Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Analyzing and Assessing Tradeoffs and Effects of Energy Related Parameters on Wireless Sensor Networks for Optimizing Sensor Network Lifetime

by

Bisratie Tesfaye

June 2014

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Analyzing and Assessing Tradeoffs and Effects of Energy Related Parameters on Wireless Sensor Networks for Optimizing Sensor Network Lifetime

Advisor

Dr. Yalemzewd Negash

A Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of Master of Science
In
Computer Engineering

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Analyzing and Assessing Tradeoffs and Effects of Energy Related Parameters on Wireless Sensor Networks for Optimizing Sensor Network Lifetime

by

Bisratie Tesfaye

Approved by Board of Examiners

Chairman, School of Electrical and Computer Engineering	Signature
Advisor	Signature
Internal Examiner	Signature
External Examiner	Signature

Declaration

I, the undersigned, hereby declare that this thesis is my original work performed under the supervision of Dr. Yalemzewd Negash, has not been presented as a thesis for a degree program in any other university and all source of materials used for the thesis are duly acknowledged.

Name

Bisratie Tesfaye__________

Signature

____

Place

Addis Ababa_____________

Date of Submission

____

This thesis has been submitted for examination with my approval as university advisor.

Advisor Signature

Dr. Yalemzewd Negash____ ___________________

Acknowledgements

First and foremost, I would like to express my sincere gratitude and respect for my thesis advisor, Dr. Yalemzewd Negash, for his valuable suggestion, constructive criticism and constant support throughout the study.

I am extremely thankful to Dr. Srinivas Nune, for his continuous encouragement, support and valuable advice which helped me to successfully complete the study.

My family has also been very supportive, not just during this study, but throughout my entire life. Their loves provided me with the motivation and endeavor to accomplish this piece of work. They have always been a great source of encouragement and support. They gave me so much that I can never pay them back. I will owe them gratitude and thankfulness forever.

Finally, I would like to thank everyone else who has supported me in one way or another throughout this study.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVATIONS

CMOS	:	Complementary Metal Oxide Semiconductor
CPU	:	Central Processing Unit
ID	:	Identity
Kb	:	Kilobit(s)
KB	:	KiloByte(s)
MAC	:	Medium Access Control
MANET	:	Mobile Adhoc NETwork
ME	:	Minimum Energy
MEMS	:	Micro Electro Mechanical Systems
MH	:	Minimum Hop
MIPS	:	Million Instructions Per Second
MSVC	:	MicroSoft Visual C
OMNeT++	:	Objective Modular Network Testbed in C++
PDA	:	Personal Digital Assistance
QoS	:	Quality of Service
RF	:	Radio Frequency
TDMA	:	Time Division Multiple Access
WSN	:	Wireless Sensor Network
W	:	Watt
WWW	:	World Wide Web

Abstract

Sensor technologies have become vital today in gathering information about close by environments and its use in wireless sensor networks is getting widespread popular every day. These networks are characterized by a number of sensor nodes deployed in the field for the observation of some phenomena. Due to the limited battery capacity in sensor nodes, energy efficiency is a major and challenging problem in such power constrained networks. To extend the life time of wireless sensor networks as well as conserving its power, some network parameters have been considered, which play an important role in the reduction of power consumption. These parameters are as battery capacity, communication radius, node density and query period. They have a direct impact on the network's lifetime. These parameters have to be chosen in such a way that the network use its energy resources efficiently. In This thesis we study these parameters that should be selected according to certain tradeoffs with respect to the network's lifetime. Their tradeoff characteristics have been investigated and illustrated in detail in various combinations. To achieve this goal, a special simulation tool that helps in analyzing the effects of the parameters on sensor network lifetime has been designed and implemented by means of OMNet++; a discrete event simulator provides the framework for the sensor network simulator's development. Ultimately, results of extensive computational tests are presented, which may be helpful in guiding the sensor network designer in optimally selecting the parameters proposed to improve the lifetime of the network.

Chapter 1

Introduction

With the recent technological advances in wireless communications, processor, memory, radio, low power highly integrated digital electronics and micro electro mechanical systems (MEMS); it becomes possible to significantly develop tiny and small size, low power and low cost multifunctional sensor nodes. These nodes are capable in wireless communications, sensing and computation. So, it is clear that wireless sensor network is the result of the combination of sensor techniques, embedded techniques, distributed information processing and communication mechanisms.

Each sensor node is capable of only a limited amount of processing. But when coordinated with the information from a large number of other nodes, they have the ability to measure a given physical environment in great detail. Thus, a sensor network can be described as a collection of sensor nodes which co-ordinate to perform some specific action. In Wireless Sensor Networks (WSNs), sensor nodes can be used for continuous sensing, event detection, event identification, location sensing and local control of actuators. The concepts of micro-sensing and wireless connection of these nodes promise many new application areas. The range of applications of WSNs is very wide and includes military, environment, health, home and other commercial areas.

WSNs are composed of a large number of sensor nodes, which are densely deployed either inside a physical phenomenon or very close to it. In many applications, the positions of sensor nodes do not need to be predefined. This allows random deployment in inaccessible terrain or disaster relief operations. So sensor network protocols and algorithms must possess self organizing capabilities. And multi-hop communication can solve the problem of long-distance wireless communication.

Sensor networks can be considered as a special type of ad hoc wireless networks, where sensor nodes are, in general, stationary. After deployment self organized sensor nodes in a network gather information and send it to the base station where end-user can retrieve the data. The sensor nodes use their processing abilities to locally carry out simple computations and transmit only the required and partially processed data. In essence, wireless sensor networks with these capabilities may provide the end users with intelligence and a better understanding of the environment.

A unique feature of sensor networks is the cooperative effort of sensor nodes. Unlike cell phone systems that deny service when too many phones are active in a small area, the interconnection of a wireless sensor network only grows stronger as nodes are added. While the capabilities of any single device are minimal, the composition of hundreds of devices offers radical new technological possibilities. The power of wireless sensor networks lies in the ability to deploy large numbers of tiny nodes that assemble and configure themselves. Unlike traditional wired systems, deployment costs would be minimal. Instead of having to deploy thousands of feet of wire routed through protective conduit, installers simply have to place small size devices at each sensing point inside a given territory. The network could be incrementally extended by simply adding more devices – no rework or complex configuration.

Current wireless systems only scratch the surface of possibilities emerging from the integration of low-power communication, sensing, energy storage, and computation. Generally, when people consider wireless devices they think of such items as cell phones or personal digital assistants (PDA), items with high costs and energy requirements that target specific, highly standardized applications and rely on the pre-deployment of extensive infrastructure support. A new direction in wireless system design, however, is extending wireless connectivity to small, low-cost embedded devices for a wide range of applications that do not rely on pre-existing infrastructure.

A sensor network normally constitutes a wireless ad hoc network that is each sensor supports a multi-hop routing algorithm where nodes function as forwarders, relaying data packets to a base station. Unlike traditional wireless devices, wireless sensor nodes do not need to communicate directly with the nearest high-power base station, but only with their local peers. Instead, of relying on a pre-deployed infrastructure, each individual sensor or actuator becomes part of the overall infrastructure. Peer-to-peer networking protocols provide a mesh-like interconnect to shuttle data between the thousands of tiny embedded devices in a multi-hop fashion. The flexible mesh architectures envisioned dynamically adapt to support introduction of new nodes or expand to cover a larger geographic region. Additionally, the system can automatically adapt to compensate for node failures.

Sensor nodes are scattered densely in a field either close to or inside the phenomenon. Since they are densely deployed, neighbor nodes may be very close to each other. As a result, multi hop communication in the wireless sensor networks is expected to consume less power than the traditional single hop communication. Furthermore, the transmission power levels may be kept low, which is highly desired for covert operations. In addition, multi hop communication may effectively overcome some of the signal propagation effects experienced in long distance wireless communication.

As sensor nodes carry limited, in general irreplaceable power sources, one of the most important constraints for WSNs is the low power consumption requirement. Thus, power conservation is of tremendous importance. Most of sensor nodes in WSN are equipped with non-rechargeable batteries that have limited lifetime. Sensor nodes must be easily and rapidly deployed in large numbers and, once deployed, must form a suitable network with a minimum of human intervention. All of these requirements must be met with a minimum of power consumption due to battery limitations and, for many applications, the inability to recharge these batteries.

In wireless sensor networks, a decrease in the number of available sensor nodes can deeply degrade the network performance. Moreover, as WSNs are often deployed in hostile and/or remote areas, replacing batteries may be infeasible. Sensor nodes carry limited, generally irreplaceable, power sources. Therefore, while traditional networks aim to achieve high quality of service (QoS) provisions, sensor network protocols must focus primarily on power conservation. They must have inbuilt trade-off mechanisms that give the end user the option of prolonging network lifetime at the cost of lower throughput or higher transmission delay.

In this study, we describe architecture for self-organizing wireless sensor networks. A wireless sensor network of the type investigated here refers to a group of sensors, or nodes, deployed randomly over a defined terrain. These sensor nodes are capable of sensing specific information within their sensing range. The nodes are linked by a wireless medium to perform distributed sensing tasks. Connections between nodes may be formed using such media as infrared devices or radios. Sensor nodes send the information that it gathers locally to the destination, which is called the sink node. While doing that, the main concern is to consume energy in an optimum way.

Nodes in a wireless sensor network have non uniform energy consumption rates. As a result, early death among highly loaded nodes is a common phenomenon which makes it impossible to use the full capacity of the network. Our claim is that significant reductions in energy consumption can be achieved if wireless networks are designed specifically for minimum energy. In order to maximize the total lifetime of a wireless network, we must minimize the energy consumption of the entire network. The way sensor networks are organized internally plays an important role in decreasing the energy budget to perform certain functions, and therefore proper design of the sensor network architecture is an important goal to be pursued.

Several different approaches have been used to optimize the lifetime of the wireless sensor network using various deployments schemes. Among them Heterogeneous deployment schemes for sensor nodes have been proposed to balance the power consumption of each node in a given area. In [1], the optimal heterogeneous sensor deployment scheme was proposed to minimize the deployment cost in different communication modes. In that work, the cost of the cluster head was determined by the optimal number of cluster head nodes, the optimal mode of communication within a cluster, and the required battery energy consumption of both types of nodes. They did not consider the sensing coverage and communication mode.

Some researchers used concentric ring deployment scheme in order to optimize the lifetime of the wireless sensor network using mathematical analysis and simulation experiments. In [2], two kinds of deployment strategies were proposed. In the first approach, the highest battery resources are allocated to the ring where the highest energy drainage takes place. Each node in a ring has the same useable battery capacity. The second approach is based on using non-uniform node densities in different regions of the network. This method assumes a dense network and redundant nodes are deployed proportional to the energy consumptions in each region. Both methods balanced the energy consumption among sensor nodes and optimized the lifetime of wireless sensor networks. In [3], the rate capacity effect is utilized to balance the lifetimes of individual nodes in a wireless sensor network by designing a battery-aware deployment using concentric ring deployment scheme.

The way sensor networks are organized internally may play a role in decreasing the energy budget to perform certain functionalities, and therefore proper design of the sensor architecture is an important goal to be pursued. To maximize the lifetime of the network, we need to minimize the energy dissipation for communication by reducing the number of sending and receiving operations and reducing the transmission distance. In this study, we used several parameters mainly related to the network lifetime. These are initial battery capacity, communication radius, query period and node density. These parameters are thought to have certain tradeoffs in terms of the lifetime and therefore the relations between these parameters should be thoroughly investigated to support our claim. After describing the relations, we illustrate the tradeoffs of our parameters by various combinations of the sensor network parameter values. An OMNet++ based simulator is developed for the experiment which helps in analyzing the effect of the parameters on sensor network lifetime.

The thesis is organized as follows:

Chapter 2, “Wireless Sensor Networks: Background and Related Work”, explains in detail what a wireless sensor network is and emphasizes the key concepts. A literature survey on past studies on these concepts is also presented.

Chapter 3, “Issues in Wireless Sensor Networks” explains in detail the characteristics of a wireless sensor networks and emphasizes on the key concepts on environmental data collection and monitoring.

Chapter 4, “System Parameters” explains in detail on energy related network parameters in sequence.

Chapter 5, “Problem Definition”, describes what the problem solved in this thesis is and gives detailed information about our approach. Constraints, limitations and assumptions are all addressed in this chapter.

Chapter 6, “Design and Implementation of a Sensor Network Simulation Experiment”, presents the development of the simulation tool. OMNeT++, a discrete event simulator environment is used as the framework for this purpose. Although our simulation study aims to evaluate the tradeoffs between the network parameters that affect the lifetime, the developed simulator can be modified and extended to be used for various other sensor network related purposes.

Chapter 7, “Simulation Study”, explains the work environment necessary for collecting the arranged results and also includes plots and their analysis.

Chapter 8, “Conclusions”, summarizes the findings and contributions of this study and outlines possible directions for future research.

Chapter 2

Wireless Sensor Networks: Background and Related Work

2.1. History

The first wireless networks were developed in the Pre-industrial age. Since the first wireless digital network based on packet radio, ALOHANET, was developed at the university of Hawaii in1971, wireless networking has witnessed an explosion of interest from consumers in recent years for its applications in mobile and personal communications. Wireless networks provide users with extended computing capabilities and mobility.

Wireless networks can be classified into two types: infrastructured network and infrastructureless (ad hoc) networks [4]. The infrastructured network architecture contains a wired backbone, which connects to a special switching node called base station. Communication between hosts has to go through the base station. In contrast to infrastructured based networks, an ad hoc network is a self-organizing system consisting of hosts that do not rely on the presence of any fixed network infrastructure. A cellular network belongs to the first type and a mobile ad hoc network (MANET) belongs to the second type. Recently a number of short-range wireless networking systems have been developed. Bluetooth intends to replace the wire and provides RF connection between devices. It is a star network where a master node is able to have up to seven active slave nodes attached to it to form a piconet. The time-division multiple access (TDMA) schedule is centrally assigned, and all nodes are synchronized to the master in this system. Another commercial short range wireless system is Home RF based on IEEE802.11 to handle single hop ad hoc networks.

In contrast to the above networks, wireless sensor networks simply sensor networks comprise many nodes. These nodes are generally stationary and self-organized into a network to perform a higher-level sensing task. After deployment, the wireless sensor nodes gather acoustic, magnetic, or seismic information and send the information to a control center or a base station, where end-users can retrieve the data.

The emergence of wireless sensor networks requires a new wireless system design paradigm. Although similar to traditional personal communication networks and wireless data networks in some respects, wireless sensor networks need to function in a fundamentally different manner since they are carrying out a very different task. The increased dynamic nature of the network means that previously used personal communication network system design techniques will not necessarily produce adequate solutions. The data flow in wireless sensor networks is controlled by a new generation of protocols, designed to handle the data rates and quantities generated by the sensors and to do so using very little power.

2.2. Current Trends

Recent advances in micro-electro-mechanical systems (MEMS) technology, wireless communication digital electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate in short distance. These tiny sensor nodes, which consist of sensing, data processing, and communicating components, leverage the idea of sensor networks based on collaborative effort of a large number of nodes.

Sensor networks represent a significant improvement over traditional sensor networks, which are deployed in the following two ways [5].

- Sensors can be located far from the actual phenomenon to be monitored. With this approach, large sensors that use some complex methods to distinguish the targets from environmental noise are required.
- Several sensors that perform only sensing can be deployed. The positions of the sensors and communications network topology are carefully designed. They

transmit time series of data about the phenomenon to central nodes where computations are performed and data are fused.

The wireless sensor node, being a microelectronic device, can only be equipped with a limited power source (<0.5 Ah, 1.2 V). In some application scenarios, replenishment of power resources might be impossible. The lifetime of a sensor node shows a strong dependence on battery lifetime. In a multi-hop sensor network, each node plays the dual role of data originator and data router. The malfunctioning of few nodes can cause significant topological changes and might require rerouting of packets and reorganization of the entire network. Hence, power conservation and power management take on additional importance. It is for these reasons that researchers are currently focusing on the design of power-aware protocols and algorithms for sensor networks. In other mobile and ad hoc networks, power consumption has been an important design factor, but not the primary consideration, simply because power resources can be replaced by the user. The emphasis is more on Quality of Service provisioning than the power efficiency. In sensor networks though, power efficiency is an important performance metric, directly influencing the network lifetime. Application specific protocols can be designed by appropriately trading off other performance metrics such as utility, delay and throughput with power efficiency.

Sensor networks may also consist of different type of sensors such as seismic, low sampling rate magnetic, thermal, visual, and infrared, radar and acoustic, which monitor a wide variety of ambient conditions that includes habitat monitoring, temperature fluctuation, air pollution control, and traffic control [6]. These are not the only application areas of wireless sensor network, these are some of the application areas found in literature. One of the attractive features of this technology is the potentially large number of areas to which it can be applied.

Realization of these and other sensor network applications require wireless ad hoc networking techniques. Although many protocols and algorithms have been proposed for traditional wireless ad hoc networks, they are not well suited for the unique features and application requirements of sensor networks. To illustrate this point, the differences between sensor networks and ad hoc networks are [7] outlined below:

- The number of sensor nodes in a sensor network can be several orders of magnitude higher than the nodes in an ad hoc network and are densely deployed and are prone to failures.
- Sensor nodes are limited in power, computational capacities, and memory.
- Sensor nodes may not have global identification (ID) because of the large amount of overhead and large number of sensors.

2.3. Challenges

A sensor network design is influenced by many factors, which include fault tolerance; scalability; production costs; operating environment; sensor network topology; hardware constraints; transmission media; and power consumption. These factors are addressed by many researchers. However, none of these studies has a full integrated view of all factors that are driving the design of sensor networks and sensor nodes. These factors are important because they serve as a guideline to design a protocol or an algorithm for sensor networks. In addition, these influencing factors can be used to compare different schemes.

Unlike traditional well-structured computer networks, where connecting devices to the network using relatively static network configuration is often cumbersome, sensor networks are unstructured and consist of very large number of sensors. Building self-organizing sensor networks is difficult for the following main reasons:

- Many different types of sensors with a range of capabilities may be deployed with different specialized network protocols and application requirements. Data-centric networks, in which data is more important than any other information like the location of the nodes, are becoming common in sensor networks. With many mixed types of sensors and applications, sensor networks may need to support several data-centric network protocols simultaneously.

- Mixed types of sensor nodes may be deployed incrementally and spontaneously with little or no pre-planning. The networks must be extensible to new types of sensor node and services. They must be deployed spontaneously to form efficient ad-hoc networks using sensors with limited computational, storage and short-range wireless communication capabilities. They rapidly coordinate with each other to detect, track and report activities and disseminate the information efficiently through the impromptu network of sensors.

- The sensor network must react rapidly to changes in the sensors composition, task or network requirements, device failure and degradation and mobility of sensor nodes. Sensor devices may be deployed in very harsh environment, and subject to destruction and dynamically changing conditions. The configuration of the network will frequently change due to constant changes in sensor position, reachability, power availability and task requirements. The network protocols must be survivable in spite of device failures and frequent real-time changes. The sensor network must be secure in the face of this open and dynamic environment.

In short, the challenge is to map the overall system requirements down to individual device capabilities, requirements and actions.

Critical sensor information must be disseminated through mobile transactions and dynamic query processing modules supported by the appropriate distributed services and network protocols to solve the problems of mobility, dispersion, weak and intermittent disconnection, dynamic reconfiguration and limited power availability. The underlying principle for building self-organizing sensor networks that can overcome the above challenges is to provide the fundamental mechanisms upon which other networking and system services may be spontaneously specified and reconfigured.

Chapter 3

Issues in Wireless Sensor Networks

3.1. Characteristics of a Wireless Sensor Network

The architecture of a sensor node's hardware consists of the usual components like processor, memory, wireless interface, power supply, as well as the sensor devices. An individual sensor device can be either an actual sensor or an actuator (for uniformity, both are referred to as “sensor device”). A single sensor node can contain a single or multiple sensor devices of the same or different types. In principle, a sensor should be able to tell a host the kind of measurements it can make its range, accuracy, linearization and signal conditioning requirements. Each sensor thus becomes an entire electronic system-complete with transducer, amplifier, analog-to-digital converter, microprocessor and lookup table. In brief, the concept of wireless sensor networks is based on a simple equation:

Sensing + CPU + Radio = Thousands of potential applications [8].

As soon as people understand the capabilities of a wireless sensor network, hundreds of applications spring to mind. It seems like a straightforward combination of modern technology.

3.2. An Application Example: Environmental Data Collection and Monitoring

An environmental data collection application is one where a research scientist wants to collect several sensor readings from a set of points in an environment over a period of time in order to detect styles and interdependencies. This scientist would want to collect data from hundreds of points extending throughout the area and then analyze the data later offline. The scientist would be interested in collecting data over several weeks, months or years in order to look for long-term and seasonal trends. For the data to be significant it would have to be collected at regular intervals and the nodes would remain at known locations. At the network level, the environmental data collection application is differentiated by having a large number of nodes continually sensing and transmitting data back to a set of base stations that store the data using traditional methods. These networks generally need very low data rates and extremely long lifetimes. In typical usage scenario, the nodes will be evenly distributed over an outdoor environment. This distance between nearby nodes will be minimal yet the distance across the entire network will be significant.

After deployment, the nodes must discover the topology of the network first and then estimate optimal routing strategies [9]. The routing strategy can then be used to direct data to a central collection points. In environmental monitoring applications, it is not necessary that the nodes develop the optimal routing strategies on their own. Instead, it may be possible to determine the optimal routing topology outside of the network and then communicate the necessary information to the nodes as required. This is possible because the physical topology of the network is relatively stable. While the time variant nature of RF communication may cause connectivity between two nodes to be alternating, the overall topology of the network will be relatively stable.

Environmental data collection applications typically use tree-based routing topologies where each routing tree is rooted at high-capability nodes that sink data. Data is periodically transmitted from child nodes to parent nodes up to the tree-structure until it reaches the sink. With tree-based data collection, each node is in charge of forwarding the data of all its descendents. Nodes with a large number of descendants transmit significantly more data than leaf nodes. These nodes can quickly become energy bottlenecks.

Once the network is configured, each node periodically samples its sensors and transmits the collected data to the central base station. For many scenarios, the interval between these transmissions can be of the order of a few minutes up to several hours. The typical environment parameters being monitored, such as temperature, light intensity and humidity, normally change very gradually and do not require higher reporting rates. In addition to large sample intervals, environmental data collection applications do not have strict requirements with regards to latency and response time. Samples of data can be delayed inside the network for moderate periods of time without significantly affecting application performance because in general the data is collected for future analysis and not for a real-time operation. In order to meet higher lifetime requirements, the data communication event must be precisely scheduled.

Over the passage of time, it is expected that sensor nodes will fail occasionally. Periodically the network will have to reconfigure itself in order to handle such a sensor node failure. The most important characteristics of the environmental monitoring application are a long lifetime, precise synchronization, low data rates and relatively static topologies. The data transmission can be delayed inside the network, as necessary, in order to improve the network efficiency.

3.3. Energy Model

The main task of a sensor node in a sensor field is to detect events, perform quick local data processing, and then transmit the data. Power consumption can hence be divided into three domains: sensing, communication, and data processing.

In general a sensor node may consist of several components. The main components are: a radio, a processor, a sensor, a battery, external memory, and periphery (e.g. a voltage regulator or debugging equipment). In the presented model we consider only the first four components. The external memory is neglected in this stage of the research since its use of energy is rather complex and needs an own energy model if the memory is a relevant part of the functional behavior of the sensor node and not only used for storage. The periphery can be quite different and, thus, cannot be integrated in an energy model of a sensor node in a uniform way. For the battery we assume that the usage of energy by the other components is independently of the current energy state of the battery. This implies that the reduction of the energy state of the battery depends only on the actions of the different components. Furthermore, we do not consider a reactivation of the battery by time or external circumstances. Based on these assumptions, it remains to give models for the energy consumption of the four components radio, processor, sensor and battery.

Communication among nodes is the major energy consumer process in wireless sensor network. To better grasp this idea let us compare energy costs of data transmission via radio and data processing. Taking the example described in [10], for ground to ground transmission, it costs 3 J of energy to transmit 1Kb of data a distance of 100 meters. On the other hand a general-purpose processor with the modest specification of 100 MIPS/W processing capability executes 3 million instructions for the same amount of energy.

In this section we present a basic version of an energy model for a sensor node. The aim of the model is to predict the current energy state of the battery of a sensor node based on historical data, on the use of the sensor node and the current energy state of the battery. The model considers only four components: the radio, the processor, the sensor and the battery.

The model most often used for the RF system is the path loss model, in which the received power is $Pr = P_t . r^{-a}$, where r is the distance between the transmitter and the receiver, a is the distance-power gradient, and has values between 2 and 4, depending on the characteristics of the communication medium, and P_t is the transmitting power. We assume that all nodes have the same power threshold for the signal detection, and we consider this value normalized to one. Therefore, the transmitting power P_t needed to support a link of length r is r^{a}.

The energy consumption of a wireless node has two components, i.e. transmitting power and the receiving/processing power. We can consider the transmitting power to be the dominate power consumption factor. We can assume that omni-directional antennas are used, which means that if a node transmits at power level r^{a}, any node within the distance of r of it can receive the signal. The factor a represents signal attenuation and is adjusted depending on the model used. For free space environment a = 2 and for noisy urban environment a = 4 [11]. In a noiseless rural environment a can be taken as 2.

3.4. Data Aggregation

Sensor data are different from the data associated with traditional wireless networks in that it is not the actual data itself that is important. Rather, the analysis of data, which allows end-user to determine something about the environment that is being monitored, is the important result of a sensor network. Sensor networks contain too much data for an end-user to process. Therefore, automated methods of combining or aggregating the data into a small set of meaningful information is required, In addition to helping avoid information overload, data aggregation, also known as data fusion, can combine several unreliable data measurements to produce a more accurate signal by enhancing the common signal and reducing the uncorrelated noise. The classification performed on the aggregated data might be performed by a human operator or automatically.

Data aggregation is the combination of data from different sources, and can be implemented in a number of ways. The simplest data aggregation function is duplicate suppression. Duplicate suppression is already practiced in commercial wireless messaging networks. Other aggregation functions could be max, min, or any other function with multiple inputs.

One of the important benefits of data aggregation is efficiency in energy consumption. The energy gain due to data aggregation can be quite significant particularly when there are many sensor nodes that are many hops away from the sink node [12].

For our modeling purposes we can make a simplifying assumption - the aggregation function is such that each intermediate node in the routing transmits a single aggregate packet even if it receives multiple input packets. We will refer to the information received by the sink when it has obtained the messages transmitted by all sources in a given flow (whether or not these messages are aggregated) as a “datum”.

3.5. Reactive and Proactive Networks

There exist two types of information dissemination in wireless sensor networks. One of them results from a stimulus, the other one occurs once the user has a query. The network in which the former exists is called reactive network. The latter is for a proactive network. Proactive networks only update (send) information that they sense on demand. In contrast, reactive networks update (send) their information by stimuli in the field. For sensor networks that experience greater dynamic changes, reactive routing algorithms are more appropriate, whereas for those that are more static and experience infrequent topological change, proactive routing algorithms are more efficient [13].

3.6. Communication

Any sensor node will be equipped with wireless communication devices. The preferred way of communication for the energy efficiency is radio-frequency communication. The radio will be expected to provide simple modem functionality, accepting and delivering a bit-serial stream of a simple serial interface and converting this into a bit-serial stream over the radio interface. In addition, a more advanced radio subsystem is also conceivable that already handles simple frame
detection or similar functionality. Either approach can be used in a sensor node with the appropriate modification of the device drivers/physical layer protocols. Important aspects in selecting appropriate devices for a prototype are the ability to perform transmission power control. Low cost, small form factor, and power efficiency will play a major role for future products (and are considered by the manufacturers of the sensor nodes), but play a minor role within the definition of the architecture.

3.7. Network Layer and Routing

Sensor nodes are scattered densely in a field either close to or inside the phenomenon area. The information collected related to the phenomenon should be transmitted to the sink, which may be located far from the sensed field. However, the limited communication range of the sensor nodes prevents direct communication between the sensor nodes and the sink node using intermediate sensor nodes as a relays. The existing routing techniques, which have been developed for wireless ad hoc networks, do not usually fit the requirements of the sensor networks. The networking layer of sensor networks is usually designed according to the following principles:

- Power efficiency is always an important consideration.
- Sensor networks are mostly data centric.
- In addition to routing, relay nodes can aggregate the data from multiple neighbors through local processing.
- Due to the large number of nodes in a WSN, unique Ids for each node may not be provided and the nodes may need to be addressed based on their data or location.

Having considered the above principles, the following well-known approaches can be used to select an energy efficient route:

- Minimum energy (ME) route: The route that consumes ME to transmit the data packets between the sink and the sensor node is the ME route.

- Minimum hop (MH) route: The route that makes the MH to reach the sink is preferred. Note that the ME scheme selects the same route as the MH when the same amount of energy is used on every link. Therefore, when nodes broadcast with the same power level without any power control, MH is then equivalent to ME [14].

Chapter 4

System Parameters

4.1. Time-Varying Node Density

In designing a sensor network a user usually has a fixed cost budget that places an upper bound on the total number of nodes that can be deployed. Also, we do not desire that the environment or the area in which nodes are deployed be disturbed. For example, sensor network employed to monitor wildlife should not affect the habitat of the animals. Thus the density of nodes is a crucial parameter in the design of the network. Furthermore, the physical environment may put a constraint on the number of nodes that can be deployed. Density relates to the number of nodes that have to be deployed in order to achieve the desired objective.

To evaluate utility at time t, we need to evaluate the evolution of density with time. If no runtime technique is used all nodes shall die approximately at the same time. This is assuming that all sensor nodes have almost similar initial energy content and are also deployed at almost the same time and they also see similar traffic. In such scenarios density of the network remains constant at the initial density for certain time and then suddenly drops to zero.

However, several cooperative cell-based strategies [13] have been proposed to minimize the energy consumption in a sensor network. These schemes shut down redundant nodes while still maintaining routing fidelity. This is indeed feasible because in general, sensor networks are envisioned to be dense networks consisting of thousands of nodes. In such scenarios nodes die at different times and density of the network decreases in a more uniform manner. The designer needs to choose between these schemes and then needs to set the parameters of such schemes. Thus a design time recipe must enable estimating the lifetime for such schemes and to tune the parameters to satisfy user’s needs.

4.2. Battery Capacity

The wireless sensor network nodes, being microelectronic devices, can only be equipped with a limited energy source. In some application scenarios, replenishment of power resources might be impossible. As time progresses, several nodes die and thus the density of the nodes decreases. The initial energy content of the nodes imposes an upper bound on the network lifetime. Sensor node lifetime, therefore, shows a strong dependence on battery capacity. The aim of the designer must be to predict the current energy state of the battery of a sensor node based on historical data on the use of the sensor node and the initial energy state of the battery.

4.3. Communication and Sensing Ranges

A key design parameter for any wireless sensor network is its communication range and sensing range. While there is an argument that the coverage of the network is not limited by the transmission range of the individual nodes, the transmission range does have a significant impact on the minimal acceptable node density. If nodes are placed too far apart it may not be possible to create an interconnected network or one with enough redundancy to maintain a high level of reliability. Most application scenarios have natural node densities that correspond to the granularity of desired sensing level. If the radio communication range demands a higher node density, additional nodes must be added to the system to increase node density to a tolerable level [13].

4.4. Query Period

In a data-collection network, effective sample rate is a primary application performance metric parameter. We define the effective sample rate as the inverse of the query period in which sensor data at each individual sensor can be taken and be communicated to a collection point in a data collection network. Fortunately, environmental data collection applications typically have sampling rates of a few samples per minute. However, in addition to the sample rate of a single sensor, we must also consider the impact of the multi-hop networking architecture on a nodes ability to effectively relay the data of surrounding nodes effectively.

4.5. Utility

The utility in essence represents the overall useful information that can be received by the user. Mathematically, it is defined as the product of probability of connectivity and accuracy [13]. The design problem is quite complex to formulate mathematically but in our simulation study, we have measured utility by using the observed throughput at the user node. Hence our utility interpretation is as follows:

Utility = (What We got) / (What We're expecting)

4.6. Lifetime

Finally, a user would be concerned of how long the network can last and deliver. For cases, where the user wants the network to detect objects with a desired accuracy as long as possible, optimizing the lifetime becomes important. For other cases, where the area needs to be monitored only for a fixed period of time, the lifetime is known a priori and thus a user would like the network to be designed for just the required amount of time. The lifetime of the network is then defined as the time where the utility falls below a certain user-defined threshold [13]. This threshold is called the user satisfaction limit.

Chapter 5

Problem Definition

In previous section, we discussed the various properties of wireless sensor network and sensor nodes. The given properties of the sensor network may vary due to varying conditions in which the network is deployed. Some properties may attenuate due to the effect of others.

The wireless sensor network closely resembles an ad hoc network deployment. In these networks, neither the initial configuration of the nodes is known nor the connection between the nodes. When the wireless sensor network is established in an unknown environment, it is quite difficult to set up an efficient network initially. Each node will try to establish a single edge routing path to the sink through the router nodes. In a monitoring type of scenario, data acquired for each sensor node is more important than the source and location of the node.

The role of any wireless sensor network is to support the detection notifications, coordinate the signal processing functions and communication protocols under a stringent energy constraint. In a broader sense, a wireless sensor network is formed from the integration of sensing, signal processing, and communication functions.

5.1. Problem Statement

The way sensor networks are organized internally may play a role in decreasing the energy budget to perform certain functionalities, and therefore proper design of the sensor architecture is an important goal to be pursued. To maximize the lifetime of the network, we need to minimize the energy dissipation for communication by reducing the number of sending and receiving operations and reducing the transmission distance.

To maximize the lifetime of the network, we need to minimize the energy dissipation in the network by adjusting the energy related parameters of the network. There are several parameters mainly related to the network lifetime. These are initial battery capacity, communication radius, query period and node density. These parameters are thought to have certain tradeoffs in terms of the lifetime and therefore the relations between these parameters should be thoroughly investigated.

Our study aims to describe these relations and find out their trade off characteristics by trying out various parameter combinations. For this purpose, a simulation tool that helps in analyzing the effects of the parameters on sensor network lifetime has been designed and implemented by means of OMNet++ [16].

To be able to analyze the results, the simulation can be iterated many times with various parameter combinations. The tradeoffs between the parameters we are dealing with may vary according to the configuration chosen. Eventually, a user interface collecting the results of the iterations is to be prepared for guiding the sensor network designer in optimally selecting the parameters proposed to improve the lifetime of the network.

5.2. Solution Approach and Network Configuration

In this section, we discuss a method of setting up a network topology for wireless sensor networks and discuss how sensor generated data flows through the network before arriving at the sink node. In this section, also we mention an efficient algorithm called Minimum Hop (MH) Routing Algorithm.

In order to conserve battery power, it is better to use a reactive and energy efficient routing protocol. The ‘dynamic’ version of the MH Routing Algorithm discussed briefly in the previous section is a protocol that determines a minimum hop route only when required. This protocol is more survivable since reactive routing does not have a single point of failure and allow multiple routes between nodes.

In the following, the self organizing network formation and the problem solution approach is outlined:

A topology implementing MH Routing Algorithm is first constructed. It is a self-configuring wireless topology connecting all nodes and each node no more than one routing edge which goes out from the node. The constructed topology is a simple realization of the existing wireless network architecture with an emphasis of features exploited by the MH Routing Algorithm.

In this work, we aim to simulate a prototype wireless sensor network. Simulating a suitable and application specific wireless network with various control parameters such as initial battery capacity, communication radius, query period, and node density is particularly difficult. Therefore, we have made some assumptions to realize our scenario as a simulation. These assumptions are presented at the end of this section.

A sensor network is required to be self-configurable when deployed. The major goal of the deployment is to cover the maximum area within which the network functions with ease.

There are various different ways that the sensors follow to establish a network. The nodes have to communicate efficiently with their neighbors after the formation of the network. Nodes need to act as both routers and sources. Due to the limited transmission range, communication has to be performed over multiple hop paths.

All active nodes sense data. Among them, some nodes also act as relay nodes to relay data to the user node. The nodes have the following properties:

- The user node is fixed and has sufficient power supply; also, it has no energy constraints.

- All sensor nodes in the network are energy constrained. In addition, they are immobile.

5.3. Constraints

Sensor networks are most valued for their small size, signal processing capabilities, and versatility to form wireless ad hoc networks. Their ability to operate without pre-existing infrastructure makes them useful in virtually any environment. However, this independence from the infrastructure also imposes a new set of constraints. One such constraint is shorter radio range, which can lower the network connectivity. Small rocks, plants, or even mild undulation in the terrain can create significant variations in radio channel characteristics. Furthermore, radio signal strength tends to drop off with higher exponent at a smaller distance than those with higher antenna.

Another factor that affects network connectivity is node density. When density is low, the network can be severely fragmented due to a low average nodal degree – the average number of neighbors within the radio transmission range. To compensate for low node density, radio power needs to be raised to extend the transmission range.

The most significant constraint on network operation is energy limitation. Lacking infrastructural support, each node depends on small and low capacity batteries as the energy source, and cannot expect replacement when operating in hostile or remote regions. As nodes deplete their batteries, there will be a gradual reduction of network connectivity and sensor coverage, which degrades the sensing and signal processing performance and introduce some dynamics in network topology. Most protocols, whether on the signal processing, networking, MAC, or physical layers, do not consider their impact on external situation such as network connectivity because they are designed for infrastructure networks in which any component failures are restored quickly, by either outside agents or sophisticated automatic recovery schemes. For such networks, loss of connectivity is a rare event that has little statistical significance to overall performance; therefore it is not a factor in system design and testing. For mobile networks, many protocols attribute the loss of connectivity to the mobility of nodes, not to energy depletion caused by the execution of the algorithm. Therefore, the task of handling mobility assumes far more importance than energy conservation.

In contrast, because of their very limited energy resources and lack of maintenance after deployment, wireless sensor networks are required to operate under degraded capacity for the system lifetime duration such that the overall system performance becomes highly dependent on the energy efficiency.

5.4. Requirements and Assumptions

In general, the following is desired when establishing a wireless sensor network.

- Route computations should be distributed since centralized routing in a dynamic network is costly even for fairly small networks.

- Broadcast should be avoided as far as possible because broadcasts are highly unreliable in wireless sensor networks.

- Data gathered is generally more important than the position from where the data is gathered. The exact position may be required during special cases like unmanned robotic explorations.

- Typical processing cost is much lower than communication costs. Hence, when the nodes are not communicating they process raw data.

For our problem and simulation experiments, we will assume the following:

- The wireless medium is ad hoc and the generic topology will be based on the distribution of the nodes on the terrain and radio propagation characteristics. We will assume that the radio propagation is noise free with ideal conditions.

- Before applying the Minimum Hop algorithm, the sensor nodes are assumed to be placed randomly in the terrain.

- The terrain is taken to be flat with no direct obstruction of radio waves transmitted.

- Nodes deployed in this topology are assumed to form a fully connected graph. In other words, every node is capable of establishing a communication link to every other node in its neighborhood.

- There is unidirectional transfer of data from the leaves to the sink.

- All nodes are assumed to be identical, consisting similar type of sensors, communication device and processing unit.

- To carry out the deployment of the nodes and to start all to operate at the same time, a global manager is assumed and implemented.

Every node is capable of finding its neighbor. The neighbor identified need not to be in line of sight.

Chapter 6

Design and Implementation of a Sensor Network Simulation Experiment

A simulation testbed for the problem introduced in the previous section was implemented in OMNeT++, a discrete event simulator environment. For this purpose, OMNeT++ simulation tool was installed on Windows Vista Operating System. In performing these simulation experiments, our goal is to understand the energy efficiency tradeoff between the sensor network parameters affecting the lifetime. Prior to explaining the configuration used for the simulation, it seems logical to introduce the OMNeT++ simulator tool first.

6.1. What is OMNet++

OMNeT++ is an object-oriented modular discrete event simulator. The name itself stands for Objective Modular Network Testbed in C++.

The simulator can be used for modeling:

- wired and wireless communication networks
- communication protocol
- queueing networks
- multiprocessors and other distributed hardware systems
- Computer networks and traffic modeling
- Administrative systems
- in general, any other system where the discrete event approach is suitable

An OMNeT++ model consists of hierarchically nested modules. The depth of module nesting is not limited; this allows the user to reflect the logical structure of the actual system in the model structure.

Some of the properties of the nested modules are:

- Modules communicate by exchanging messages. Messages can contain arbitrarily complex data structures.
- Modules can send messages either directly to their destination or along a predefined path, through gates and connections.
- Modules can have parameters. Parameters can be used to customize simple module behavior, to parameterize the model topology and for module communication.
- Modules at the lowest level of the module hierarchy contain the algorithms of the model. They are provided by the user. During simulation execution, simple modules appear to run in parallel, since they are implemented as co routines (sometimes termed lightweight processes). To write simple modules, the user does not need to learn a new programming language, but he/she is assumed to have some knowledge of C++ programming.

OMNeT++ simulations can feature different user interfaces for different purposes: debugging, demonstation and batch execution. Advanced user interfaces make the inside of the model visible to the user, allow him/her to start/stop simulation execution and to intervene by changing variables/objects inside the model. This is very important in the development/debugging setPhase of the simulation project. User interfaces also facilitate demonstration of how a model works. Since it was written in C++, the simulator is basically portable; it should run on most platforms with a C++ compiler. OMNeT++'s advanced user interfaces support X-window, DOS and are portable to Win3.1/Win95/WinNT. OMNeT++ has been extended to execute the simulation in parallel. Any kind of synchronisation mechanism can be used. One suitable synchnonization mechanism is the statistical synchronisation, for which OMNeT++ provides explicit support [16].

6.2. The Simulation Implementation

The simulator is designed to model a wide range of physical sensor network sizes, node densities and offered message rates. The location of the sink/user node is placed randomly at the left edge of a rectangle; the other network nodes are randomly placed within the rectangle.

The simulator was configured with the following parameters:

- Physical array area is 800 x 500 (centimeter);
- Nodes in the area are randomly and uniformly distributed;
- Length of the inter-nodal messages is 7 bits;
- Messages are generated periodically with a period of T (query period);
- Maximum connectivity capacity of a node is equal to the number of nodes in the area;
- The processing delay is assumed to be 1 sec for each sensor node;
- The user satisfaction limit is accepted as 0.2 for the network utilization.
- The power consumption amount corresponding to sending a packet is 1 unit of energy which is $C \times R^2$, where R is the communication radius in centimeter and C is a scaling constant. In this example, 1 unit of energy is taken as $(R/100)^{2}$ [17].

The simulator has an optional color graphics (animation) mode. In this mode, the physical layout of the generated network is displayed; a color code identifies the state of each node and each inter-nodal message.

Verification of the simulation was simplified by performing simulations in its animation mode, at a pace slow enough for a human expert to observe and record all simulated network behavior and compare it to that expected. The raw data is placed in a Microsoft Excel-readable file for post processing. The simulations were performed over a wide range of input parameter combinations which are depicted in Table 1 below.

Table 1. The parameters and their selected values

PARAMETERS	VALUES	UNITS
Initial Battery Capacity	1000, 2000, 3000	Milli Joule (mJ)
Communication Radius	300, 400, 500	Centi Meter (cm)
Query Period	10, 20, 30	Second (s)
Node Density	15, 30, 45	No. of Nodes (# of Nodes)

The Simulator was designed with the relatively narrow goal of modeling the behavior of wireless sensor networks, so several potential network non idealities (listed and discussed in the previous chapter) are neglected, and some simplifications of network traffic are assumed (including defining all messages to be identical in length). For many potential applications, such as temperature sensing (wireless thermostats), the message model used is a good approximation of reality; for others, such as security systems, which may have more bursty, correlated message generation, other message models would be appropriate.

It is possible to conduct the simulation on randomly generated sensor networks, which are defined by the following four parameters:

- Initial Battery Capacity,
- Communication Radius,
- Query Period,
- # of Nodes (denotes also the node density since the terrain is fixed).

One can change either of the parameters to produce a different network. In our simulation, we use a rectangular grid as the sensing area, one of the corners being fixed at the origin. The simulator randomly distributes the sensor nodes to the sensing area, each node having a predefined initial energy capacity. The size of each data packet (inter-nodal message) is chosen to be 7 bits for simplicity after all encapsulations in intra-nodal layers. In this scenario, we measure the network lifetime as the simulation time passes. For each parameter combination, ten random networks are generated and the results are averaged.

The scenario implemented is as follows:

Once the simulation is initialized, randomly distributed sensor nodes are generated. Then, the nodes set up their connections with the neighbors and the routing paths are established according to the MH Routing Algorithm applied to sensor networks.

To implement this algorithm on a self-configured sensor networks, the grades assigned to the sensor nodes were used as follows. First of all, the user node, which will be the root of the tree, gets the lowest grade, say “0”; and then its neighbors get the next grade that is “1”; by using this method each sensor node takes the next grade of the neighbor having lowest grade among the other neighbors. Having been assigned all grades, each node prefers lower grade node, which is actually the node having minimum hop to the user node, to establish its connection. By using this methodology, minimum hop routes are formed from the source sensor nodes to the sink. Moreover, all edges have the same weight as 1.

All nodes and the user node are stationary. The sensor network is modeled as a collection of these nodes, which transmit and receive packets over their radio channels. The channels are also modeled as specific entities, which receive messages from the nodes.

Inter-layer communication within a single node is accomplished by means of message passing. When a packet is generated at a node, it is passed down from layer to layer; until it reaches the radio layer (which is called "layer0") of the sensing node.
The radio layer generates an over the air packet, and sends it to the channel entity reserved for the routing. The channel entity than simulates the conditions of a radio channel, and delivers the packet to its neighbor, which is in the route among the nodes close enough to receive it (within the communication range).

For aggregation process, each intermediate node in the routing paths transmits a single aggregate packet even if it receives multiple input packets one after another. In other words, successive packets coming to a router node are to be aggregated and the node generates only one packet to represent all those aggregated packets.

As the simulation progress, the nodes, which are under heavy traffic, begin to die one after another. The network will be accepted as alive until the time at which the user node is not satisfied with the utility level of the network anymore. This time value is called the "lifetime" of the network, which is the output of the simulation for a particular parameter configuration.

After taking the definition of the utility in Chapter 2 into account, utility evaluation of this simulation is performed as follows. The user nodes expects to get all packets generated by the sensor nodes in the defined period, but it gets some of them due to some failures that have occurred on the way and due to the data aggregation used. Therefore, the utility takes a value between 0 and 1. The user is then satisfied with values that are greater than the threshold defined in Chapter 3, Problem Definition.

The next chapter, Simulation Study, interprets the results of this extensive simulation study.

Chapter 7

Simulation Study

We now present our simulation results showing the sensor network lifetime for the parameter configuration chosen.

All simulations were performed in a simulation testbed in OMNeT++, a discrete event simulator environment [16], on a network of:

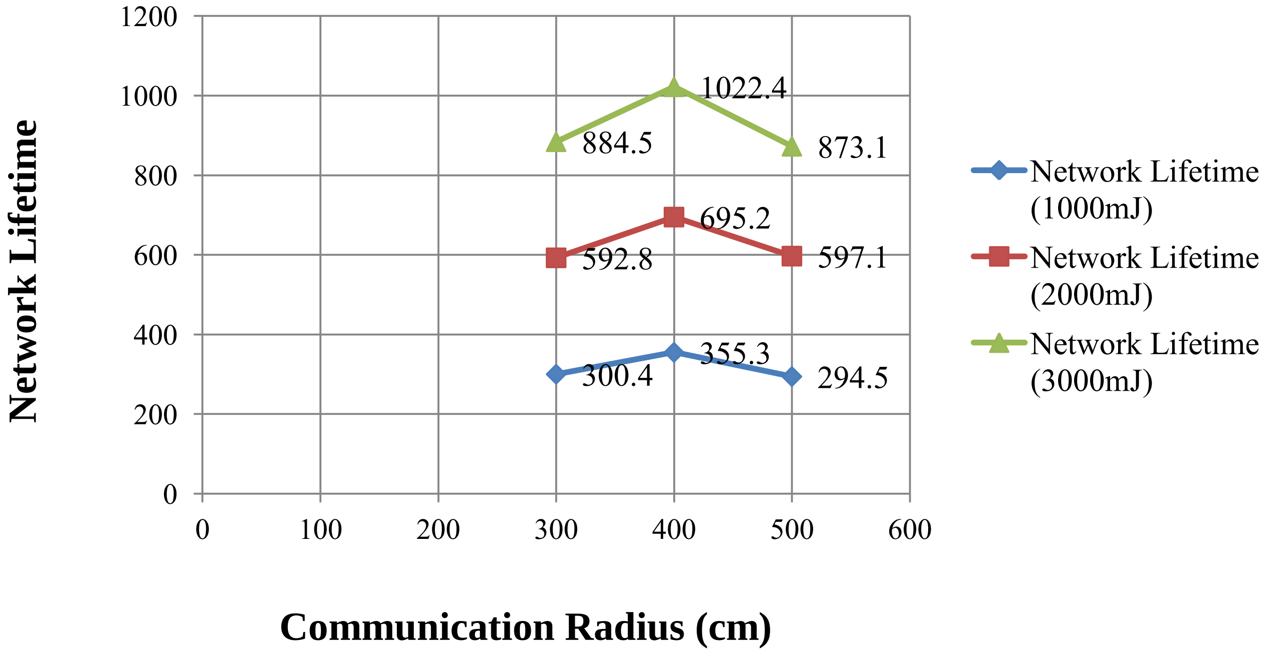
- Two dimensional field of 800 x 500 cm.
- Randomly distributed nodes on the field.
- For each combination of the parameters, 10 simulations were run and averaged.
- Any runs resulting in unconnected graphs which can happen occasionally when the values of node density and communication radius are low, were also taken into account to be able to get realistic results.

The selected parameter values are again summarized in the following:

B = {1000, 2000, 3000} amounts of battery capacity in mJ were used.
R = {300, 400, 500} were used as communication radius in cm.
T = {10, 20, 30} were taken as the query period in sec.
N = {15, 30, 45} nodes scattered; one of them being the user node.

In performing these simulation experiments, our goal is to understand the relations between our design parameters. In order to do that, results of many iterations were recorded on an Excel Sheet, which were then processed with a Macro Program running on this excel sheet. We got 54 different unique plots as a result and 14 crucial plots of them are examined and analyzed in the following paragraphs.

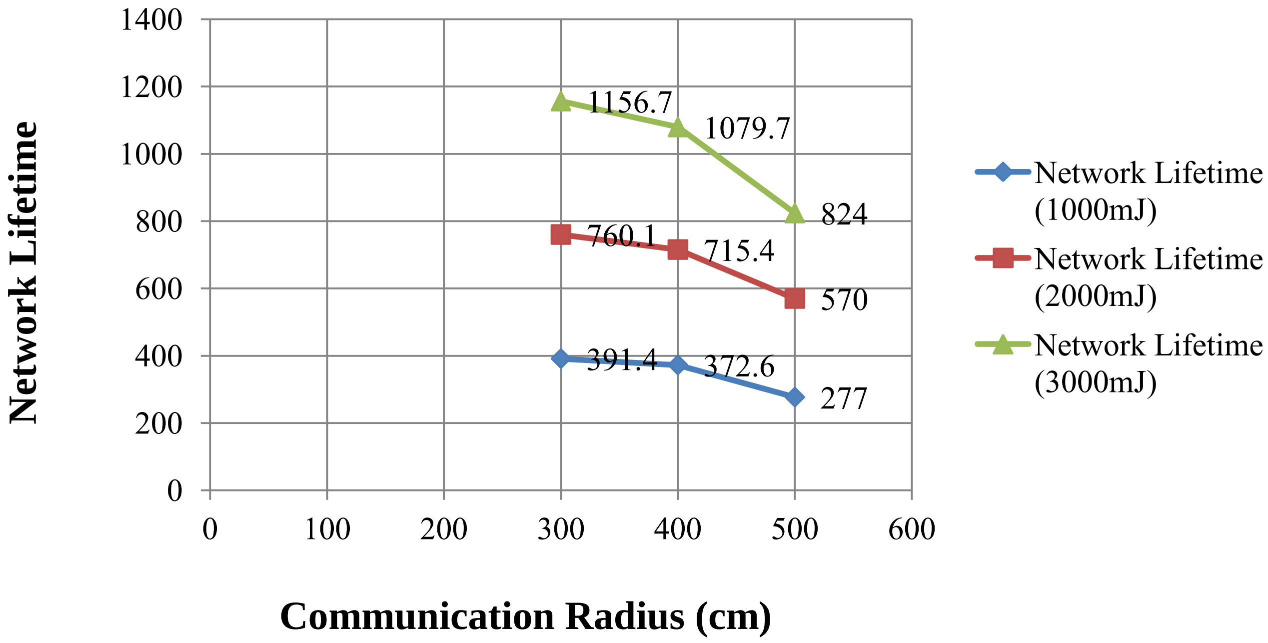
In the following plots, two of the parameters are fixed and the remaining two are varying. The fixed parameter values are shown at the bottom of each figure.



Query Period (sec):	● 10	○ 20	○ 30
Node Density (# of Nodes):	● 15	○ 30	○ 45

Figure 1. Lifetime of the Network vs. Communication Radius - 1

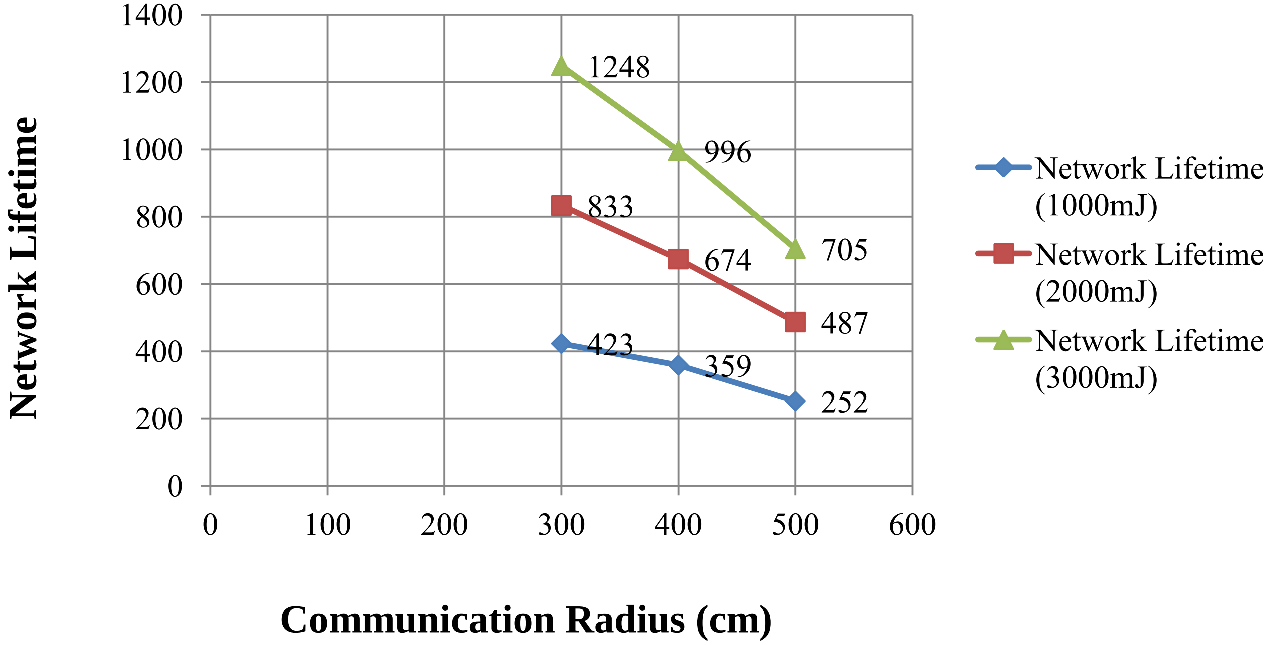
For the configuration seen above (i.e., query period and node density being fixed as 10 and 15, respectively), Figure 1 compares the lifetime of the network as the communication radius and initial battery capacity are varied. The figure illustrates that as the communication radius increases up to a point, the lifetime increases and beyond that point, it begins to fall. This is mainly due to the fact that beyond that certain point of the communication radius, the nodes start consuming much power and this will cause them to die soon.



Query Period (sec):	● 10	○ 20	○ 30
Node Density (# of Nodes):	○ 15	● 30	○ 45

Figure 2. Lifetime of the Network vs. Communication Radius – 2

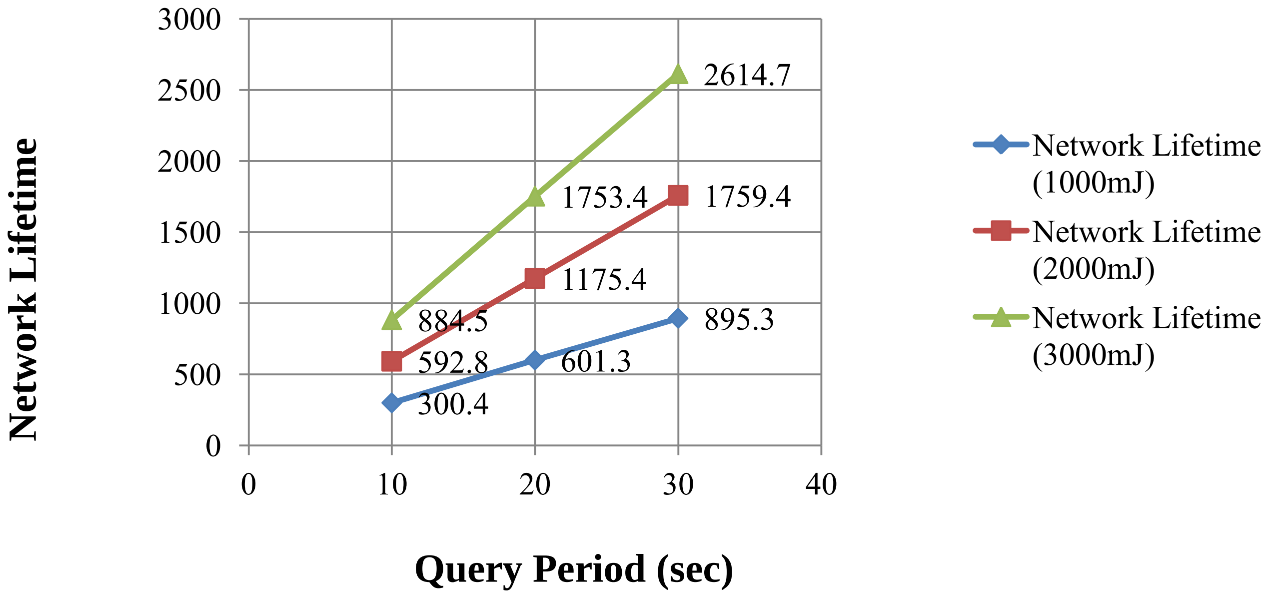
Similar to Figure 1, Figure 2 and 3 also compare the lifetime of the network as the communication radius and the initial battery capacity are varied. The selected configurations in these plots are the node density parameter being 30 and 45 in Figures 2 and 3, respectively. It is seen from these figures that as the communication radius increases, the lifetime decreases. One thing to note in Figure 2 is the optimal value of the communication radius, which may be around 300cm for this configuration. As the battery capacity increases, the margin between the lifetime values for the different communication radius becomes wider as well.



Query Period (sec):	● 10 ○ 20 ○ 30
Node Density (# of Nodes):	○ 15 ○ 30 ● 45

Figure 3. Lifetime of the Network vs. Communication Radius – 3

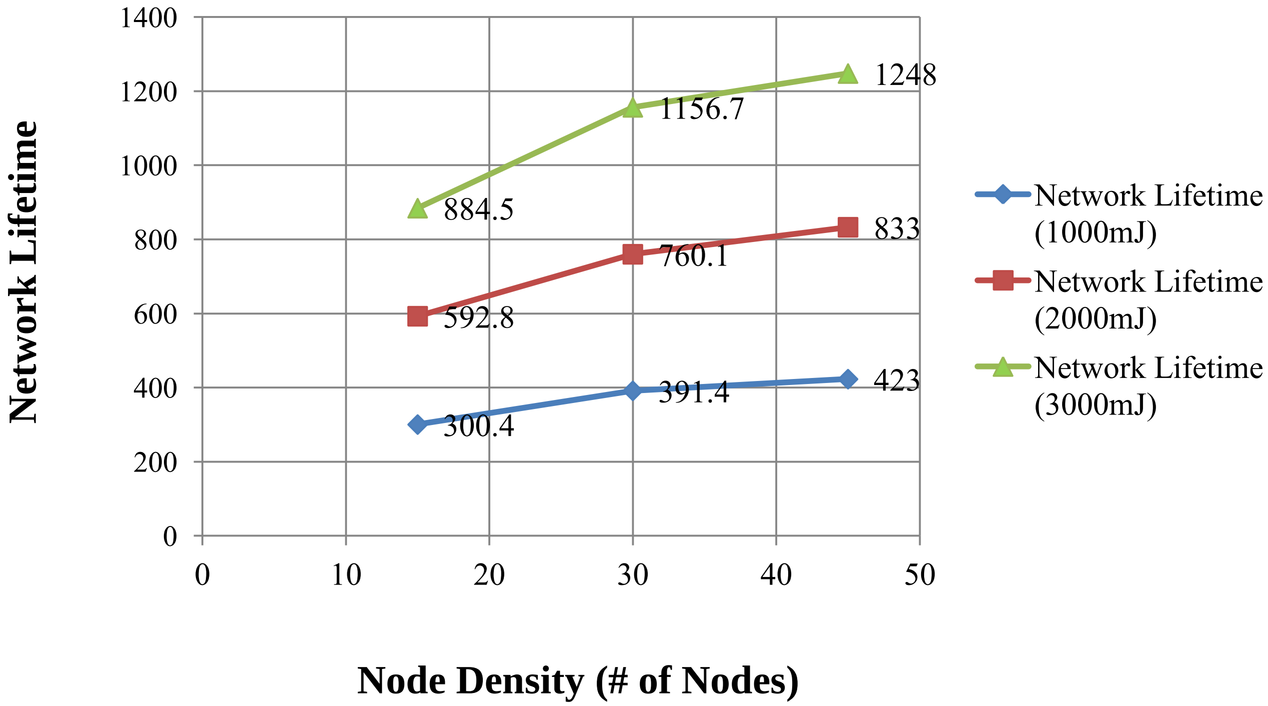
Moreover, Figure 3 illustrates a catastrophic decrease in the lifetime while the communication radius augments for this configuration. This is mainly because of the fact that in this configuration the number of nodes is high and this causes much more traffic on the network and therefore it means there will be much more power consumption per node while the communication radius increases. Hence, increasing the number of nodes in the terrain for a better coverage may lead to marginal increase after a certain point and also communication radius increases drops the life considerably in such cases. The figure also shows that as the initial battery capacity increases, the lifetime increases at this ratio.



Communication Radius (cm):	● 300 ○ 400 ○ 500
Node Density (# of Nodes):	● 15 ○ 30 ○ 45

Figure 4. Lifetime of the Network vs. Query Period

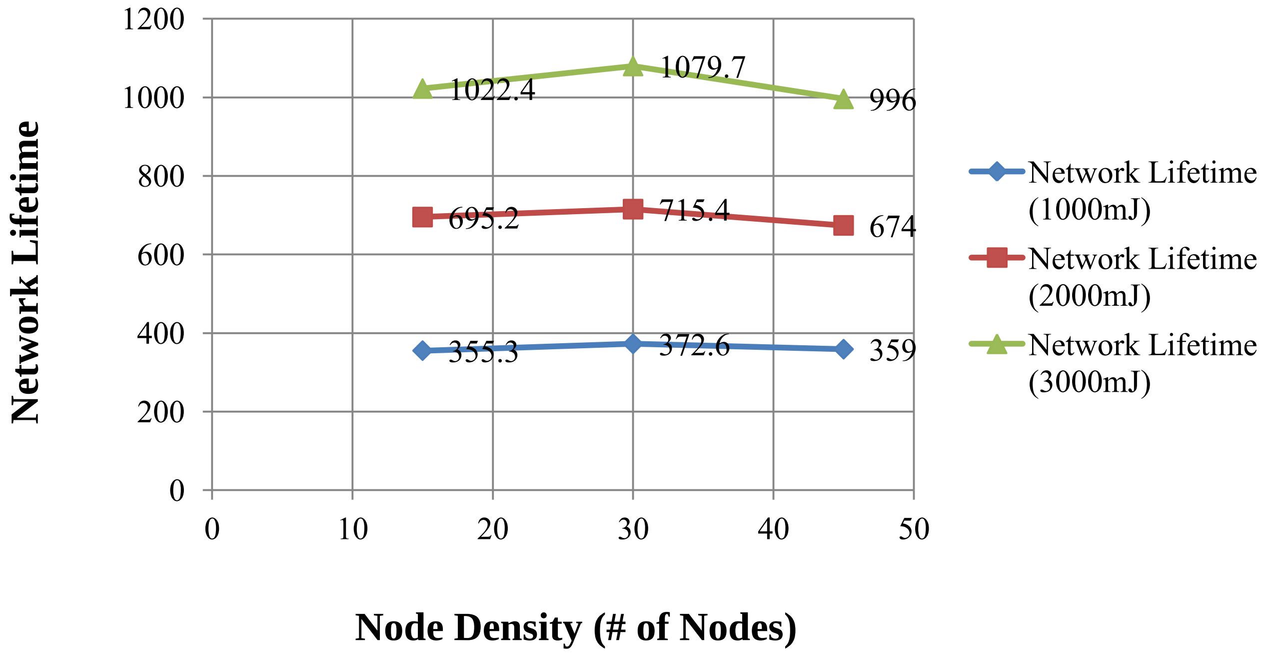
For the configuration seen above (i.e., communication radius and node density fixed at 300 and 15, respectively), Figure 4 compares the lifetime of the network as the query period and the initial battery capacity are varied. It is illustrated that the increase in both the initial battery capacity and the query period causes the lifetime to increase significantly. These increases are almost linear. It is possible to conclude from this plot that there is a linear relationship between the query period and the lifetime and also between the initial battery capacity and the lifetime. This is because both of these parameters have some contribution to the network in only nodal base. This means both the initial battery capacity and the query period have a direct effect on the sensor node's lifetime. Hence, for example, if the lifetime of the nodes is increased two times then the network's lifetime will also increase two times (i.e. by the same amount).



Communication Radius (cm):	● 300 ○ 400 ○ 500
Query Period (sec):	● 10 ○ 20 ○ 30

Figure 5. Lifetime of the Network vs. Node Density – 1

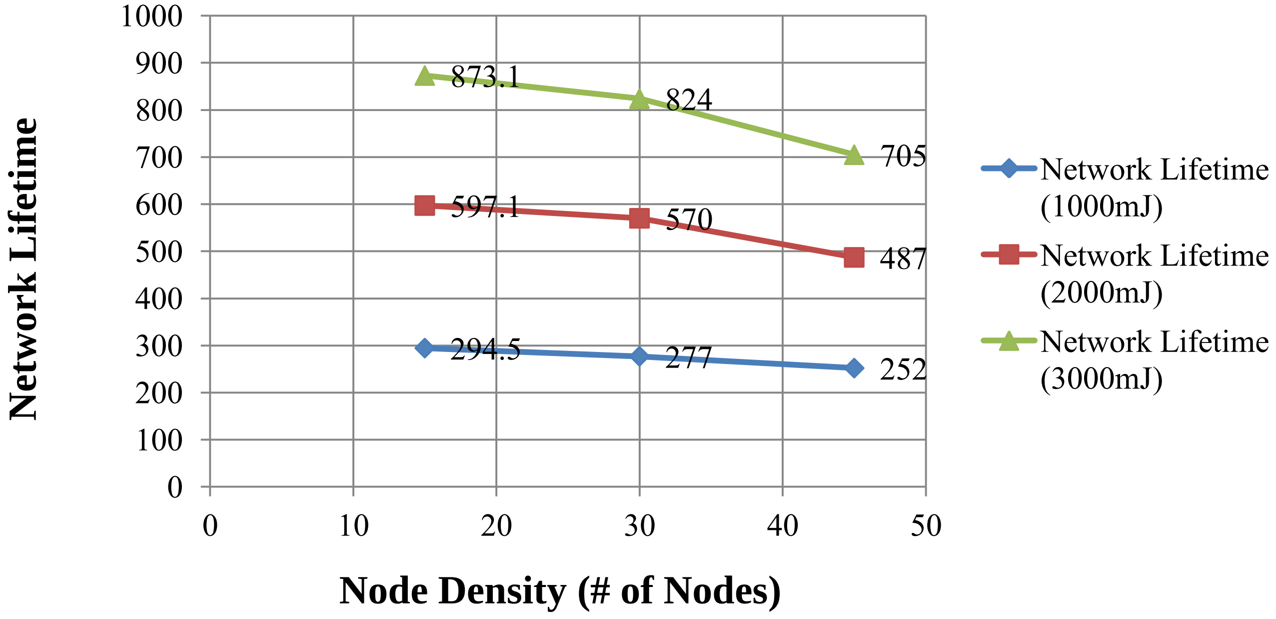
Figure 5, 6, and 7 compare the lifetime of the network as the node density and the initial battery capacity are varied. In Figure 5, the communication radius is taken as a fixed value of 300cm. It is clearly seen from this figure that when the node density goes up, the lifetime increases by decreasing amount. This is mainly due to the fact that increasing in the node density beyond a certain point causes the traffic to be crowded. These figures also show that for given configuration there is a linear relation between the initial battery capacity and the lifetime.



Communication Radius (cm):	○ 300	● 400	○ 500
Query Period (sec):	● 10	○ 20	○ 30

Figure 6. Lifetime of the Network vs. Node Density – 2

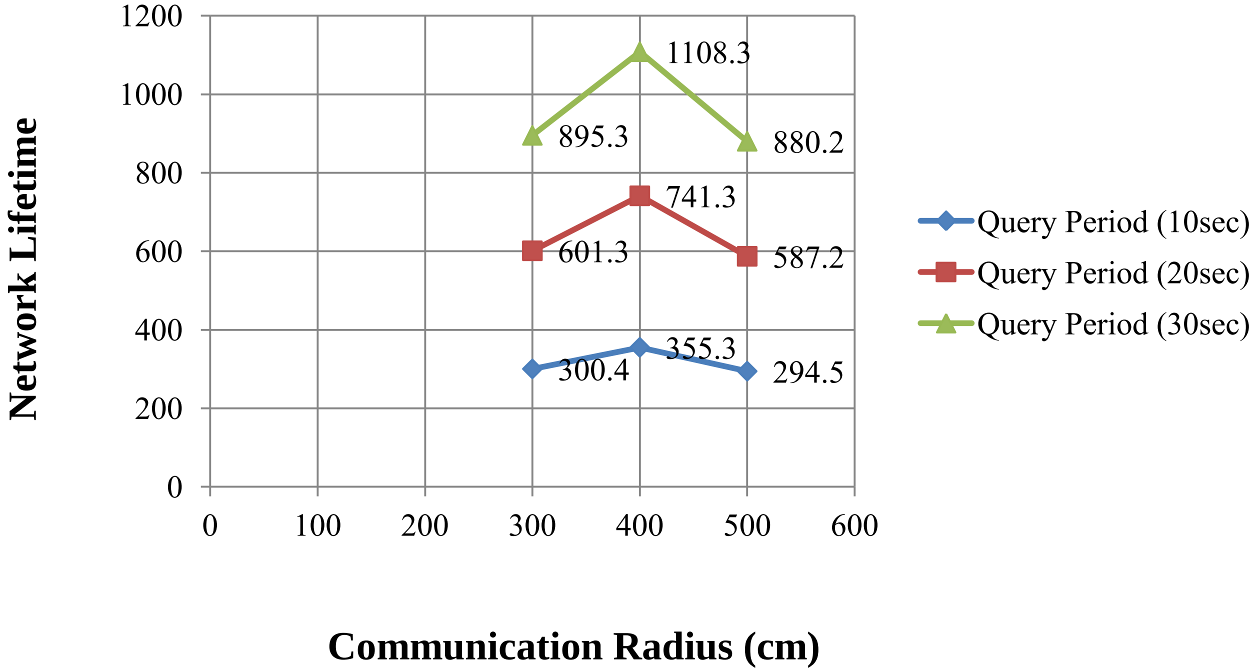
For the configuration seen above (the communication radius is 400cm), Figure 6 compares the lifetime of the network as the initial battery capacity and the node density are varied. It can be seen from the figure that as if we are looking into a window showing that the lifetime is in steady state condition for this configuration given. Actually, there is an optimum value of the node density for this case. While the node density is increasing, before and after the optimum value of the node density, the lifetime is smaller than that of the optimum value.



Communication Radius (cm):	○ 300	○ 400	● 500
Query Period (sec):	● 10	○ 20	○ 30

Figure 7. Lifetime of the Network vs. Node Density – 3

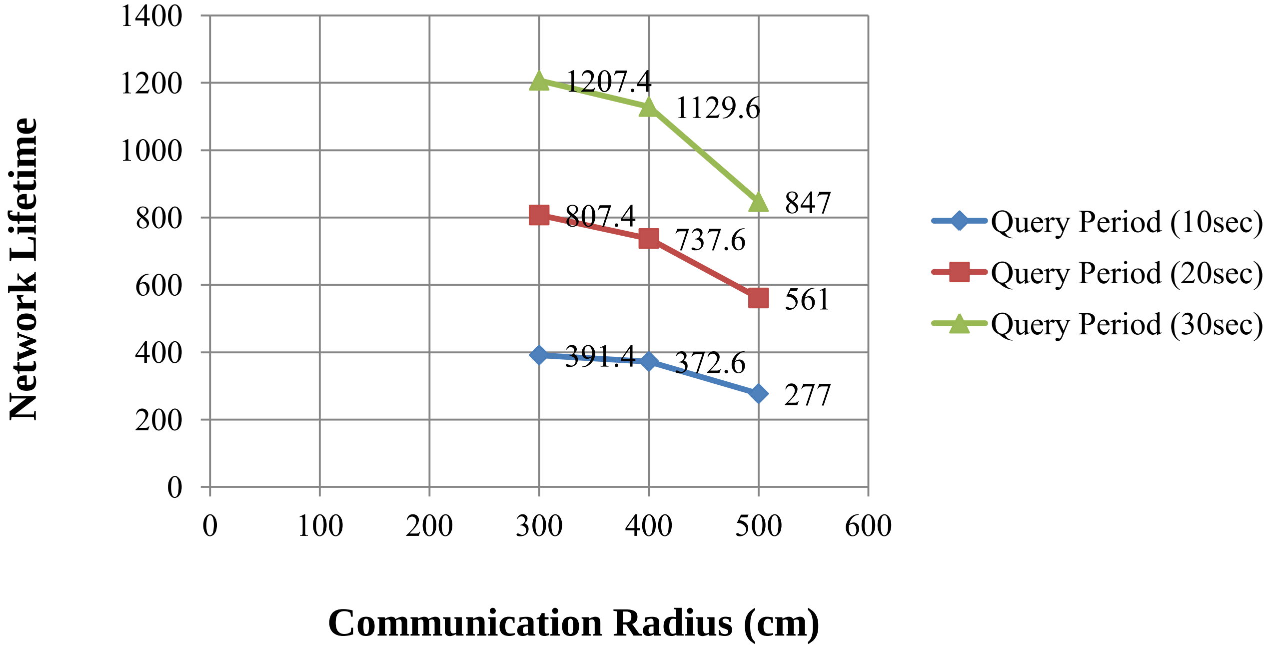
In Figure 7, where the communication radius is 500cm, the lifetime of the network is illustrated as the initial battery capacity and the node density are varied. It is depicted in the figure that when the communication radius is 500cm, while the node density increases from 15 nodes to beyond 45 nodes, the lifetime begins to drop for this configuration given. This is because, for 500cm of communication radius, optimum value of the node density is less than 15 nodes, hence going further from that value of the node density causes the lifetime to fall slowly.



Initial Battery Capacity (mJ):	● 1000 ○ 2000 ○ 3000
Node Density (# of Nodes):	● 15 ○ 30 ○ 45

Figure 8. Lifetime of the Network vs. Communication Radius – 4

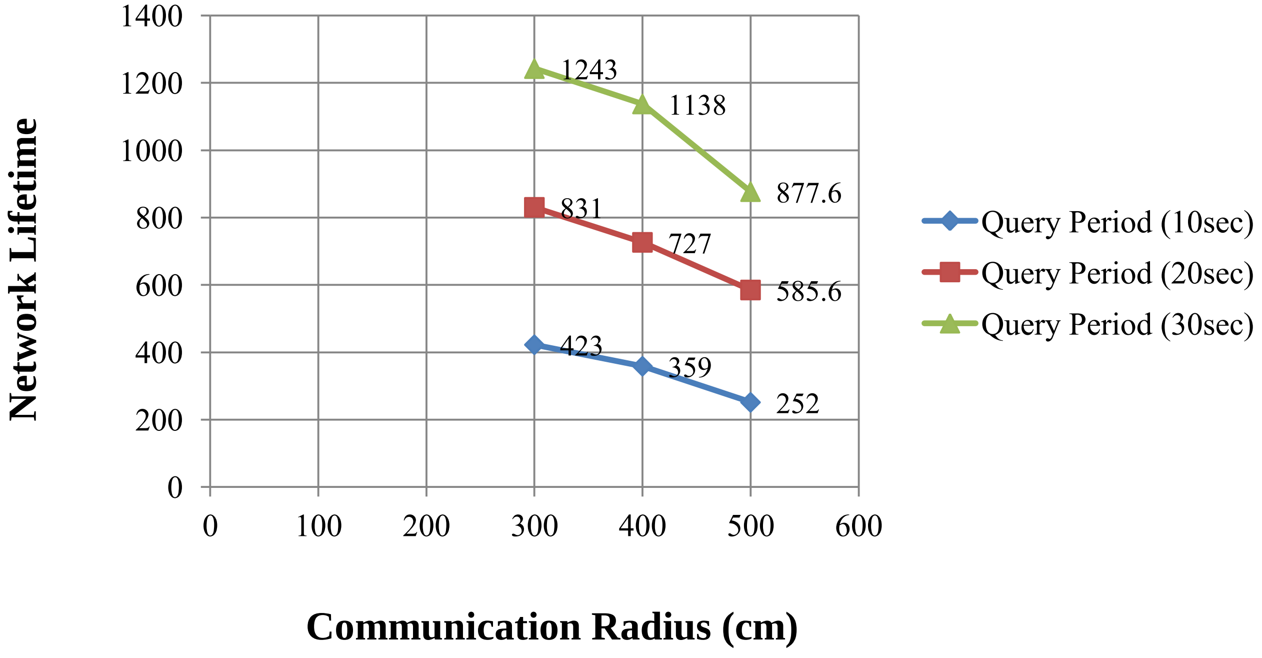
For the configuration seen in Figure 8, 9, and 10; it compares the lifetime of the network as the communication radius and the query period are varied. The node density is taking the value of 15, 30, and 45 nodes in Figure 8, 9, and 10, respectively. Figure 8 shows that as the communication radius increases up to a point, the lifetime increases; beyond that point the lifetime begins to fall. This is mainly due to the fact that the power consumed for transmission is related to the square of the distance and beyond a certain point of the communication radius, the nodes begins to consume much power and this will cause them to die soon. This optimum communication radius is around 400cm for this configuration chosen. It can also be seen in all those three figures that while the query period increases, the lifetime goes up. This is because the scale of the lifetime of the network increases when the lifetime of a sensor node is extended.



Initial Battery Capacity (mJ):	● 1000	○ 2000	○ 3000
Node Density (# of Nodes):	○ 15	● 30	○ 45

Figure 9. Lifetime of the Network vs. Communication Radius – 5

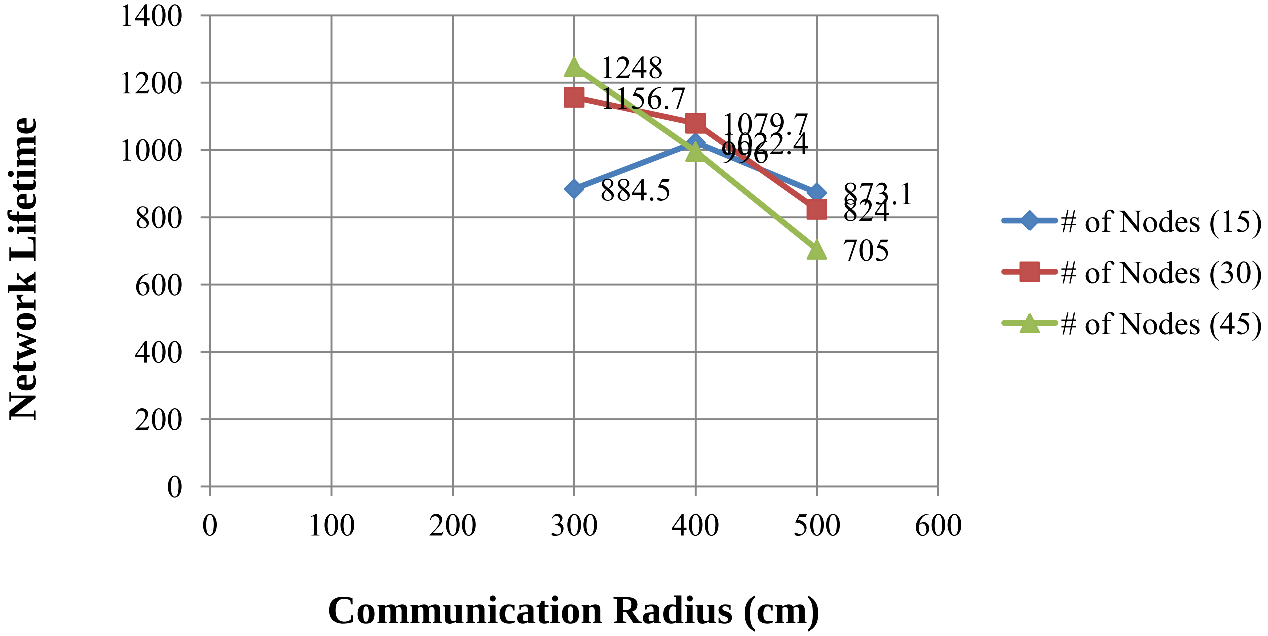
In Figure 9, the fixed value of node density is taken as 30 nodes per area. It is illustrated in the figure that when the node density becomes 30 nodes per the area, the result in the previous scenario is different. In this case, as the communication radius increases, the lifetime begins to decrease. This is because the node density chosen is so large that one cannot find an optimum value for the communication radius by increasing it further any more. We can also extract from the figure that the optimum value for the communication radius is around 300cm.



Initial Battery Capacity (mJ):	● 1000 ○ 2000 ○ 3000
Node Density (# of Nodes):	○ 15 ○ 30 ● 45

Figure 10. Lifetime of the Network vs. Communication Radius – 6

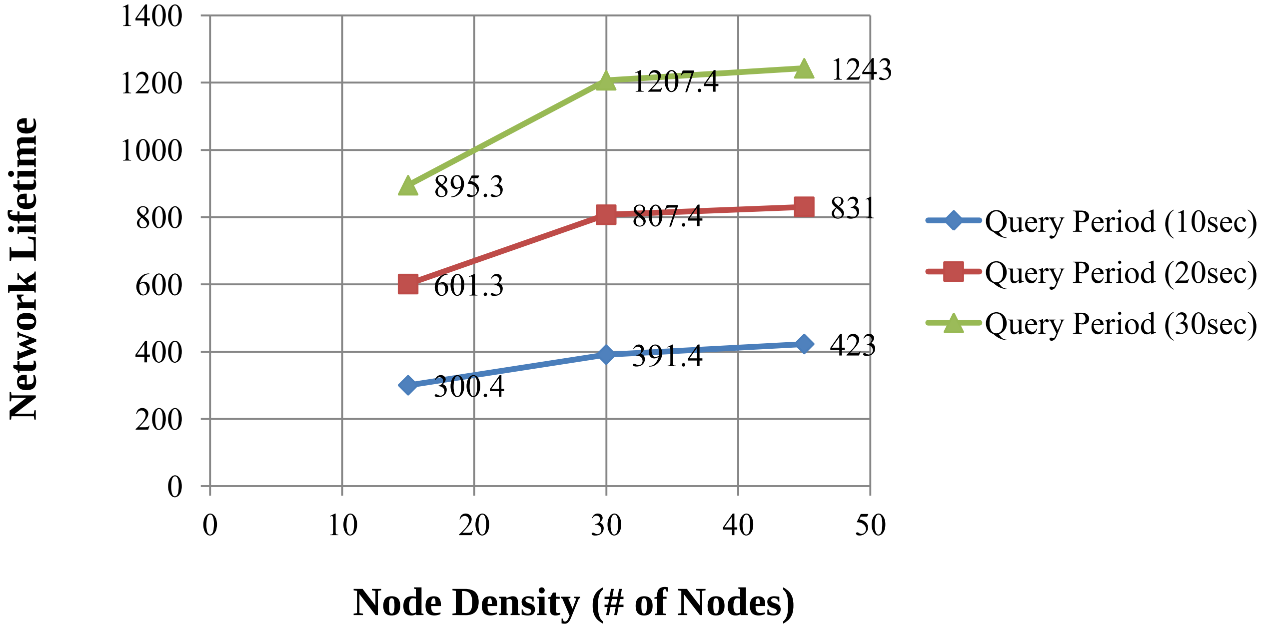
For the configuration seen above, the node density is 45 nodes per area, Figure 16 illustrates that when the node density become 45 nodes per the area, the result in the previous scenario is not so different. In this case, as the communication radius increases, the lifetime continues to decrease, but at this case a bit more quickly. This is because the node density chosen is too large to find an optimum value for the communication radius by increasing it further. It can be examined in the figure that, the optimum value for the communication radius is maybe around 200cm.



Initial Battery Capacities (mJ):	○ 1000	○ 2000	● 3000
Query Period (sec):	● 10	○ 20	○ 30

Figure 11. Lifetime of the Network vs. Communication Radius – 7

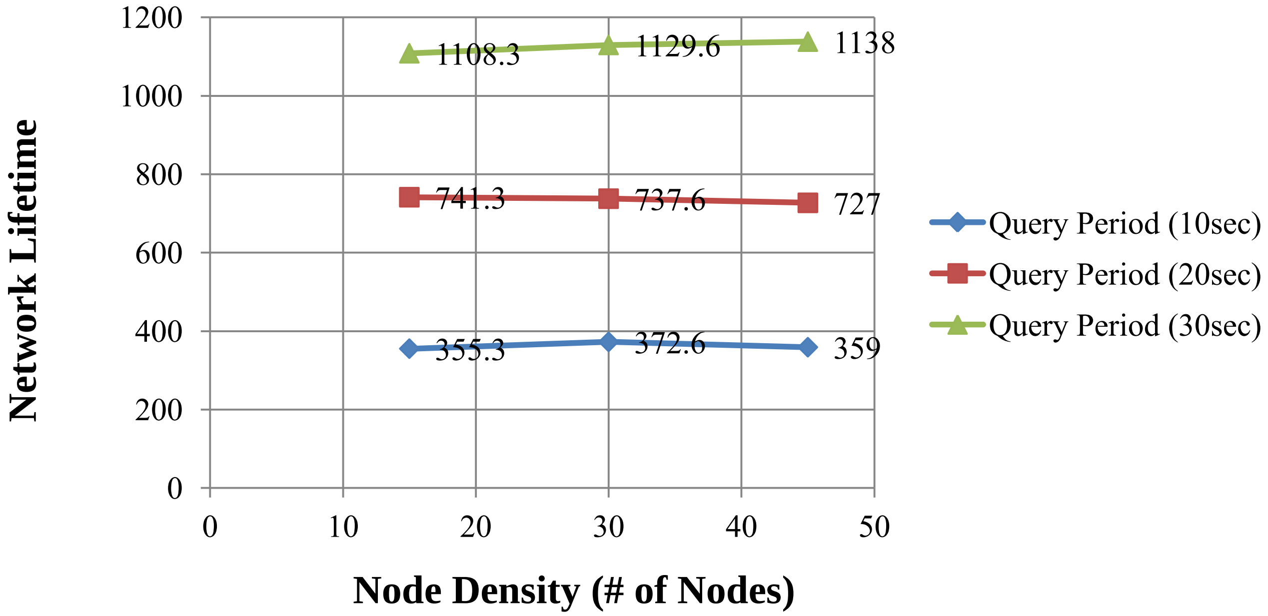
For the configuration seen above, Figure 11 compares the lifetime of the network as the node density and the communication radius are varied. The selected fixed values are 3000mJ and 10 sec for the initial battery capacity and the query period, respectively. When the node density is high, it is clearly seen in the figure that as the communication radius increases, the lifetime falls rapidly. When the node density is medium, the figure shows that as the communication radius goes up, the lifetime falls gradually. When the node density is low, the figure shows that as the communication radius increases, the lifetime reaches it optimum value for the value of the communication radius, around 400cm. This is because; for all the different values of the node density there is one optimal value of the communication radius. By looking the plots, we can understand somehow these values those are; for 45 nodes per the area, approximately 200cm; for 30 nodes per the area, approximately 300cm; for 15 nodes per the area, approximately 400cm.



Initial Battery Capacities (mJ):	● 1000	○ 2000	○ 3000
Communication Radius (cm):	● 300	○ 400	○ 500

Figure 12. Lifetime of the Network vs. Node Density - 4

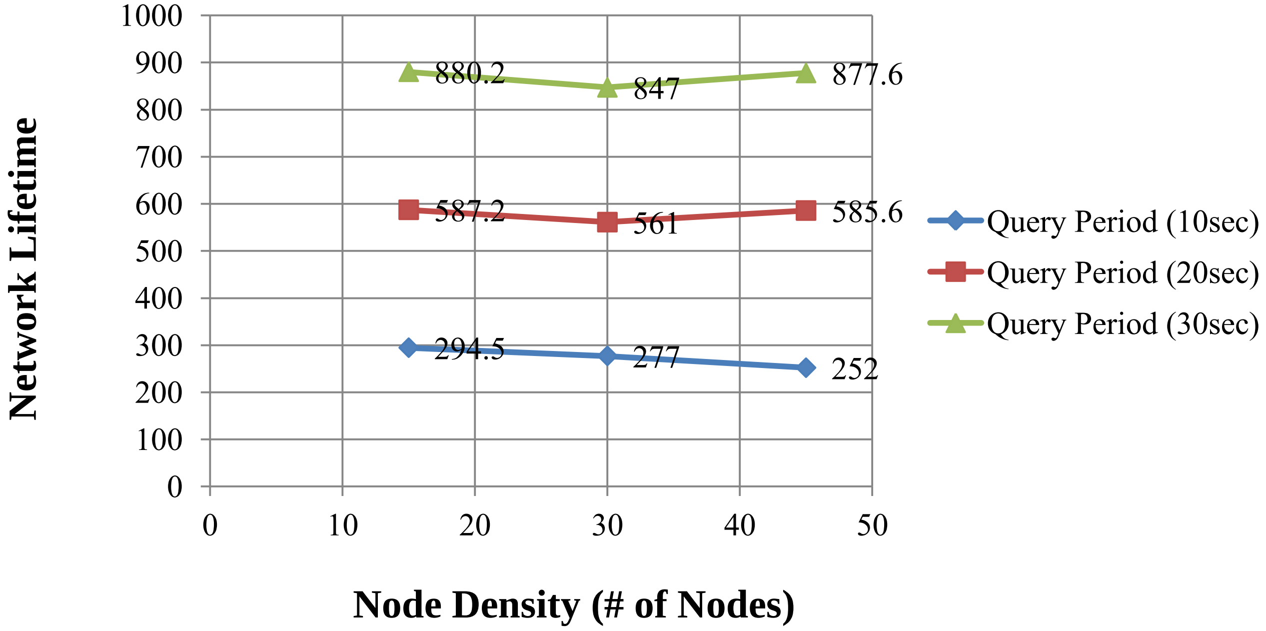
For the entire configurations seen in Figure 12, 13, and 14; the figures compare the lifetime of the network as the query period and the node density are varied. It is observed from Figure 12 that as the node density goes up to a certain value, which is 45 nodes per the area here, the lifetime increases. This is mainly due to the fact that; for the constant communication radius, there is an optimum value for the node density; beyond that value the lifetime begins to drop. It can also be seen in all those figures that increase in the query period causes the lifetime to increase, as stated in the previous plots. There is one thing to note in Figure 12; as the node density goes up, the increase in the lifetime attenuates and the plot becomes almost flat.



Initial Battery Capacities (mJ):	● 1000	○ 2000	○ 3000
Communication Radius (cm):	○ 300	● 400	○ 500

Figure 13. Lifetime of the Network vs. Node Density – 5

Figure 13 compares the lifetime of the network as the communication radius is fixed at the value of 400 cm. The figure shows that as the node density goes up; the lifetime is almost steady for this configuration. This is mainly because of the fact that; for this value of the communication radius, the lifetime is robust against the change in the number of nodes. It is depicted in the figure that increase in the query period does not change this attitude. There is one thing to note in the figure; as the node density goes up to a higher value, the increase in the lifetime become attenuate and the plot starts to fall. This is due to the fact that when the node density increases the number of massage in the network in a period will also increase and this will cause the lifetime to tend to go down.



Initial Battery Capacities (mJ):	● 1000	○ 2000	○ 3000
Communication Radius (cm):	○ 300	○ 400	● 500

Figure 14. Lifetime of the Network vs. Node Density – 6

As a last plot, Figure 14 represents the lifetime of the network as the query period and the node density are varied. In this case the communication radius is chosen to be 500cm. For this configuration, it is understood from the figure that as the node density goes up; the lifetime begins to fall slowly. This is because; for this value of the communication radius, a node in the network consumes higher amount of energy to send a message with respect to the previous two values of the communication radius. The figure also shows that; as the node density goes up to a higher value, the decrease in the lifetime becomes larger and the plot starts to fall rapidly. This is as a result of the facts that when the node density increases, the number of massages in the network in a period will also increase and this will cause the lifetime to be attenuate.

Chapter 8

Conclusion

Recent advances in micro-electro-mechanical systems (MEMS) technology, wireless communication digital electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate in short distance. These tiny sensor nodes, which consist of sensing, data processing, and communicating components, leverage the idea of sensor networks based on collaborative effort of a large number of nodes.

The wireless sensor node, being a microelectronic device, can only be equipped with a limited power source (<0.5 Ah, 1.2 V). In some application scenarios, replenishment of power resources might be impossible. The lifetime of a sensor node shows a strong dependence on battery lifetime. In a multi-hop sensor network, each node plays the dual role of data originator and data router. The malfunctioning of few nodes can cause significant topological changes and might require rerouting of packets and reorganization of the entire network. Hence, power conservation and power management take on additional importance. It is for these reasons that researchers are currently focusing on the design of power-aware protocols and algorithms for sensor networks. In other mobile and ad hoc networks, power consumption has been an important design factor, but not the primary consideration, simply because power resources can be replaced by the user. The emphasis is more on Quality of Service provisioning than the power efficiency. In sensor networks though, power efficiency is an important performance metric, directly influencing the network lifetime. Application specific protocols can be designed by appropriately trading off other performance metrics such as utility, delay and throughput with power efficiency.

Building self-organizing sensor networks has some challenges. All are related to map the overall system requirements down to individual device capabilities, requirements and actions The underlying principle for building self-organizing sensor networks that can overcome the challenges is to provide the fundamental mechanisms upon which other networking and system services may be spontaneously specified and reconfigured.

The way sensor networks are organized internally may play a role in decreasing the energy budget to perform certain functionalities, and therefore proper design of the sensor architecture is an important goal to be pursued. To maximize the lifetime of the network, we need to minimize the energy dissipation for communication by reducing the number of sending and receiving operations and reducing the transmission distance. There are several parameters mainly related to the network lifetime. These are initial battery capacity, communication radius, query period and node density. These parameters are thought to have certain tradeoffs in terms of the lifetime and therefore the relations between these parameters should be thoroughly investigated in this thesis.

The thesis first presents a simplified system architecture for wireless sensor nodes that is capable of addressing the strict requirements of wireless sensor networks. This architecture has been applied to the developed simulation tool. We actually present a generalized architecture, which addresses the key issues that arise when building a wireless sensor network device with strict power consumption requirements. We have identified the core application scenario of environmental data collection.

To validate our general architecture we have realized the following scenario: A prototype of the wireless sensor network was simulated. Simulating a suitable and application specific wireless network with the desired control parameters that are initial battery capacity, communication radius, query period, and node density was particularly difficult. Therefore, to realize the scenario as a simulation, we have made some assumptions that were defined in Problem Definition Section. The sensor network when deployed requires itself to be able to configure and start building the network. The major goal of the deployment is to cover the maximum area within which the network will be able to function with ease. The sensor node in the network communicates efficiently with its neighbors after formation. Nodes act as both routers and sources. Due to the limited transmission range, hops are established so that the information flows from the source to the sink (i.e. user node) through the best possible way.

The scenario briefly mentioned above was implemented in OMNeT++, a discrete event simulator environment. For this purpose, OMNeT++ simulation tool was installed on top of Windows Vista Operating System. In performing these simulation experiments, our goal is to understand the energy efficiency tradeoff between the sensor network parameters affecting the lifetime.

Verification of the simulation was simplified by performing simulations in its animation mode, at a pace slow enough for a human expert to observe and record all simulated network behavior and compare it to that expected. The raw data is placed in a Microsoft Excel-readable file for post processing. The simulations were performed over a wide range of input parameter combinations As a result, we got 54 different unique plots and we examined 14 crucial plots of them as illustrated in Simulation Study Section.

In brief, four parameters were considered in this study. Two of them, initial battery capacity and query period, have directly effects on a sensor node's lifetime. In other words, change in these parameters causes the lifetime of the network to go up linearly. In contrast, the other parameters, communication radius and node density, have tradeoffs in terms of the network's lifetime. We would like to note that the results of this study are somehow applicable to any kind of multi-hop sensor system (not only radio sensors; but also for example, underwater acoustic sensors).

As a main contribution to the sensor networks, this study presents a guide to a designer. First of all, it is better for the designer to examine the whole report in order to get a feeling about the parameters of the sensor networks. After that, he/she ought to observe the results of the parameters selected combinations by using the analyses tool in MS Excel. After all, to be able to construct the design, the designer is supposed to execute his/her own parameter values in the simulation tool. While our specific approach is an important first step, much further research is needed in developing a detailed and accurate understanding of the interplay between the parameters considered in this study. We envision that the simulation tool designed for this analysis will play an instrumental role in the design and implementation of new application specific sensor networks.

Additional exploration of network behavior as nodes fail is important. When does the network partition? How do mixes of nodes with different initial power levels affect the results? These results are likely to be sensitive to the traffic mix. Finally, experimentation is needed to validate these results with physical hardware in actual scenarios. While the platforms presented here are ready to meet the demands of real world commercial applications, the technology enabling wireless sensor networks will continue to evolve. As advances in CMOS processes and RF radio technology are incorporated into next-generation wireless sensor nodes, the power consumption and lifetime will continually improve.

The upcoming technology advances will most likely be applied to decreasing the power consumption of the device. In turn, this will enable a reduction of physical size of the energy storage required for any given application. All application scenarios can benefit from reduced power consumption, which is translated into longer network lifetime. Nowadays sensors are a “behind-the-scenes” technology that has an impact on every aspect of our lives. All factory and machine command and control systems will have switched over to relying on wireless sensing and control points. The millions of miles of cumbersome wiring we hear about in building control and automation systems will be replaced by an invisible wireless mesh. The devices themselves will become as commonplace as today’s light switches and thermostats. They will be tiny, cheap, commodity pieces of silicon that interact with the physical world.

References

[1] V. Mhatre and C. Rosenberg, “Design guidelines for wireless sensor networks: communication, clustering and aggregation,” Ad Hoc Networks Journal, vol. 2, pp. 45–63, 2004.

[2] M. Gun, R. Kosar, and C. Ersoy, “Lifetime optimization using variable battery capacities and non uniform density deployment in wireless sensor networks,” in 22nd international symposium on computer and information sciences, 2007.

[3] Zhang, J., Ci, S., Sharif, H., Alahmad, M.: Lifetime optimization for wireless sensor Networks using the nonlinear battery current effect. In: Communications, 2009. ICC '09. IEEE International Conference on. pp. 1 {6 (June 2009)

[4] A. Sharma, S. Takkar, “Routing Protocols in Wireless Ad-hoc Networks: A comparative study” Vol. 3, Issue. 5, pp. 108-111, 2013

[5] A. Shukla, A. Pandey, S. Srivastava, “Virtual Energy Based Encryption & Keying on Wireless Sensor Network”, IOSR Journal of Computer Engineering (IOSR-JCE), Vol. 9, Issue. 3 (Mar. – Apr. 2013), pp. 34–43.

[6] P. Krishan, “Comparison and Performance Analysis of Dynamic and Static Clustering Based Routing Scheme in Wireless Sensor Network”, International Journal of Advanced Research in Computer and Communication Engineering Vol. 2, Issue 4, April 2013.

[7] Jun, Z, Abbas J., (2009). “Wireless Sensor Networks A Networking Perspective”, John Wiley & Sons, Inc., Hoboken, New Jersey, pp. 188-189.

[8] D. Sharma, N. Sharma, N. Shrivastava, “Wireless Sensor Network and Its Architecture”, VSRD International Journal of Computer Science & Information Technology, VSRD-IJCSIT Vol. 1 (6), 2011, pp. 408-412.

[9] A. Abdelgawad, M. Bayoumi., (2012). “Resource-Aware Data Fusion Algorithms for Wireless Sensor Networks”, Springer, pp. 3-5.

[10] G. J. Pottie, W. J. Kaiser, “Wireless Integrated Network Sensors,” Communication of the ACM, Vol. 43, No. 5, May 2000, pp. 51–58.

[11] V. Rodoplu, T. H. Meng, “Minimum Energy Mobile Wireless Networks” IEEE Journal on Selected Areas in Communications, Vol. 17, No. 8, August 1999.

[12] B. Krishnamachari, D. Estrin, S. Wicker, “The Impact of Data Aggregation in Wireless Sensor Networks”, International Workshop on Distributed Event-Based Systems - DEBS02, July 2002.

[13] S. Adlakha, S. Ganeriwal, C. Schurgers, M. Srivastava, "Density, Accuracy, Latency and Lifetime Tradeoffs in Wireless Sensor Networks- A Multidimensional Design Perspective", Networked and Embedded Systems Lab (NESL), Electrical Engineering Department, UCLA 56-125B Eng. IV, UCLAEE Dept., Los Angeles, CA, 2003.

[14]. I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, “Wireless Sensor Networks: A Survey”, Computer Networks, Vol. 38, 2002, pp. 393-422.

[15] D. Blough, P. Santi, “Investigating Upper Bounds on Network Lifetime Extension for Cell Based Energy Conservation Techniques in Stationary Ad-hoc Networks,” Mobicom 2002, September 2002, Atlanta Georgia.

[16] OMNeT++ Home Page On The Web: http://www.omnetpp.org/

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

Appendix

The iterations are conducted until the results of all combinations are gathered.

The number of iterations is:

# of iterations = (# of possible values for a parameter) $^{\text{(\# of parameters concerned)}}$

That is; $3^4 = 81$

Moreover, for each parameter combination, we generate 10 random networks, that;

The total # of iterations = 34 x 10 = 810

In the following Table A.1, the results of all these iterations are given.

Table A.1. The Result Sheet

	Parameters	Configuration	1	2	3	4	5	6	7	8	9	10	Average
1	Initial Battery Capacity	1000mJ	422	471	231	11	151	421	311	184	571	231	300.4
	Communication Radius	300cm											
	Query Period	10s											
	Node Density	15											
2	Initial Battery Capacity	2000mJ	845	931	461	11	291	821	601	375	1131	461	592.8
	Communication Radius	300cm											
	Query Period	10s											
	Node Density	15											
3	Initial Battery Capacity	3000mJ	1282	1401	681	11	431	1221	891	565	1681	681	884.5
	Communication Radius	300cm											
	Query Period	10s											
	Node Density	15											
4	Initial Battery Capacity	1000mJ	423	321	161	262	251	361	411	491	481	391	355.3
	Communication Radius	400cm											
	Query Period	10s											
	Node Density	15											
5	Initial Battery Capacity	2000mJ	841	631	301	522	471	711	801	961	942	771	695.2
	Communication Radius	400cm											
	Query Period	10s											
	Node Density	15											
6	Initial Battery Capacity	3000mJ	1264	941	441	791	701	1051	1051	1431	1422	1131	1022.4
	Communication Radius	400cm											
	Query Period	10s											
	Node Density	15											
7	Initial Battery Capacity	1000mJ	301	256	261	221	291	331	341	341	261	341	294.5
	Communication Radius	500cm											
	Query Period	10s											
	Node Density	15											
8	Initial Battery Capacity	2000mJ	671	502	491	621	571	621	661	661	501	671	597.1
	Communication Radius	500cm											
	Query Period	10s											
	Node Density	15											
9	Initial Battery Capacity	3000mJ	1001	742	731	781	851	931	991	961	741	1001	873.1
	Communication Radius	500cm											
	Query Period	10s											
	Node Density	15											
10	Initial Battery Capacity	1000mJ	841	941	481	21	301	841	621	364	1141	461	601.3
	Communication Radius	300cm											
	Query Period	20s											
	Node Density	15											

11	Initial Battery Capacity	2000mJ	1681	1861	841	21	581	1641	1201	745	2261	921	1175.4
	Communication Radius	300cm											
	Query Period	20s											
	Node Density	15											
12	Initial Battery Capacity	3000mJ	2541	2801	1241	21	861	2441	1781	1125	3361	1361	1753.4
	Communication Radius	300cm											
	Query Period	20s											
	Node Density	15											
13	Initial Battery Capacity	1000mJ	843	641	321	522	821	721	821	981	961	781	741.3
	Communication Radius	400cm											
	Query Period	20s											
	Node Density	15											
14	Initial Battery Capacity	2000mJ	1681	1281	601	1042	941	1421	1601	1921	1882	1541	1391.2
	Communication Radius	400cm											
	Query Period	20s											
	Node Density	15											
15	Initial Battery Capacity	3000mJ	2524	1901	881	1581	1401	2101	2101	2861	2541	2261	2015.3
	Communication Radius	400cm											
	Query Period	20s											
	Node Density	15											
16	Initial Battery Capacity	1000mJ	601	503	521	441	581	661	681	681	521	681	587.2
	Communication Radius	500cm											
	Query Period	20s											
	Node Density	15											
17	Initial Battery Capacity	2000mJ	1341	982	981	1241	1141	1241	1321	1321	1001	1341	1191.1
	Communication Radius	500cm											
	Query Period	20s											
	Node Density	15											
18	Initial Battery Capacity	3000mJ	2001	1445	1461	1561	1701	1861	1981	1921	1481	2001	1741.4
	Communication Radius	500cm											
	Query Period	20s											
	Node Density	15											
19	Initial Battery Capacity	1000mJ	1261	1411	661	31	451	1261	931	544	1711	691	895.3
	Communication Radius	300cm											
	Query Period	30s											
	Node Density	15											
20	Initial Battery Capacity	2000mJ	2521	2791	1231	31	871	2461	1801	1115	3391	1381	1759.4
	Communication Radius	300cm											
	Query Period	30s											
	Node Density	15											

21	Initial Battery Capacity	3000mJ	3784	4201	1741	31	1291	3661	2671	1685	5041	2041	2614.7
	Communication Radius	300cm											
	Query Period	30s											
	Node Density	15											
22	Initial Battery Capacity	1000mJ	1263	961	481	782	1201	1081	1231	1471	1441	1171	1108.3
	Communication Radius	400cm											
	Query Period	30s											
	Node Density	15											
23	Initial Battery Capacity	2000mJ	2521	1921	901	1562	1411	2131	2401	2881	2881	2311	2092.1
	Communication Radius	400cm											
	Query Period	30s											
	Node Density	15											
24	Initial Battery Capacity	3000mJ	3784	2851	1321	2371	2101	3151	3151	4291	4291	3391	3070.3
	Communication Radius	400cm											
	Query Period	30s											
	Node Density	15											
25	Initial Battery Capacity	1000mJ	901	753	781	661	871	991	1021	1021	781	1021	880.2
	Communication Radius	500cm											
	Query Period	30s											
	Node Density	15											
26	Initial Battery Capacity	2000mJ	2011	1472	1471	1861	1711	1861	1981	1981	1501	2011	1786.1
	Communication Radius	500cm											
	Query Period	30s											
	Node Density	15											
27	Initial Battery Capacity	3000mJ	3001	2162	2191	2341	2551	2791	2971	2881	2221	3001	2611.1
	Communication Radius	500cm											
	Query Period	30s											
	Node Density	15											
28	Initial Battery Capacity	1000mJ	391	411	141	281	301	455	371	441	531	591	391.4
	Communication Radius	300cm											
	Query Period	10s											
	Node Density	30											
29	Initial Battery Capacity	2000mJ	771	661	261	561	591	912	751	871	1061	1161	760.1
	Communication Radius	300cm											
	Query Period	10s											
	Node Density	30											
30	Initial Battery Capacity	3000mJ	1151	1211	391	841	871	1368	1121	1311	1571	1731	1156.7
	Communication Radius	300cm											
	Query Period	10s											
	Node Density	30											

31	Initial Battery Capacity	1000mJ											
	Communication Radius	400cm											
	Query Period	10s											
	Node Density	30	326	291	361	261	341	392	401	471	461	421	372.6
32	Initial Battery Capacity	2000mJ											
	Communication Radius	400cm											
	Query Period	10s											
	Node Density	30	636	561	701	440	651	791	781	871	911	811	715.4
33	Initial Battery Capacity	3000mJ											
	Communication Radius	400cm											
	Query Period	10s											
	Node Density	30	955	821	1021	731	971	1174	1131	1401	1391	1201	1079.7
34	Initial Battery Capacity	1000mJ											
	Communication Radius	500cm											
	Query Period	10s											
	Node Density	30	221	181	281	311	321	221	301	341	231	361	277
35	Initial Battery Capacity	2000mJ											
	Communication Radius	500cm											
	Query Period	10s											
	Node Density	30	501	421	551	451	601	681	581	681	521	711	570
36	Initial Battery Capacity	3000mJ											
	Communication Radius	500cm											
	Query Period	10s											
	Node Density	30	741	631	751	431	891	961	981	1091	661	1101	824
37	Initial Battery Capacity	1000mJ											
	Communication Radius	300cm											
	Query Period	20s											
	Node Density	30	781	801	281	561	601	905	741	1181	1041	1181	807.4
38	Initial Battery Capacity	2000mJ											
	Communication Radius	300cm											
	Query Period	20s											
	Node Density	30	1541	1321	521	1101	1181	1822	1501	1721	2061	2301	1507.1
39	Initial Battery Capacity	3000mJ											
	Communication Radius	300cm											
	Query Period	20s											
	Node Density	30	2301	2361	781	1641	1741	2728	2241	2561	3081	3461	2289.7
40	Initial Battery Capacity	1000mJ											
	Communication Radius	400cm											
	Query Period	20s											
	Node Density	30	646	541	681	521	681	782	801	941	941	841	737.6

41	Initial Battery Capacity	2000mJ	1266	1041	1341	981	1301	1581	1561	1741	1861	1641	1431.5
	Communication Radius	400cm											
	Query Period	20s											
	Node Density	30											
42	Initial Battery Capacity	3000mJ	1905	1521	1961	1441	1941	2344	2261	2801	2781	2421	2137.7
	Communication Radius	400cm											
	Query Period	20s											
	Node Density	30											
43	Initial Battery Capacity	1000mJ	441	361	641	621	641	441	601	681	461	721	561
	Communication Radius	500cm											
	Query Period	20s											
	Node Density	30											
44	Initial Battery Capacity	2000mJ	1001	821	1301	901	1201	1361	1161	1361	1041	1421	1157
	Communication Radius	500cm											
	Query Period	20s											
	Node Density	30											
45	Initial Battery Capacity	3000mJ	1481	1241	1501	861	1781	1921	1961	2181	1321	2201	1645
	Communication Radius	500cm											
	Query Period	20s											
	Node Density	30											
46	Initial Battery Capacity	1000mJ	1171	1201	421	811	901	1355	1111	1771	1561	1771	1207.4
	Communication Radius	300cm											
	Query Period	30s											
	Node Density	30											
47	Initial Battery Capacity	2000mJ	2311	1981	781	1591	1801	2732	2251	2581	3091	3451	2257.1
	Communication Radius	300cm											
	Query Period	30s											
	Node Density	30											
48	Initial Battery Capacity	3000mJ	3451	3511	1171	2371	2671	4088	3361	3841	4621	5191	3427.7
	Communication Radius	300cm											
	Query Period	30s											
	Node Density	30											
49	Initial Battery Capacity	1000mJ	966	811	1021	781	1231	1172	1231	1411	1411	1261	1129.6
	Communication Radius	400cm											
	Query Period	30s											
	Node Density	30											
50	Initial Battery Capacity	2000mJ	1896	1531	1981	1471	1951	2371	2341	2611	2671	2461	2128.5
	Communication Radius	400cm											
	Query Period	30s											
	Node Density	30											

51	Initial Battery Capacity	3000mJ	2855	2221	2911	2161	2911	3514	3391	4201	4171	3631	3196.7
	Communication Radius	400cm											
	Query Period	30s											
	Node Density	30											
52	Initial Battery Capacity	1000mJ	661	541	1021	931	961	661	901	1021	691	1081	847
	Communication Radius	500cm											
	Query Period	30s											
	Node Density	30											
53	Initial Battery Capacity	2000mJ	1501	1231	1951	1351	1801	2041	1741	2041	1561	2191	1741
	Communication Radius	500cm											
	Query Period	30s											
	Node Density	30											
54	Initial Battery Capacity	3000mJ	2221	1831	2731	1291	2671	2881	2941	3271	1981	3271	2509
	Communication Radius	500cm											
	Query Period	30s											
	Node Density	30											
55	Initial Battery Capacity	1000mJ	401	331	221	241	481	401	471	621	541	521	423
	Communication Radius	300cm											
	Query Period	10s											
	Node Density	45											
56	Initial Battery Capacity	2000mJ	801	661	441	471	961	741	921	1241	1051	1041	833
	Communication Radius	300cm											
	Query Period	10s											
	Node Density	45											
57	Initial Battery Capacity	3000mJ	1191	981	651	701	1421	1201	1361	1851	1571	1551	1248
	Communication Radius	300cm											
	Query Period	10s											
	Node Density	45											
58	Initial Battery Capacity	1000mJ	361	311	251	311	421	411	181	461	481	401	359
	Communication Radius	400cm											
	Query Period	10s											
	Node Density	45											
59	Initial Battery Capacity	2000mJ	701	591	481	631	821	841	341	891	651	791	674
	Communication Radius	400cm											
	Query Period	10s											
	Node Density	45											
60	Initial Battery Capacity	3000mJ	1031	881	711	931	1221	1251	491	1311	961	1171	996
	Communication Radius	400cm											
	Query Period	10s											
	Node Density	45											

61	Initial Battery Capacity	1000mJ	321	221	321	191	301	351	161	121	281	251	252
	Communication Radius	500cm											
	Query Period	10s											
	Node Density	45											
62	Initial Battery Capacity	2000mJ	431	431	631	381	641	631	221	241	601	661	487
	Communication Radius	500cm											
	Query Period	10s											
	Node Density	45											
63	Initial Battery Capacity	3000mJ	821	631	941	571	891	931	381	361	881	641	705
	Communication Radius	500cm											
	Query Period	10s											
	Node Density	45											
64	Initial Battery Capacity	1000mJ	801	641	401	381	921	781	881	1241	1121	1141	831
	Communication Radius	300cm											
	Query Period	20s											
	Node Density	45											
65	Initial Battery Capacity	2000mJ	1581	1281	761	761	1801	2021	1721	2461	2101	2241	1673
	Communication Radius	300cm											
	Query Period	20s											
	Node Density	45											
66	Initial Battery Capacity	3000mJ	2361	1881	1121	1121	2681	3203	2561	3701	3321	3061	2501.2
	Communication Radius	300cm											
	Query Period	20s											
	Node Density	45											
67	Initial Battery Capacity	1000mJ	701	581	441	581	841	821	741	921	841	801	727
	Communication Radius	400cm											
	Query Period	20s											
	Node Density	45											
68	Initial Battery Capacity	2000mJ	1361	1141	821	1121	1601	1661	1141	1781	1881	1581	1409
	Communication Radius	400cm											
	Query Period	20s											
	Node Density	45											
69	Initial Battery Capacity	3000mJ	2021	1681	1201	1641	2381	2441	2101	2621	2441	2341	2087
	Communication Radius	400cm											
	Query Period	20s											
	Node Density	45											
70	Initial Battery Capacity	1000mJ	601	441	621	667	601	701	481	681	561	501	585.6
	Communication Radius	500cm											
	Query Period	20s											
	Node Density	45											

71	Initial Battery Capacity	2000mJ	861	861	1181	1301	1181	1261	921	1241	1201	1321	1133
	Communication Radius	500cm											
	Query Period	20s											
	Node Density	45											
72	Initial Battery Capacity	3000mJ	1841	1261	1701	1881	1861	1861	1681	1901	1761	1281	1703
	Communication Radius	500cm											
	Query Period	20s											
	Node Density	45											
73	Initial Battery Capacity	1000mJ	1201	961	601	571	1381	1171	1291	1861	1681	1711	1243
	Communication Radius	300cm											
	Query Period	30s											
	Node Density	45											
74	Initial Battery Capacity	2000mJ	2371	1921	1141	1141	2701	3031	2551	3691	3151	3361	2506
	Communication Radius	300cm											
	Query Period	30s											
	Node Density	45											
75	Initial Battery Capacity	3000mJ	3541	2821	1681	1681	4021	4803	3811	5551	6031	5041	3898.2
	Communication Radius	300cm											
	Query Period	30s											
	Node Density	45											
76	Initial Battery Capacity	1000mJ	1051	901	931	871	1321	1231	1231	1381	1261	1201	1138
	Communication Radius	400cm											
	Query Period	30s											
	Node Density	45											
77	Initial Battery Capacity	2000mJ	2041	1711	1231	1681	2401	2491	1711	2671	2161	2371	2047
	Communication Radius	400cm											
	Query Period	30s											
	Node Density	45											
78	Initial Battery Capacity	3000mJ	3031	2521	1801	2461	3571	3661	3151	3931	3241	3511	3088
	Communication Radius	400cm											
	Query Period	30s											
	Node Density	45											
79	Initial Battery Capacity	1000mJ	901	661	931	997	901	1051	721	1021	841	751	877.6
	Communication Radius	500cm											
	Query Period	30s											
	Node Density	45											
80	Initial Battery Capacity	2000mJ	1291	1291	1771	1951	1771	1891	1381	1861	1801	1981	1699
	Communication Radius	500cm											
	Query Period	30s											
	Node Density	45											
81	Initial Battery Capacity	3000mJ	2791	1891	2551	2821	2791	2791	2521	2851	2641	1921	2557
	Communication Radius	500cm											
	Query Period	30s											
	Node Density	45											