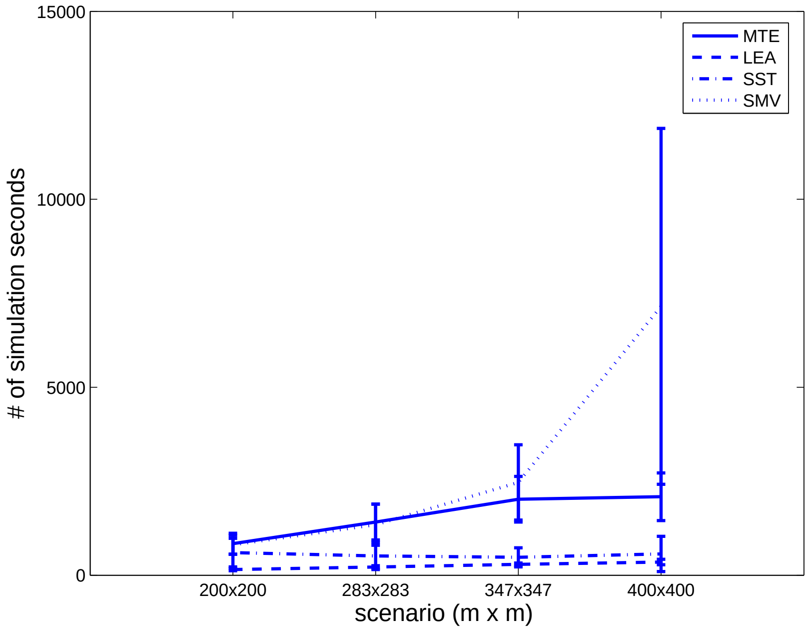

Figure 4.7 Average lifetime of the network in simulation seconds

Table 4.5 Average network lifetime in simulation seconds after restricting the maximum radio range to cross-over distance (86.2 m)

Routing Protocol	Scenarios			
	200 × 200	283 × 283	347 × 347	400 × 400
MTE	494	1280	1542	1404
95% CI for MTE	(231.14 to 756.86)	(534.55 to 2025.45)	(285.59 to 2798.41)	(408.13 to 2399.87)
LEACH	153.2	188.78	170	265.56
95% CI for LEACH	(118.95 to 187.45)	(120.63 to 256.93)	(121.10 to 218.90)	(138.99 to 392.13)
SST	601.43	514	476	566
95% CI for SST	(222.67 to 980.19)	(151.88 to 876.12)	(223.61 to 728.39)	(98.13 to 1033.87)
SMV	809.57	1343.83	2469.05	7151.31
95% CI for SMV	(557.16 to 1061.98)	(795.12 to 1892.54)	(1469.41 to 3468.69)	(2418.37 to 11884.25)

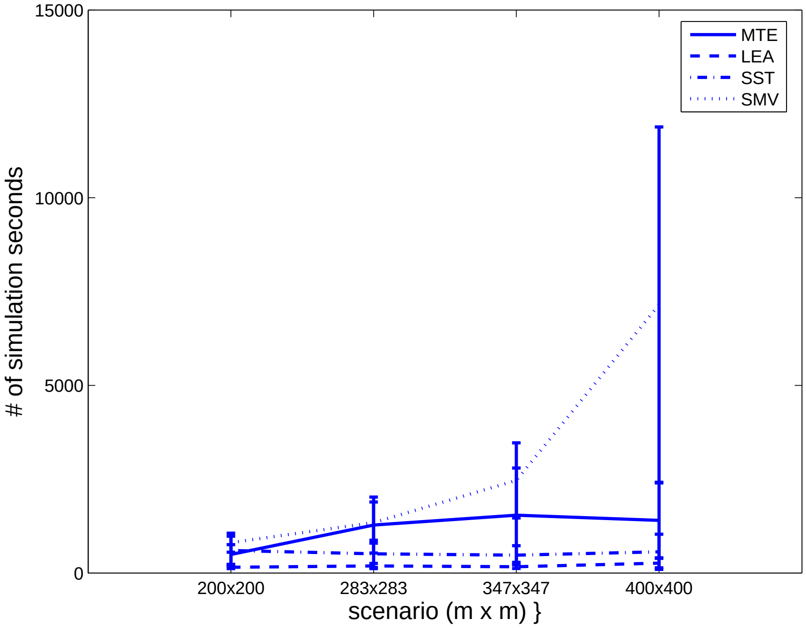

Figure 4.8 Average lifetime of the network in simulation seconds after restricting the maximum radio range to cross-over distance (86.2 m)

4.6.3 Energy distribution for MTE

Figures 4.9, 4.10 and 4.11 show the energy distribution of sensor nodes running MTE with around 90, 50 and 10 sensor nodes alive respectively using the 400×400 scenario with 100 nodes. Again, the diameter of the nodes represent their amount of energy. From the figures the following can be observed about MTE:

- Sensor nodes which are on the path of other sensor nodes way to the base station die faster than the rest of the nodes.
- Node energy dissipation is uneven in such a way that certain parts of the sensor network die faster than others.

Figures 4.12, 4.13 and 4.14 show the energy distribution of sensor nodes running MTE (with maximum radio range restricted to cross-over distance, 86.2 m) with around 90, 50 and 10 sensor nodes alive respectively. The dissipation of node energy is similar to that by nodes with no radio range restrictions. One difference being that the nodes far away from the base station dissipate energy at a slower rate when compared to the energy dissipation of the same nodes running MTE with no radio range restrictions. This can be observed comparing 4.10 and 4.13.

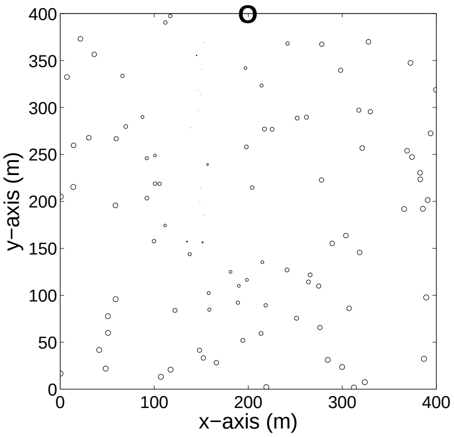

Figure 4.9 Energy distribution for MTE with around 90 nodes alive

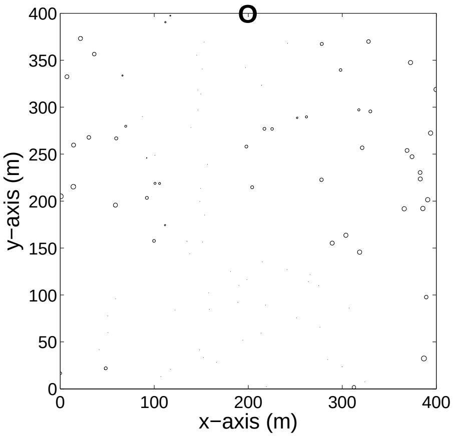

Figure 4.10 Energy distribution for MTE with around 50 nodes alive

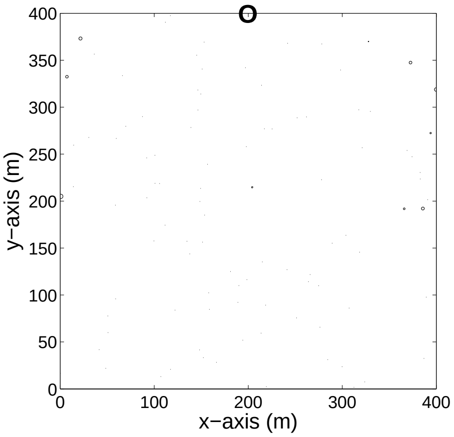

Figure 4.11 Energy distribution for MTE with around 10 nodes alive

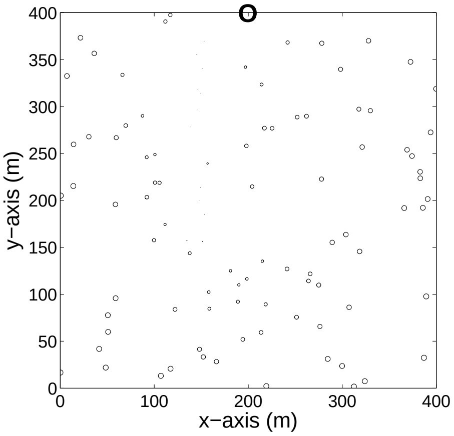

Figure 4.12 Energy distribution for MTE (maximum radio range restricted to cross-over distance, 86.2 m) with around 90 nodes alive

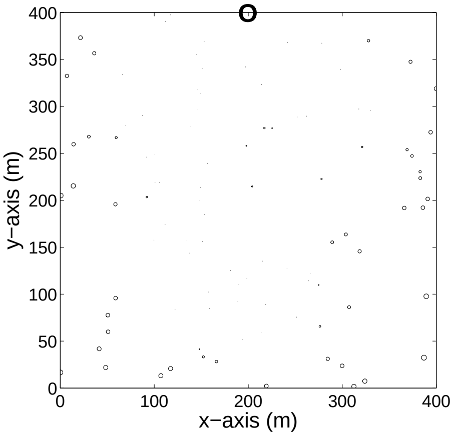

Figure 4.13 Energy distribution for MTE (maximum radio range restricted to cross-over distance, 86.2 m) with around 50 nodes alive

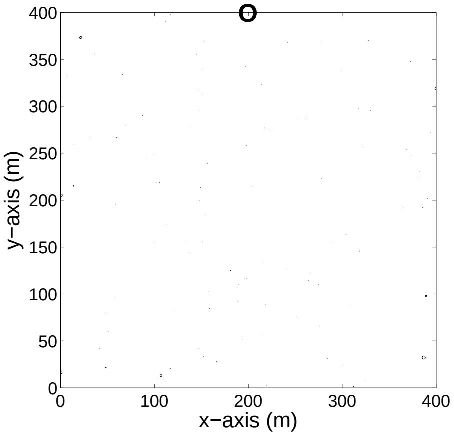

Figure 4.14 Energy distribution for MTE (maximum radio range restricted to cross-over distance, 86.2 m) with around 10 nodes alive

4.6.4 Energy distribution for LEACH

Figures 4.15, 4.16 and 4.17 show the energy distribution of sensor nodes running LEACH with around 90, 50 and 10 sensor nodes alive, respectively. From the figures the following can be observed about LEACH:

- Sensor nodes dissipate node energy randomly.
- When around 50 nodes are dead, most of the dead nodes are found to be the ones far away from the base station. This happens because the nodes farther away from the base station has to spend significantly more energy on becoming clusterheads than that spend by the nodes nearer to the base station on becoming clusterheads. Hence, nodes farther away from the base station dissipate their energy faster than the nodes nearer to the base station.

Figures 4.18, 4.19 and 4.20 show the energy distribution of sensor nodes running LEACH (with maximum radio range restricted to cross-over distance, 86.2 m) with around 90, 50 and 10 sensor nodes alive respectively. The following can be observed about LEACH with restricted radio range:

- Sensor nodes toward the center of the network topology dissipate energy faster than other nodes
- Sensor nodes near the edges and especially the ones at the corners seem to have more energy than other nodes. This could be because they do not receive advertisement packets every set-up phase and subsequently do not send data packets during those rounds.

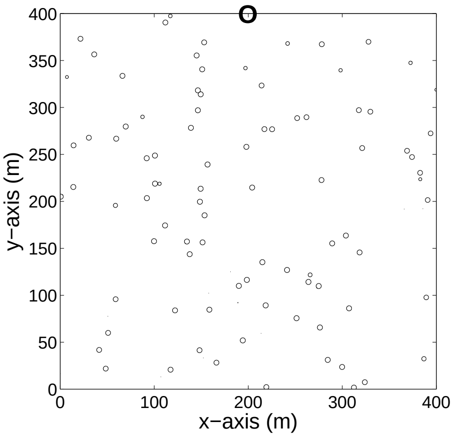

Figure 4.15 Energy distribution for LEACH with around 90 nodes alive

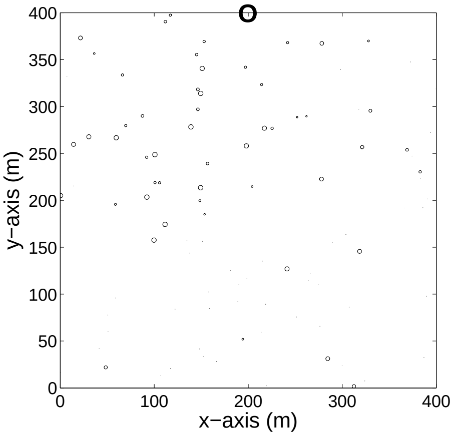

Figure 4.16 Energy distribution for LEACH with around 50 nodes alive

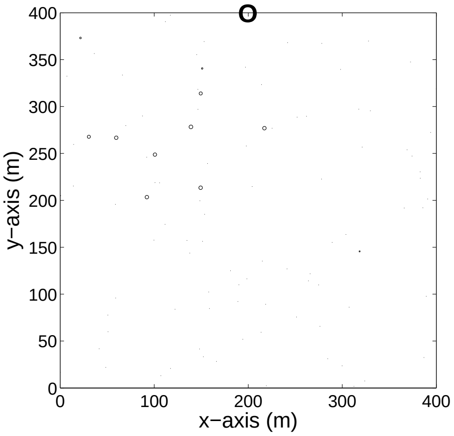

Figure 4.17 Energy distribution for LEACH with around 10 nodes alive

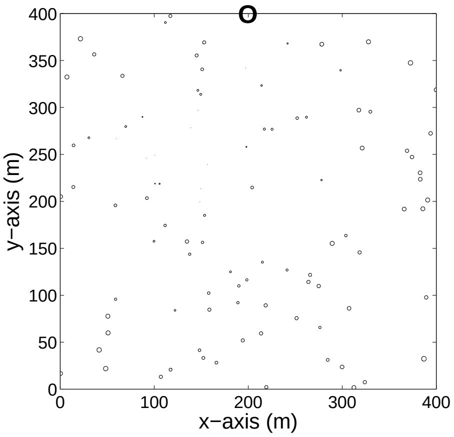

Figure 4.18 Energy distribution for LEACH (maximum radio range restricted to cross-over distance, 86.2 m) with around 90 nodes alive

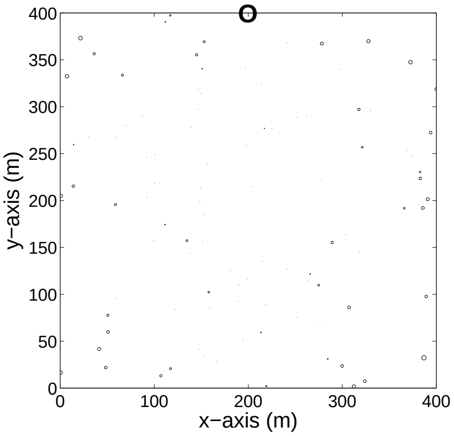

Figure 4.19 Energy distribution for LEACH (maximum radio range restricted to cross-over distance, 86.2 m) with around 50 nodes alive

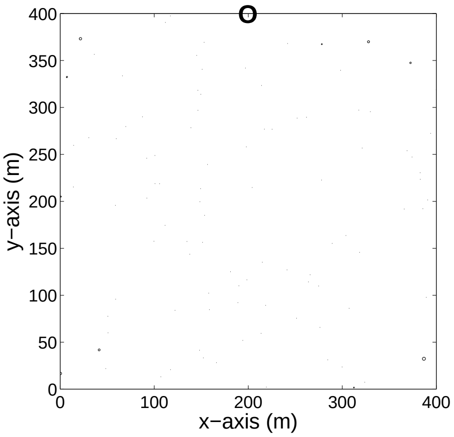

Figure 4.20 Energy distribution for LEACH (maximum radio range restricted to cross-over distance, 86.2 m) with around 10 nodes alive

4.6.5 Energy distribution for SELAR with stationary base station

Figures 4.21, 4.22 and 4.23 show the energy distribution of sensor nodes running SELAR (stationary base station) with around 90, 50 and 10 sensor nodes alive respectively. From the figures the following can be observed about SELAR with stationary base station:

- Energy dissipation follows a pattern. As nodes are farther away from the base station, they consume less energy. This is expected because nodes closer to the base station will route packets on behalf of farther nodes.
- Sensor nodes with similar distance to the base station dissipate energy similarly. This proves that packet forwarding in SELAR is energy aware.

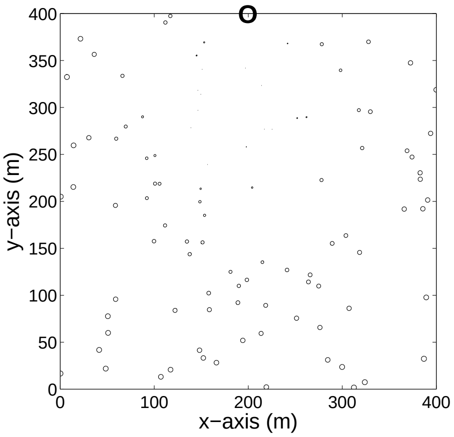

Figure 4.21 Energy distribution for SELAR (stationary base station) with around 90 nodes alive

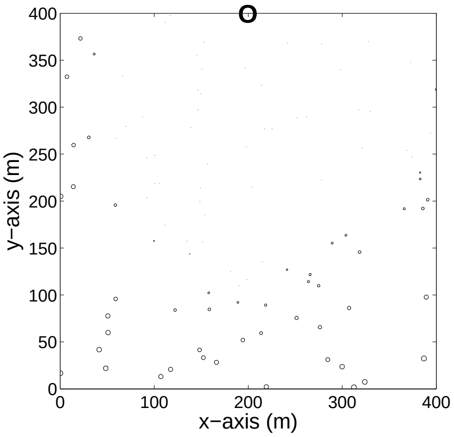

Figure 4.22 Energy distribution for SELAR (stationary base station) with around 50 nodes alive

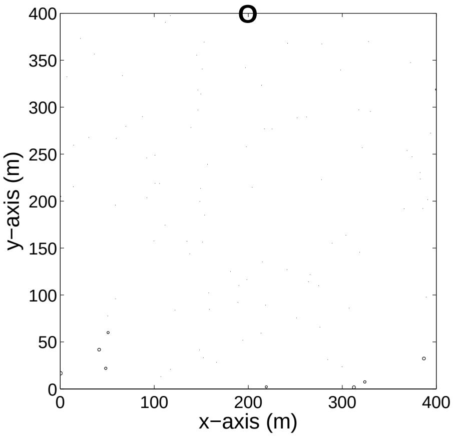

Figure 4.23 Energy distribution for SELAR (stationary base station) with around 10 nodes alive

4.6.6 Energy distribution for SELAR with moving base station

Figures 4.24, 4.25 and 4.26 show the energy distribution of sensor nodes running SELAR (moving base station) with around 90, 50 and 10 sensor nodes alive respectively. From the figures the following can be observed about SELAR with moving base station:

- Sensor nodes with similar distance to the base station dissipate energy similarly.
- The alive sensor nodes which were previously isolated are made use of.
- The productivity of the sensor network has been increased. This can be explained by taking into account the fact that more data packets reach the base station as well as that the network lifetime of the sensor network increases by moving the base station .
- By moving the base station at the right time to the right spot, it is possible to uniformly dissipate energy of the sensor nodes.

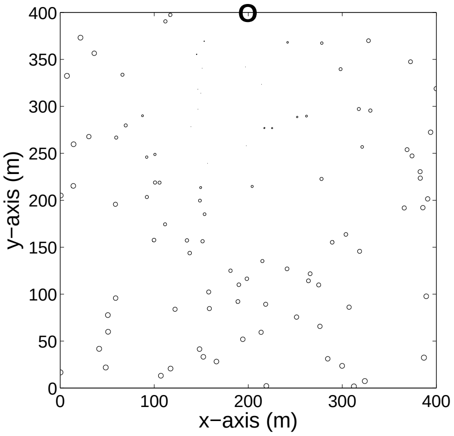

Figure 4.24 Energy distribution for SELAR (moving base station) with around 90 nodes alive

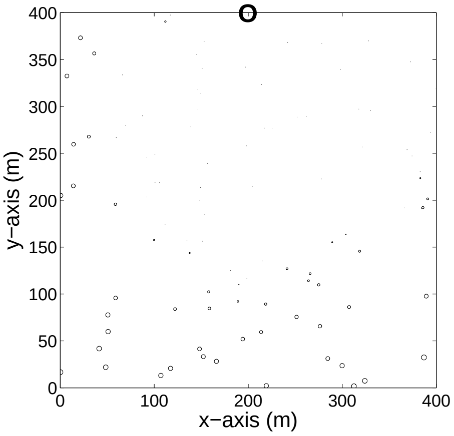

Figure 4.25 Energy distribution for SELAR (moving base station) with around 50 nodes alive

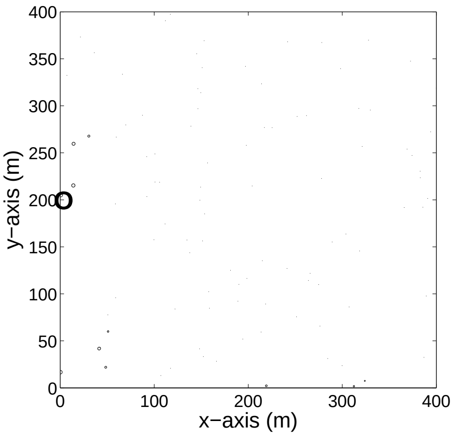

Figure 4.26 Energy distribution for SELAR (moving base station) with around 10 nodes alive

By considering all the above results it can be seen that SELAR with a moving base station is the best suited protocol for wireless sensor networks which have a large number of sensor nodes with limited energy and power. By moving the base station in SELAR at the appropriate time to the right position, it is ensured that the energy dissipation within the network is uniform. Even with a stationary base station, we see that SELAR performs better than MTE and LEACH, as it delivers more data packets than both the protocols. LEACH with restricted radio range delivers very few number of data packets because many of the cluster heads chosen in a particular round do not have the base station in their radio range.

By performing the routing functions locally, SELAR ensures that it is fault-tolerant and simple. Again, every sensor node takes into account the energy left in the neighbor node, before forwarding data packets. This ensures that power is dissipated in a uniform manner. SELAR is implemented assuming that the maximum radio range of each sensor node does not cover the entire sensor network. The LEACH and MTE protocols obtained from the MIT uAMPS project do not place any restriction on the maximum radio range of the sensor node. LEACH when run without any restrictions deliver upto 3 times more data packets to the base station than SELAR. But this gain is hypothetical, since in reality the radio range of wireless sensor networks is restricted [37] [38]. The results indicate that in realistic senarios, SELAR delivers upto 12 times more and upto 1.4 times more data packets to the base station than LEACH and MTE respectively. It was also seen from the results that for realistic scenarios, SELAR with moving base station has upto 5 times and upto 27 times more lifetime duration compared to MTE and LEACH respectively. With radio restrictions applied on LEACH and MTE, it is seen that SELAR performs significantly better than both of them. Further, by moving the base station during the operation of the sensor network, the performance of the wireless sensor network is seen to improve even more.

CHAPTER 5

CONCLUSION AND FUTURE WORK

Wireless sensor networks consist of hundreds or even thousands of power, energy contrained sensor nodes. They have a myriad of possible applications. Wireless sensor network can be used in habitat monitoring, surveillance in buildings, measuring pressure, temperature in hazardous areas, in military applications and so on. Routing in wireless sensor networks is important. In large scale wireless sensor networks designing an appropriate routing protocol can be challenging due to the contraints in power energy and computational capabilities for individual sensor nodes. The main design considerations for routing protocols in large-scale wireless sensor networks are: *fault tolerance*, *scalability*, *production costs*, *power/energy constraints*. SELAR has been designed taking these design considerations into account.

Using simulations, SELAR has been evaluated and compared with LEACH (Low-Energy Adaptive-Clustering Hierarchy) [10] [1] and MTE (Minimum Transmission Energy) [11] [12], two very well known routing protocols. The results show that SELAR delivers upto 12 times more and upto 1.4 times more data packets to the base station than LEACH and MTE respectively. It was also seen from the results that for realistic scenarios, SELAR with moving base station has upto 5 times and upto 27 times more lifetime duration compared to MTE and LEACH respectively. The results indicate that SELAR is able to send more data, extend the network lifetime and distribute the energy more uniformly than LEACH and MTE. Further the scalability of LEACH and MTE was shown to be poor while SELAR will work the same regardless of the number of nodes and size of the network. From the results, it can be concluded that SELAR is an energy-efficient, fault-tolerant and scalable routing protocol for wireless sensor networks. The results obtained show that SELAR performs better than MTE and LEACH. Further, by moving the base station at appropriate times, it is shown that the performance of SELAR can be increased.

Several aspects related to SELAR need further investigation. More work need to be done to determine the optimal time intervals or time at which to broadcst control packets to neighbor nodes so that control overhead is minimized without losing energy awareness. Also, a detailed study needs to be conducted on moving the base station during the operation of the wireless sensor networks. Two of the main questions to be answered about moving the base station are: *When to move the base station?* and *Where to move the base station?*.

REFERENCES

[1] W. Heinzelman, “Application-Specific Protocol Architectures for Wireless Networks,” PhD thesis, Massachusetts Institute of Technology, 2000.

[2] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A Survey on Sensor Networks,” in *IEEE Communications Magazine*, vol. 40, August 2002, pp. 102–114.

[3] J. N. Al-Karaki and A. E. Kamal, “Routing Techniques in Wireless Sensor Networks: A Survey,” Department of Electrical and Computer Engineering, Iowa State University, Ames, 50011.

[4] K. Akkaya and M. Younis, “A Survey on Routing Protocols for Wireless Sensor Networks,” Department of Computer Science and Electrical Engineering, University of Maryland, Baltimore County, Baltimore, MD 21250.

[5] “The mit uamps ns code extensions.” [Online]. Available: www-mtl.mit.edu/researchgroups /icsystems/uamps/research/leach/leach_code.shtml

[6] D. Culler, D. Estrin, and M. Srivastava, “Overview of Sensor Networks,” in *IEEE Computer Magazine*, vol. Vol. 37, No. 8, August 2004, pp. 41–49.

[7] G. Lukachan and M. A. Labrador, “SELAR: Scalable Energy-Efficient Location Aided Routing Protocol for Wireless Sensor Networks,” in *Proceedings of the 29th Annual International Conference on Local Computer Networks (LCN’04)*, November 2004, pp. 694–695.

[8] C. Shen, C. Srisathapornphat, and C. Jaikaeo, “Sensor Information Networking Architecture and Applications,” in *IEEE Pers. Commun.*, August 2001, pp. 52–59.

[9] G. Hoblos, M. Saroswiecki, and A. Aitouche, “Optimal Design of Fault Tolerant Sensor Networks,” in *IEEE Int’l Conf. Cont. Apps.*, September 2000, pp. 467–472.

[10] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-Efficient Communication Protocol for Wireless Microsensor Networks,” in *Proceedings of 33rd Hawaii International Conference on System Sciences (HICSS ’00)*, January 2000.

[11] M. Ettus, “System Capacity, Latency and Power Consumption in Multihop-Routed SS-CDMA Wireless Networks,” August, 1998, pp. 55–58.

[12] T. Shepard, “A Channel Access Scheme for Large Dense Packet Radio Networks,” in *Proc. ACM SIGCOMM*, August 1996, pp. 219–230.

[13] W. Heinzelman, J. Kulik, and H. Balakrishnan, “Adaptive Protocols for Information Dissemination in Wireless Sensor Networks,” in *Proc. Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom ’99)*, August 1999, pp. 174–185.

[14] C. Intanagonwiwat, R. Goovindan, and D. Estrin, “Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks,” in *Proceedings of the 6th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom ’00)*, August 2000.

[15] D. Braginsky and D. Estrin, “Rumor Routing Algorithm for Sensor Networks,” in *Proceedings of the First Workshop on Sensor Networks and Applications (WSNA)*, October 2002.

[16] S. Lindsey and C. Raghavendra, “PEGASIS: Power-Efficient Gathering in Sensor Information Systems,” in *Proc. IEEE Aerospace Conference*, vol. Vol. 3, 9-16, October 2002, pp. 1125–1130.

[17] L. Li and J. Y. Halpern, “Minimum Enrgy Mobile Wireless Networks Revisited,” in *IEEE International Conference on Communications (ICC)*, vol. 1, October 2001, pp. 278–283.

[18] Y. Xu, J. Heidemann, and D. Estrin, “Geography-informed Energy Conservation for Ad-Hoc Routing,” in *Proc. 7th Annual ACM/IEEE International /Conference on Mobile Computing and Networking*, 2001, pp. 70–84.

[19] Y. Yu, D. Estrin, and R. Govindan, “Geographical and Energy-Aware Routing: A Recursive Data Dissemination Protocol for Wireless Sensor Networks,” UCLA Computer Science Department Technical Report, UCLA-CSD TR-01-0023, May 2001.

[20] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, “SPAN: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks,” in *Wireless Networks*, vol. Vol. 8, No. 5, September 2002, pp. 481–494.

[21] S. Hedetniemi, S. Hedetniemi, and A. Liestman, “A Survey of Gossiping and Broadcasting in Communication Networks,” in *Networks*, vol. Vol. 18, 1998, pp. 70–84.

[22] K. Sohrabi et al., “Protocols for Self-Organization of a Wireless Sensor Network,” in *IEEE Pers. Commun.*, October 2000, pp. 16–27.

[23] T. He et al., “SPEED: A Stateless Protocol for Real-Time Communication in Sensor Networks,” in *Proc. International Conference on Distributed Computing Systems*, Providence, RI, May 2003.

[24] V. Rodoplu and T. H. Meng, “Minimum Energy Mobile Wireless Networks,” in *IEEE Journal Selected Areas in Communications*, vol. Vol. 17, No. 8, August 1999, pp. 1333–1344.

[25] S. Basagni, I. Chlamtac, V. R. Syrotiuk, and B. A. Woodard, “A Distance Routing Effect Algorithm for Mobility (DREAM),” in *Proceedings of the Fourth ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom’98)*, 1998, pp. 76–84.

[26] N. Bulusu, J. Heidemann, and D. Estrin, “GPS-less Low Cost Outdoor Localization for Very Small Devices,” in *IEEE Personal Communications Magazine*, vol. Vol. 7, No. 5, October 2000, pp. 28–34.

[27] N. Bulusu, J. Heidemann, and D. Estrin, “Adaptive Beacon Placement,” in *Proceedings of the 21st International Conference on Distributed Computing Systems (ICDCS-21)*, April 2001.

[28] N. Bulusu, J. Heidemann, V. Bychkovskiy, and D. Estrin, “Density-adaptive Beacon Placement Algorithms for Localization in Ad Hoc Wireless Networks,” Technical Report UCLA-CS-TR-010013, Computer Science Department, University of California at Los Angeles, Los Angeles, California, USA, May 2001.

[29] B. Blum, T. He, S. Son, and J. Stankovic, “IGF: A State-Free Robust Communication Protocol for Wireless Sensor Networks,” Department of Computer Science, University of Virginia, USA, Tech. Rep. CS-2003-11, 2003.

[30] T. Camp, J. Boleng, B. Williams, L. Wilcox, and W. Navidi, “Performance Comparison of Two Location Based Routing Protocols for Ad Hoc Networks,” Department of Math and Computer Sciences, Colorado School of Mines, Golden, CO 80401.

[31] S. R. Gandham, M. Dawande, R. Prakash, and S. Venkatesan, “Energy Efficient Schemes for Wireless Sensor Networks with Mobile Base Station,” Department of Computer Science, School of Management, University of Texas at Dallas, Richardson, TX 75080.

[32] “The Network Simulator - ns-2.” [Online]. Available: www.isi.edu/nsnam/ns/

[33] “CMU Wireless and Mobility Platform.” [Online]. Available: www.monarch.cs.rice.edu/cmu-ns.html

[34] J. Broch, D. Maltz, D. Johnson, Y. Hu, and J. Jetcheva, “A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols,” in *Proc. 4th ACM International Conference on Mobile Computing and Networking (Mobicom ’98)*, October 1998.

[35] S.Sheng, L. Lynn, J. Peroulas, K.Stone, I. O’Donnell, and R. Brodersen, “A Low Power CMOS Chipset for Spread Spectrum Communications,” in *Proceedings of the 42nd Solid-State Circuits Conference (ISSCC’96)*, February 1996.

[36] T. Rappaport, *Wireless Communications: Principles & Practice*. Prentice-Hall Inc., New Jersey, 1996.

[37] “The uAMPS project.” [Online]. Available: www-mtl.mit.edu/researchgroups/icsystems/uamps/

[38] “Xbow product details.” [Online]. Available: www.xbow.com/Products/productsdetails.aspx?sid=62