LIFETIME OPTIMIZATION USING NONUNIFORM DEPLOYMENT AND HETEROGENEOUS SENSORS IN WIRELESS SENSOR NETWORKS

by

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DEDICATION

Dedicated to my wife and our daughter.

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ABSTRACT

LIFETIME OPTIMIZATION USING NONUNIFORM DEPLOYMENT AND HETEROGENEOUS SENSORS IN WIRELESS SENSOR NETWORKS

Wireless sensor networks consist of a large number of sensor nodes deployed in a region of interest for monitoring purposes. As sensor nodes are battery powered devices, their operation time is limited. In a multi-hop sensor network with many-to-one communication characteristics, the nearer a node is to the sink, the more energy it consumes. Therefore, the nodes closest to the sink deplete their batteries faster than the others. Moreover, the network lifetime is bounded by the lifetime of these nodes, since when they fail, other nodes will no longer be connected to the sink.

Unbalanced energy consumption in the network can be compensated by deploying sensors non-uniformly and using heterogeneous battery capacity sensors. This paper investigates the benefits of topologies which exploit nonuniformity and heterogeneity. In the first part of the thesis, we study the possibility of using different battery capacity nodes in different regions of the network. In the second part of the thesis, we consider dense networks and study how the network lifetime is affected by using different densities in different regions of the network.

The thesis shows that heterogeneous network topologies offer efficient usage of the total network energy resources. This efficiency results in significantly longer network lifetimes with the same total cost when variable capacity sensors or variable densities are used.

ÖZET

KABLOSUZ ALGILAYICI AĞLARIN ÖMÜRLERİNİN FARKLI YOĞUNLUKLU YERLEŞTİRME VE FARKLI ALGILAYICILAR KULLANILARAK ENİYİLENMESİ

Kablosuz algılayıcı ağlar, ilgilenilen bir alanın gözlenmesi amacıyla yerleştirilen çok sayıda algılayıcı düğümden oluşur. Algılayıcı düğümler pil ile çalışan cihazlar oldukları için, çalışma süreleri kısıtlıdır. Çoktan-bire çok-hoplamalı iletim karakteristiğine sahip algılayıcı bir ağda çıkış düğümüne daha yakın düğümler daha çok enerji tüketir. Böylelikle, çıkış düğümüne en yakın düğümler pillerini diğerlerine göre daha hızlı bitirirler. Bunun yanında, bu düğümler öldüklerinde diğer düğümler çıkış düğümüne artık bağlanamayacağı için, ağ ömrü bu düğümlerin ömürleri ile sınırlıdır.

Ağdaki dengesiz enerji tüketimi algılayıcıların farklı yoğunlukta yerleştirilmesi ve farklı pil kapasitesine sahip algılayıcılar kullanılarak telafi edilebilir. Bu tez, homojen olmayan topoloji dizaynlarının faydalarını incelemektedir. Tezin ilk bölümünde ağın farklı bölgelerinde farklı pil kapasiteleri kullanılması olasılığı incelenmektedir. Tezin ikinci kısmında ise, kalabalık ağları ele alarak, ağın farklı bölgelerinde farklı yoğunlukta düğüm kullanımının ağ ömrü üzerinde etkisi incelenmektedir.

Bu tez homojen olmayan ağ topolojilerinin ağ enerji kaynaklarının toplamını etkin bir şekilde kullandığını göstermektedir. Bu etkililik, homojen olmayan ağ topolojileri kullanıldığında, aynı toplam maliyet ile çok daha uzun ağ ömrü sağlamaktadır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

a	Radius of circles
B	Budget
C	Total cost
d	Number of active sets
E	Battery capacity
g	Number of data packets generated in the first ring
h	Number of concentric rings
k	Propagation loss exponent
l	Length of packets in bits
n	Number of nodes
P	Average energy expenditure during a cycle
R	Communication radius
s	Relay load
T	Lifetime
x	Transmission distance

α	Hardware cost
β	Unit battery cost
ϵ	Connectivity bound
μ	Energy to run the Power amplifier
ν	Energy to run the radio electronics

ASCENT	Adaptive Self-Configuring sEnsor Networks Topologies
GAF	Geographic Adaptive Fidelity
GPS	Global Positioning System
MAC	Medium Access Control
OGDC	Optimal Geographical Density Control
PEAS	Probing Environment and Adaptive Sleeping

1. INTRODUCTION

A wireless sensor network consists of small and cheap sensing devices, deployed over a region of interest for different monitoring purposes like environmental monitoring, seismic activity detection, high-precision agriculture, forest fire detection, and border surveillance [1]. These small sensing devices, also called sensor nodes, have sensing, data processing and wireless communication capabilities. The sensor nodes in these networks are powered by batteries with limited energy, which is dissipated during the data transmission and reception mostly.

Sensor nodes send their collected information to a data collection point called the sink, typically in a multi-hop fashion, using other sensor nodes in the process. Therefore, each node transmits its own traffic, as well as the traffic it forwards towards the base station on behalf of other nodes. The sink aggregates and analyzes received messages to determine any occurrence of a concerned event in the deployed area [2, 3, 4, 5].

Sensor nodes are expected to work for days, weeks, and sometimes for years. However, a combination of several sensor network peculiarities makes the power problem especially challenging. First, the large number of cheap sensors precludes equipping each sensor with very large and expensive batteries. Second, in most situations, it is impossible to replace the batteries, especially in large, randomly scattered networks. Therefore, the scarce energy resources in the network should be used very efficiently in order to achieve the required operational network lifetimes.

1.1. The Background

The most critical requirement for wireless sensor networks is power efficiency since the battery capacities of sensor nodes are usually small. Moreover, due to the nature of the deployment scenarios such as harsh desert, deep forest, remote areas or hostile terrain; recharging or replacement of a node's battery is not a viable option for these networks [6, 7]. In order to obtain a prolonged system lifetime, the limited energy resources should be used economically. The main inefficiency arises in wireless sensor networks due to the unbalanced energy usage among sensor nodes.

The radio ranges of wireless sensor nodes are not long enough to enable them to reach the sink in a single hop of transmission. The reason is twofold: On one hand, the limited energy capacities put limitations on radio transmit powers. On the other hand since sensing ranges are smaller compared to the typical radio ranges, assigning long transmission ranges gives rise to overhearing and interference problems. Therefore multi-hop transmission is necessary, which is realized by the intermediate message relays of other nodes.

This many-to-one multi-hop characteristic of the network causes uneven energy consumption among the nodes located in different areas of the network. That is, the nodes which are located close to the sink have more relaying load compared to the nodes which are located away from the sink. As a direct consequence of this uneven energy consumption, the closer a node is to the sink, the faster it depletes its battery. For a wireless sensor network with fixed sinks, this is the inevitable problem of designing the topologies.

It is important that network functionality can be fulfilled by the active sensor nodes at any moment in the system lifetime. The nodes in the close vicinity of the sink are critical nodes, since the early deaths due to the high relaying load of these nodes bring an end to the network functionality. This is because, although the other nodes have battery capacity to do sensing and communication, they are no longer connected to the sink when the intermediate relaying nodes disappear. Figure 1.1 shows the distribution of dead and live nodes in such a situation. As soon as the last three surviving critical nodes die, the network will be disconnected, leaving most of the total network energy unused.

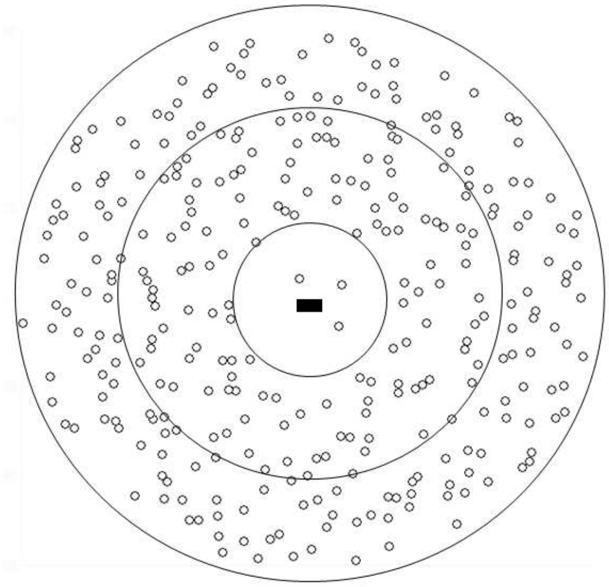

Figure 1.1. When the critical nodes in the close vicinity of the sink disappear, many nodes will no longer be connected to the sink

1.2. Heterogeneous Deployments

Homogeneous network deployments have obvious inefficiency that at the time the network functionality can no longer be retained, vast majority of the nodes retain battery capacities to enable them continue their operations. The total of this remaining energy is wasted since the collected information can't reach to a point to become useful. Instead of deploying all nodes homogeneously with the same energy resources and distributing them with the same density throughout the network, we choose to use heterogeneous deployment strategies in order to better distribute the total network resources in facing uneven energy consumption problem. We propose mainly two different heterogeneous deployment methods.

In the first approach, battery capacities of the nodes in different regions of the network are chosen differently so as to just meet their energy consumptions. The ultimate goal is to maximize the system lifetime using the available total system resources by saving the wasted energy amount and utilize it wherever needed. the wasted energy amount and utilize it wherever needed.

The analysis made in order to decide on the necessary battery capacities is based on the deployment strategy of forming different regions in accordance with the distance from the sink point. The equidistant collection of coverage areas from a common sink point is in the form of concentric ring shapes. Therefore, we divide the monitored area into concentric ring areas and deploy the nodes in these areas such that the nodes with the highest battery capacity are located in the ring where the highest energy drainage takes place. Each node in a ring has the same battery capacity and ring energies increase with decreasing distance from the sink. All nodes exhaust their batteries at about the same time with this deployment; hence, the maximum network lifetime can be achieved using the full capacity of the network.

The second approach is based on using nonuniform node densities in different regions of the network. This solution assumes a dense network and decides upon the node densities in different regions of the network in order to maximize the network lifetime.

In order not only to enhance the accuracy of collected data and the reliability of the network, but also to sustain a long network lifetime, nodes may be deployed with high densities (up to 20 nodes/m^3) [8]. Since all nodes share common sensing tasks, not all the nodes are required to perform the sensing tasks during the whole system lifetime. Making some nodes sleep does not affect the overall system function, as long as there are enough working nodes to assure it. Moreover, if all sensor nodes operate in the active mode, an excessive amount of energy will be wasted, sensor data collected are likely to be highly correlated and redundant. Last but not the least; excessive packet collision may occur as a result of sensors intending to send packets simultaneously in the presence of certain triggering events. Hence, it is neither necessary nor desirable to have all nodes simultaneously operate in the active mode.

One effective method to overcome this problem is the density control, which only keeps part of sensors in active mode while maintaining complete sensing coverage. When active sensors die, remaining nodes in that region can replace them in order to continue the network functions.

Due to the aforementioned uneven energy consumption rates, lifetime periods of the nodes show great variation across the network, i.e. the nodes closer to the sink will consume their energy more quickly. If the nodes are deployed with uniform density everywhere in the network, at the time when there are not enough working nodes in the vicinity of the sink to carry out the system functionality, most of the nodes in the outer regions continue to operate in vain. Instead, if nodes are deployed with nonuniform densities, the number of nodes in each region can be balanced in the entire course of the network lifetime. As a result of this balance, the network lifetime increases considerably.

The node densities are determined by dividing the monitored area into concentric rings formed around the sink as before. The node densities are such that, as the distance to the sink increases density decreases. With such a heterogeneous deployment, no surplus energies exist at the end of the network lifetime, since for each ring total lifetimes of active nodes will be equal to each other.

1.3. Related Work

Considerable amount of research has gone into studying the design and performance of wireless sensor networks. Among them, authors in [9] design a Markov model in order to evaluate the different performance characteristics, like network lifetime and data delivery capacities, for wireless sensor networks. They use this model in order to investigate the trade-offs between network performance and node-energy saving strategies. The authors in [10] on the other hand, study two sensor deployment schemes and use a statistical model and reliability theory for lifetime evaluation of sensor networks. The authors state that the theoretical results in this paper can be used as basis for performance and lifetime evaluation of other deployment schemes.

Ordonez and Krishnamachari in [11] present non-linear optimization models of static wireless sensor networks. They use the formal methodology in order to find the bounds on the system performance and information capacities of wireless sensor networks. They also analyze the relation between total network energy and total information capacity of the network. In [12] Perillo *et al.* discuss the fundamental problem of unbalanced load distribution and effects of transmission range distribution on the network lifetime.

Hu and Li studies energy-constrained wireless sensor networks and pose some questions about the lifetime and information extraction capacities of wireless sensor networks in [13]. They draw a conclusion that keeping the node density fixed, any increase in the number of initially deployed nodes results in degradation in network lifetime. Another work on the fundamental capacity restraints on wireless sensor networks is [14]. The authors focus on the capacity limitations of wireless sensor networks imposed by the wireless sensor network topologies. They discuss the main capacity and performance limits in a wireless sensor network. Furthermore, they show that geometrical topology of the network give rise to capacity limitations.

In [15], authors model statistically the state of individual nodes and using these models, they infer the model of the entire large-scale wireless sensor network systems. They use this model in order to evaluate the performance of some large-scale wireless sensor networks. Rivas *et al.* consider the problem of early deaths among the nodes closest to the sink in [16]. As a solution they propose to add more nodes around the sink nodes. They use a mathematical model in order to analyze the gains of adding these extra nodes. The results found in this work reveals that nonuniform node density results in a big increase in network lifetime, supporting the results in this work.

As a solution to the unbalanced load distribution, Akkaya *et al.* suggest that sinks could be relocated in order to decrease the total transmission power and extend the network lifetime in [17]. They analyze when the relocation should take place, where the sink should be moved and how the relocation could be achieved without side effects. In [18] authors considers early deaths caused by uneven load distribution in multi-hop wireless sensor networks. They state that using transmission power control, the network lifetime could only be improved to some extent. As an alternative they suggest data aggregation which provides more efficient energy consumption. They compare the effectiveness of different policies used for mitigating the sensor network hot spot problem. Authors in [19] consider large-scale multi-cluster sensor network and derive analytically the effect of communication distance of cluster heads on the power consumption and throughput of such networks.

Since the traffic is towards a single destination in the many-to-one communications, the capacity of a wireless sensor network is more limited compared to the random one-to-one communications. In [20], authors give a survey about distributed in-network computation. In this approach, the nodes not only collect and forward the data, but also perform computations on those data. They review several approaches to solve in-network computation related problems. Gupta and Kumar, analyze the optimal throughput capacity of wireless sensor networks in [21]. They obtain bounds on transport capacity under different power control schemes.

In [22], authors study data-gathering wireless sensor networks. They obtain the transmission capacity of such networks with different communication organizations. They obtain bounds on transmission capacity and the conditions that these bounds can be achieved. They also discuss the transport capacity increase with clustering and in-network processing. In [23], authors consider a hierarchical wireless sensor network composed of clusters of sensors, powerful relaying nodes and central sink points. Capacity bounds on this network are presented in this paper also.

Authors in [24] consider the following problem: If the node density increased indefinitely, is there any chance to cope with the increased data flow with a data compression scheme. They conclude that with no data compression scheme the ever increasing data transport requirements can be fulfilled. In [25], authors design an off duty scheduling algorithm and compare energy and the delivery capacity of this scheme to other proposed duty-cycling protocols. The authors analyze the energy and delivery capacities and compare the spatial reuse and energy savings of different schemes.

The most important problem in the field of wireless sensor network is extending the network lifetime [26]. As mentioned in [12] also, wireless sensor networks suffer from unbalanced load distribution due to the many-to-one traffic pattern. In order to overcome the early deaths among the nodes, which are closest to the sink, some heterogeneous wireless sensor network designs have been proposed. We can group these proposed heterogeneous wireless sensor networks solutions into three main categories.

1.3.1. Heterogeneous Wireless Sensor Networks Which Use Different Transmission Range with Transmission Power Control

Transmitting at high power is inefficient because of mutual interference in the shared radio channel and the excessive energy consumption. Using minimum transmission powers just enough to ensure connectivity may lead to a good energy saving. Authors in [27] investigate the optimal minimum transmit power used by all nodes which also guarantees network connectivity. In [28], Wang and Zhong study the problem of minimum-cost sensor placement problem. They try to select a set of sensors from different type of sensors with different sensing ranges and different costs, and a subset of points to place these sensors such that every point in sensed area is covered and the total cost of the sensors is minimized.

In [29], authors point out that the quality of radio communication between sensor nodes varies with time and environment. They propose to use a lightweight adaptive online transmission power control algorithm to address this issue. In [12], the authors study the problem of energy imbalance in sensor networks. Allowing each node to set its transmission range according to its location, they try to optimize individual transmission range, in order to balance the energy consumption in the network. However, this can be achieved at the expense of using the energy resources of some nodes inefficiently. Therefore using heterogeneous transmission ranges, the lifetime of the network can be extended up to a point.

1.3.2. Heterogeneous Wireless Sensor Networks Which Deploy Relay Nodes In Order To Relieve the Relaying Burden on the Sensor Nodes

In [30], Xu *et al.* propose to use relay nodes as powerful cluster heads. In their model, sensor nodes do not have relaying function and reach to a relay node in one hop. They explore the effects of using heterogeneous capacity nodes on the network lifetime with three different deployment strategies. In [31], Xin *et al.* propose to use extra simple relay nodes in order to improve the network lifetime. Relay nodes in their model are simpler devices than the sensor nodes, in the sense that they do not possess any sensing component. They increase the relay node density as the distance to the sink becomes smaller. Furthermore, since they find out that relay node density in the proximity is so high that, they also utilize transmission power control.

In [32], Lloyd *et al.* assume that relay nodes are powerful devices with longer transmission ranges than sensor nodes and study two versions of relay node placement problems. In the first version, they try to deploy minimum number of relay nodes so that each pair of sensor nodes are connected by a path consisting both relay and sensor nodes. In the second version, they seek that each pair of nodes are connected by a path consisting of just relay nodes. They present also a polynomial algorithm for both versions.

Xu *et al.* studies the problem of the optimal wireless sensor deployment, with an objective of minimizing the network cost with lifetime constraint in [33]. They use relaying nodes and base station nodes in constructing the network. Sensing nodes send their data through relaying nodes to the base station nodes in this deployment scenario. In [34] authors consider cluster based two-tier network model and obtain a fault-tolerant relay node placement strategy. According to this strategy each sensor node can communicate with at least two relay nodes and relay nodes are two-connected.

1.3.3. Heterogeneous Wireless Sensor Networks Which Use Different Energy Capacity Nodes

A few researchers have studied wireless sensor networks with heterogeneous energy capacity sensor nodes. Among them, authors in [35] discuss the performance and energy consumption of wireless sensor networks, with two types of sensor organizations, one with a single layer of identical sensors and the other with additional overlay of fewer but more powerful sensors. They calculate the optimal number of clusters based on their model. Similar to their work, in [36] Mhatre *et al.* consider a heterogeneous clustered network in which there are two types of nodes. They identify the regular sensing nodes as type zero nodes and type one nodes are those more powerful nodes which do sensing and also act as cluster heads. An aircraft periodically collects data from type one nodes. Based on this model, they try to find the optimum node densities and node energies to guarantee a lifetime period with the least cost.

In [37], Ma *et al.* consider wireless in-home sensor networks lifetime optimization problem and propose to use a hub-spoke topology in order to distribute the total network energy resource in a more balanced way. They note that sensors in wireless in-home sensor networks have heterogeneous resources, like different energy capacities. The topology is formed adaptively according to the resources of its members using a protocol named Resource Oriented Protocol. Lee *et al.* in [38] discuss the heterogeneous deployment of sensor nodes with different capabilities and studies the impact of this deployment on sensing lifetime coverage.

Chakrabarty *et al.* [39] present a solution for minimizing the cost of heterogeneous sensor deployment with complete coverage of the sensor field. They formulate an integer linear programming problem to minimize the cost in grid-based sensor deployment network. They do not consider the energy consumption and lifetime of heterogeneous sensor deployment. Authors in [40] focus on energy heterogeneity and consider resource-aware MAC and routing protocols to utilize those resources. They evaluate the impact of number and placement of heterogeneous resources on the performance of sensor networks. They note that heterogeneity can provide five-times increase in the network lifetime.

1.3.4. Topology Control Algorithms

Topology control is an important feature for energy saving in dense wireless sensor networks, and many topology control protocols have been proposed. GAF [41] assumes the availability of GPS and conserves energy by dividing a region into rectangular grids, ensuring that the maximum distance between any pair of nodes in adjacent grids is within the transmission range of each other, and electing a leader in each grid to stay awake and relay packets while putting all other nodes to sleep. Span [42], decides if a node should be working or sleeping based on connectivity among its neighbors. Cerpa and Estrin in [43] present ASCENT, to automatically configure sensor network topologies. In ASCENT, each node measures the number of active neighbors and the per-link data loss rate through data traffic. Based on these two values, it decides whether to sleep or keep awake.

Tian *et al.* in [44] devise an algorithm that ensures complete coverage using the concept of sponsored area. Whenever a sensor node receives a packet from one of its working neighbors, it calculates its sponsored area which is defined as the maximal sector covered by the neighbor. If the union of all the sponsored areas of a sensor node covers the coverage disk of the node, the node turns itself off. Ye *et al.* [45] present PEAS, a distributed, probing based density control algorithm for robust sensing coverage. In this work, a subset of nodes operates in the active mode to maintain coverage while others are put into sleep. A sleeping node wakes up occasionally to check if there is working nodes in the vicinity. If no working nodes are within its probing range it starts to operate in the active mode; otherwise it sleeps again.

In [46], authors present a decentralized and localized density control algorithm called Optimal Geographical Density Control (OGDC). OGDC gives rules that specify what action one node should adapt and how to change state. Zou and Chakrabarty present a technique for the selection of active sensor nodes in dense sensor networks in [47]. They also describe an optimal coverage-centric centralized approach based on integer linear programming.

In [48], Newman *et al.* consider wireless sensor networks with redundant array of sensor nodes and seek for optimal design using a method of fault detection based on Artificial Neural Networks. Du and Lin in [49] point out that in many scenarios some key areas need higher coverage degrees. They propose a differentiated coverage algorithm which can provide different coverage degrees for different areas. In [50], authors consider the area coverage problem with equal sensing and communication radii. Their aim is to minimize the number of active sensor nodes involved in area coverage while obtaining a connected set. The proposed solution is localized, and each sensor decides to sleep based on the messages coming from other nodes.

Moreover, coverage and connectivity conditions of wireless sensor networks were discussed in a number of works. Lifetime optimization problems need to take the coverage and connectivity requirements into account. Among the works on this subject, [51] is about the connectivity and coverage conditions in a unit area square region. The authors assume that sensor nodes may fail with some probability and obtain necessary and sufficient conditions for the random network grid network to cover the unit area and obtain a connected set of active nodes. In [52], Adlakha and Srivastava study the problem of finding the minimum node density that satisfy the complete coverage of a monitored area. They consider the target characteristics and sensor node characteristics in their analytical model.

Study in [53] is a survey of wireless sensor network coverage centered works. The authors present different solutions in the literature and their assumptions and formulations in this paper. In [54], authors study the coverage and connectivity in wireless sensor networks. They state that, proposed protocol provides the coverage and connectivity by the active nodes in sleep scheduled network. Furthermore, the protocol supplies different coverage and connectivity degrees depending on the requirements of the application. Moreover, they study the geometrical relationship between coverage and connectivity.

In [55], authors analyze coverage conditions for wireless sensor networks from different perspectives. They define the coverage problem from deterministic, statistical, worst and best case point of views. They also use Voronoi diagram and graph search algorithms in establishing optimal polynomial time average and worst case coverage algorithms. Authors in [56] describe some distributed and coverage algorithms that they designed for improved monitoring quality. Moreover, in [57] authors study a dominating connected coverage set forming problem for wireless sensor networks with redundant sensor nodes.

1.4. Research Contribution

This thesis focuses on the heterogeneous wireless sensor network deployment scenarios. The research contributions of this work are twofold:

- Based on the analysis made on the models, we solve the problem of heterogeneous energy resource distribution which maximize the network lifetime. We obtain an expression for the required battery capacity of the nodes and evaluate the performance of the proposed solution.
- We design a nonuniform node density deployment scheme for dense wireless sensor networks. We formulate the density distribution of the sensor nodes which maximize the network lifetime.

1.5. Thesis Organization

The remainder of this thesis is structured as follows. The next chapter introduces the system lifetime as a performance metric, discusses connectivity and coverage issues and presents the problem. Furthermore proposed deployment scheme is also described in this chapter. Chapter 3 introduces different versions of the problem and gives solutions to these problems. Different topology design alternatives are considered in this chapter, which are based on heterogeneous battery capacities and nonuniform densities. Chapter 4 is about the detailed performance evaluation of the proposed deployment alternatives. The thesis ends with conclusions and future work in Chapter 5.

2. NETWORK MODEL AND PROBLEM STATEMENT

In this chapter we introduce not only our wireless sensor network lifetime definition, but also coverage and connectivity perspectives adapted in our model. The chapter also includes the definition of the problem. Moreover, we present concentric ring deployment scheme in this chapter.

2.1. Network Lifetime

Performance of a wireless sensor network is mainly evaluated by the length of its lifetime. It is well-known that most of the time sensor nodes in sensor networks have limited energy capacity and the longer system lifetime can be achieved with more efficient energy usage strategies in the network. The system lifetime is defined as the time period starting from the setup of the network until there are not enough nodes to keep the network functioning.

For our problem, the network lifetime is the time until the first critical node dies. The critical nodes are the ones located closest to the sink. Although the network does not fail entirely with this first critical node loss, it may soon be unable to meet the coverage and communication requirements anymore. Hence, some uncovered regions form or the nodes behind this dead node may be unable to communicate with the sink.

Typically, the first node to die is one of the critical nodes in the vicinity of the sink. This is a result of uneven distribution of energy consumption; the nodes adjacent to the sink have the highest energy burden. If all nodes have the same battery capacity, the system lifetime is equal to the lifetime of the most heavily loaded node. Instead, if more energy consuming nodes are equipped with higher energy capacity, the system lifetime increases considerably. In the ideal case, all nodes exhaust their batteries at about the same time; hence, no energy is wasted.

In the densely deployed networks due to the redundancy in node numbers, nodes may participate in network activity alternately. Because of the aforementioned unbalanced energy consumption, the alternating frequency in different regions of the network is not the same. Since the nodes in the vicinity of the sink will bear the largest relaying load, the active nodes in these places will have the shortest lifetime periods, therefore new set of nodes become active the most frequently. Moreover, when there are not enough nodes to provide the coverage and relay the packets from the outer nodes, the connectivity of the network will be broken. Therefore the cumulative lifetime of these critical nodes constitute the network lifetime.

If all nodes are uniformly distributed in the network, the system lifetime is equal to the cumulative lifetimes of the nodes in the most heavily loaded region. Instead, if nodes are more densely deployed in inner regions than outer regions, the system lifetime increases considerably. In the ideal case, the last set of active nodes in each region exhaust their batteries at about the same time; hence, no energy is wasted.

2.2. Coverage and Connectivity

Sensor nodes in the network perform two tasks, namely sensing and communication. Both of the activities consume energy which constitutes the total energy requirement in a node. Usually the energy spent on sensing is small as compared to the communication energy.

Sensing radius varies depending on the type of application. Communication radius, on the other hand is a part of the radio characteristics of the node. The quality of a sensor network depends on the coverage area of the sensed field and abundance of connected components in the network. These two measures are directly related not only with the number and the relative positions of operational sensor nodes, but also with the sensing and communication radius of individual nodes.

In Figure 2.1 necessary condition for connection and coverage is depicted, where circles show the communication and coverage areas respectively. In order for two nodes

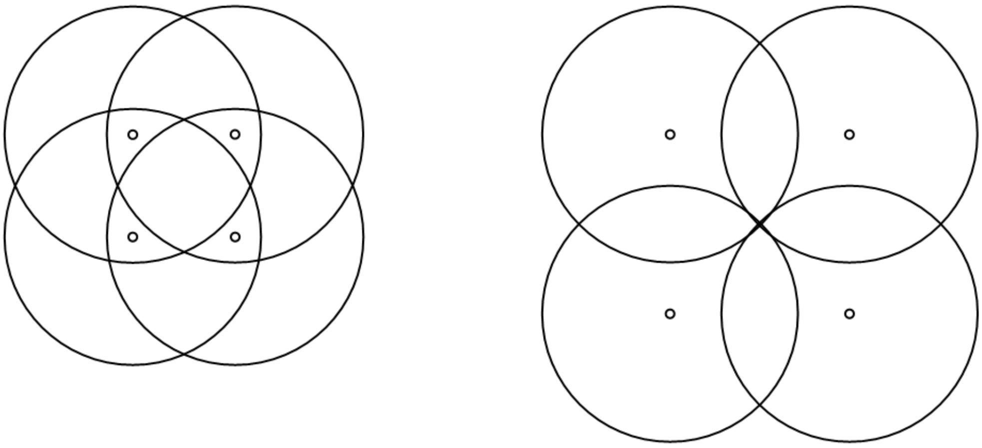

Figure 2.1. The communication and coverage conditions illustrated

to communicate the distance between them must be less than the communication radius. The higher the number of deployed nodes are, the better the coverage and communication characteristics of the network are.

At this point we assume that using sufficient number of nodes, we may be able to uniformly distribute the nodes in a way that, the distance between neighboring nodes satisfies the necessary condition both to cover the area in between and also to communicate with each other.

In [58], the authors consider the following problem: Determine the communication radius R which guarantees that when n nodes are placed uniformly and independently in a unit-area circle, the resulting network is asymptotically connected. They have obtained a lower bound on R in order to ensure connectivity of the nodes with a high probability. Moreover, the authors state that the results they found also satisfy the condition that unit-area circle is covered.

When n nodes are uniformly and randomly distributed over a unit circle A, the probability of connectivity of nodes is lower bounded by Lemma 3.1, (1.13) of [58].

$$\text{P (connectivity) } \leq 1 - ne^{-n\pi R^2} \tag{2.1}$$

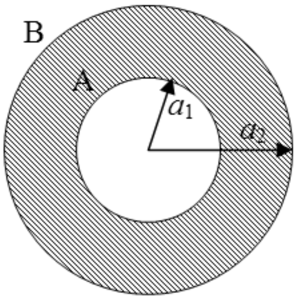

Figure 2.2. Ring 2 illustrated

This is a sufficient condition for connectivity, and therefore is a loose bound. To have node connectivity with a probability of at least $1-\varepsilon$, we have the following;

$$\text{P (A is connected)} \geq 1 - ne^{-n\pi R^2} \tag{2.2}$$

$$1 - ne^{-n\pi R^2} \geq 1 - \varepsilon \tag{2.3}$$

As in (2) of [59], after scaling all distances by a normalizing factor, we can get the minimum number of nodes in order to cover the circle A and obtain a connected network as given in Equation (2.4)

$$\frac{n}{\log\left(\frac{n}{\varepsilon}\right)} \geq \left(\frac{a}{R}\right)^2 \tag{2.4}$$

2.2.1. Coverage and Connection Conditions for a Ring

In our solution, we will deploy the nodes in concentric ring shaped areas, therefore we need to obtain the minimum number of nodes to fulfill the coverage and communication constraints in a ring. In order to obtain the sufficient conditions for the coverage and connectivity within a ring, we can extend the results found in [58] for circle coverage and connectivity. We consider Ring two shown in Figure 2.2 with shaded area, which is formed between Circle B and Circle A (which is also considered as Ring one) in the derivation of conditions for the connectivity and coverage within a ring as follows:

From Inequality (2.3) we obtain the following inequality:

$$\frac{n}{\log\left(\frac{n}{\varepsilon}\right)} \geq \frac{1}{\pi R^2} \tag{2.5}$$

Inequality (2.5) gives the minimum number of nodes to cover a unit area and obtain a connected network. When we consider Ring two shown in Figure 2.2 with shaded area, scaling the area and communication radius in Inequality (2.5), we obtain the following inequality for minimum number of nodes in Ring two:

$$\frac{n_2}{\log\left(\frac{n_2}{\varepsilon}\right)} \geq \frac{a_2^2 - a_1^2}{R^2} \tag{2.6}$$

2.3. Problem Statement

We are given an area to be covered with wireless sensor networks for the purpose of environmental monitoring. We have a fixed budget which consists of cost of sensor nodes. Moreover, the cost of a sensor node varies with the capacity of the batteries used on it. We use heterogeneous sensor nodes and concentric ring deployment, and we should decide on the battery capacities and the number of nodes in each ring. With the optimum configuration, the lifetime of the network is maximized. While deciding the configuration, we should also satisfy the coverage and connection criteria.

2.4. Concentric Ring Deployment

2.4.1. Introduction

In a multi-hop sensor network with many-to-one delivery, nodes nearer the sink spend more energy. Using network resources homogenously throughout the network causes lifetime variations among nodes in different regions. Consequently, the whole network resources cannot be utilized and a large portion of the available resources are wasted. In turn, the network lifetime is subdued due to the unfeasible resource usage.

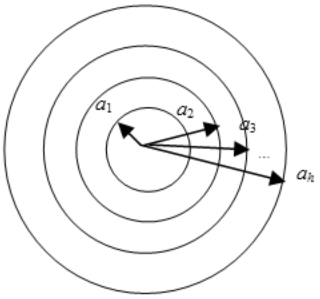

Figure 2.3. Nodes are deployed in concentric rings formed between circles with radii $a_1, a_2, a_3 \ldots a_h$

Heterogeneity is necessary in order to eliminate the uneven distribution of relaying load. Employing heterogeneous deployment, the nodes in different regions of the network can be equipped with the resources proportional to their relaying burden. Consequently the network resources are not wasted and all nodes complete their operational lifetimes at about the same time. The maximum network lifetime of the considered network can be achieved with heterogeneous deployment strategies.

The difference in loads in different portions requires an analysis to group and treat nodes based on their relative distance to the sink position. Since the equidistant areas from a point are in ring shape, we make the analysis by dividing the network into concentric rings and deploy the sensor nodes accordingly.

2.4.2. System Description

We propose to use heterogeneity and deploy sensor nodes in concentric ring shaped areas as shown in Figure 2.3. We assume that there are h different types of node groups differing in their given heterogeneity measures, i.e. either the battery capacity or the node density. The radii of the circles forming the concentric rings are a_1, $a_2 \ldots a_h$; hence, the thicknesses of each of the h rings are $a_1 - a_0$, $a_2 - a_1$,$a_3 - a_2 \ldots a_h - a_{h-1}$, where we assume that there is a hypothetical circle with a radius $a_0 = 0$ exists in the sink location in order not to deviate from concentric rings approach in the first ring, which is a circle actually. Furthermore the nodes in these rings have energy-levels given as E_1, $E_2 \ldots E_h$, if heterogeneous battery capacity is the solution. The number of nodes in each ring is denoted by n_1, $n_2 \ldots n_h$. Each type of node has a cost namely C_1, $C_2 \ldots C_h$. Let C_i be the cost of a Type i node. We can use a simple cost model similar to the one used in [59] as $C_i = \alpha + \beta E_i$, where the constant α is the cost of the hardware (excluding the battery cost), while β is the unit battery cost. The overall cost of the network is then:

$$C = \sum_{i=1}^{h} n_i(\alpha + \beta E_i) \tag{2.7}$$

We assume a communication model similar to the one discussed in [60]. The amount of energy required for a transceiver to transmit an l bits packet over a distance x is given by, $l(\nu + \mu x^k)$, where ν is the amount of energy spent in the transmitter, while μx^k is the amount of energy spent in RF amplifiers. Propagation loss exponent k is dependent on the surrounding environment. For free space its value is two. When receiving a packet, only the receiver circuitry is invoked, so the energy spent on receiving a packet is $l\nu$. Thus to relay this packet over distance x, $l(2\nu + \mu x^k)$ amount of energy is spent.

2.4.3. Assumptions

Our analysis is related more with the data gathering sensor networks instead of the event detection sensor networks. In data gathering networks, the nodes periodically send their sensed data to the base station, while in event detection sensor networks, the nodes are idle for long periods of time, and jump into activity only when the event of interest occurs. The nodes in the network send their sensed data to the sink node by hopping through intermediate nodes.

We assume in our analysis that the area covered by the sensors is a circular area with the sink in the center. This is a reasonable assumption and useful as an idealization because it is simple and symmetric, which eases analysis. In fact, in any realistic spatial distribution of sensors, it is likely that a small fraction of the sensor nodes will be within direct range of the sink, and increasingly larger fractions will be further and further away. Indeed, most such distributions can be thought of as a connected sub-area of the circular area, we assume.

Next, we discuss two important routing strategies employed in the current multi-hop wireless networks. The first is a shortest path routing approach where the farthest node (within the transmission radius) towards the sink is selected as the next hop. However, this approach may lead to imbalance in the energy consumption at the sensor nodes, which may eventually lead to the reduced lifetime. An alternative routing approach [61, 62] is to choose neighbors to dynamically load-balance the energy consumption at each node. This requires choosing a neighbor with the maximum residual energy as the next hop.

Note that there can be two major disadvantages of ideal load-balancing, particularly if the transmission range is large and network is dense. Firstly, it requires significant overhead to keep track of the residual energy at all the neighbors, and secondly the average path length may increase leading to the increased energy consumption. Thus, the optimal energy efficient routing should be an ideal combination of the shortest-path and load-balanced routing. In [63], authors present two energy-aware, load balanced routing schemes for sensor networks. We assume that using such routing approaches, we may be able to distribute the relaying load equally on each node in a ring. We will make use of this assumption in the maximum lifetime heterogeneous deployment calculations in the next chapter.

3. HETEROGENEOUS DEPLOYMENT SOLUTIONS

3.1. Maximum Lifetime Heterogeneous Battery Capacity Solution

3.1.1. Introduction

Since the communication in sensor networks is mostly multi-point to point (i.e., from sensor nodes to an information sink node), sensor nodes in the proximity of the sink node have to relay comparably excessive traffic. For this reason, such nodes inevitably deplete their energy rapidly regardless of the routing algorithm utilized. Early deaths among these highly loaded critical nodes bring the network to the end of its lifetime. This is the main energy bottleneck in a typical sensor network.

As a solution, we propose to deploy sensor nodes with different levels of battery energy in such a way that the initial battery energy is higher for the nodes that are closer to the sink node. This way the energy drainage due to heavy traffic burden around the sink can be handled by the battery energies distributed proportional to the loads of sensor nodes. In this section, we find heterogeneous energy resource distribution for the maximum network lifetime using heterogeneous battery capacity sensor nodes.

3.1.2. Network Lifetime Optimization with Variable Battery Capacities

We propose to use heterogeneous energy-capacity sensor nodes and deploy them in concentric ring shaped areas as shown in Figure 2.3. In order to obtain the sufficient conditions for the coverage and connectivity within a ring, we can generalize the results found in (3.1) for ring coverage and connectivity.

$$\frac{n_i}{\log(\frac{n_i}{\varepsilon})} \geq \frac{a_i^2 - a_{i-1}^2}{R^2} \; (i = 1, 2 ... h) \; , \tag{3.1}$$

The lifetime of a node is the sum of the time passed while it transmits its own packet and the time passed while it relays the packets generated by other nodes. We use the partitioning shown in Figure 2.3 in order to calculate the average energy expenditure of a node in Ring i. As seen in Figure 2.3, h is the total number of the rings. The number of sensor nodes which lie outside Ring i is:

$$\sum_{j=i+1}^{h} n_j \tag{3.2}$$

If we denote the average number of packets that a typical node in Ring i has to relay in a data collection period by s_i, then we obtain:

$$s_i = \frac{\sum_{j=i+1}^{h} n_j}{n_i} \tag{3.3}$$

In addition to relaying these s_i packets, the node also has to transmit its own packet. The total average energy spent during one periodic data gathering cycle is equal to:

$$P_i = l\left[(v + \mu R^k) + (2v + \mu R^k)s_i\right] \tag{3.4}$$

The lifetime T_i of a node in Ring i is equal to the time when the energy spent is equal to the total energy of that node, E_i.

$$T_i = \frac{E_i}{P_i} \tag{3.5}$$

Therefore nodes have average lifetimes as follows:

$$T_i = \frac{E_i}{l\left[(v + \mu R^k) + (2v + \mu R^k)\left(\frac{\sum_{j=i+1}^{h} n_j}{n_i}\right)\right]} \quad (i = 1,\, 2 \ldots h\text{ - }1),$$

$$T_h = \frac{E_h}{l(v + \mu R^k)} \tag{3.6}$$

The average lifetime of nodes should be equal to each other in order that the energy of nodes is used most efficiently.

$$\frac{E_1}{l\left[(v+\mu R^k)+(2v+\mu R^k)\left(\frac{\sum\limits_{j=2}^{h} n_j}{n_1}\right)\right]} = \frac{E_2}{l\left[(v+\mu R^k)+(2v+\mu R^k)\left(\frac{\sum\limits_{j=3}^{h} n_j}{n_2}\right)\right]} \cdots$$

$$= \frac{E_h}{l(v+\mu R^k)} = T \tag{3.7}$$

We would like to determine the number of nodes and battery capacities for a given h different type of nodes required to monitor a circular area, with a radius a_h, for the maximum attainable lifetime, where the total cost of the wireless sensor nodes remains within a given budget B. Hence, we may formulate the problem as follows:

Problem P_1:

Maximize $T = \min\ (T_i)\ (i = 1, 2 \ldots h,)$

subject to

$$\frac{n_i}{\log(\frac{n_i}{\varepsilon})} \geq \frac{a_i^2 - a_{i-1}^2}{R^2}\ (i = 1, 2 \ldots h) \tag{3.8}$$

$$\frac{E_1}{l\left[(v+\mu R^k)+(2v+\mu R^k)\left(\frac{\sum\limits_{j=2}^{h} n_j}{n_1}\right)\right]} = \frac{E_2}{l\left[(v+\mu R^k)+(2v+\mu R^k)\left(\frac{\sum\limits_{j=3}^{h} n_j}{n_2}\right)\right]} \cdots$$

$$= \frac{E_h}{l(v+\mu R^k)} = T \tag{3.9}$$

$$B \geq C = \sum_{i=1}^{h} n_i(\alpha + \beta E_i) \tag{3.10}$$

In this problem formulation, Inequality (3.8) checks for the communication and coverage requirements. The equalities in (3.9) ensure that each node in the network has the same lifetime and no residual energy is left in the network after the end of the network lifetime. Lastly, Equation (3.10) checks if the total cost of the sensor nodes is within the available budget.

3.1.3. Maximum Lifetime Solution

In order to use equal energy capacity nodes in a ring, energy consumption of these nodes must be close to each other. If the ring thicknesses are chosen to be equal to the communication radius R, the nodes in a ring are in at most one hop neighborhood of each other, and their loads are virtually equal. In this case the ring radii are multiples of $R; a_i = iR$. Therefore, the minimum number of nodes in each ring is:

$$\begin{aligned} \frac{n_i}{\log(\frac{n_i}{\varepsilon})} &\geq \frac{i^2R^2 - (i-1)^2R^2}{R^2} \\ &\geq 2i - 1 \ (i = 1, 2 ... h) \end{aligned} \tag{3.11}$$

If we put the minimum number of nodes found with Inequality (3.11) in Equation (3.9), only unknowns become the energies in each ring. If we write the energies in terms of T and insert in Inequality (3.10), we may get T; which then could be used to obtain the energy requirement in each ring.

3.1.4. Demonstrative Example

We apply the obtained solution to a sample case and present the results in this section. The communication model parameters and the packet length are the same as the ones used in simulations in [60]. The common parameters are in Table 3.1.

First, we cover a circular shaped area with 500 m radius; therefore there exists five rings with 100 m thickness. After the calculations, the number of nodes and the battery capacities of nodes in each ring are found as shown in Table 3.2.

As seen in Table 3.2, the required energy capacity for the nodes in the first ring is 34.26 kJ as compared to 0.87 kJ capacity needed in the outmost ring. This is due to the aforementioned high energy burden on the nodes in the first ring. Moreover, energy capacity requirement in other rings drops considerably starting from the second ring as we see in Figure 3.1.

Table 3.1. Common system parameters

Symbol	Parameter Name	Value
R	communication radius	100 m
l	packet length	525 bytes = 4200 bits
v	energy to run the radio electronics	50 nJ / bit
μ	energy to run the power amplifier	0.0013 pJ / bit / m^4
k	path loss exponent	4
α	cost of hardware	70 units
β	unit battery cost	1 unit / kJ
ε	connectivity bound	0.01
B	total budget	16000 units

Table 3.2. Number of nodes and battery capacities

Ring No	Number of Node	Capacity of Nodes(kJ)	Number and Type of Battery
1	7	34.26	2 AA
2	24	9.49	2 N
3	42	4.68	2 CR2032
4	62	2.33	1 CR2032
5	81	0.87	1 CR2016

The calculated lifetime of the network for this deployment case is about 1.16 million cycles. With the same total cost of 16000 units, we afford to have 4.07 kJ capacity nodes if homogeneous capacity nodes are used throughout the whole network. Such a homogenous network has an average lifetime of 158500 cycles. In this case using a heterogeneous network with concentric ring approach provides more than 6 times longer system lifetime. This ratio is independent of α and β.

The same average lifetime of 1.16 million cycles is possible for a homogenous network, if all nodes in the network are equipped with the same capacity batteries as the nodes in the first ring of the heterogeneous network, which is 34.26 kJ. The cost of

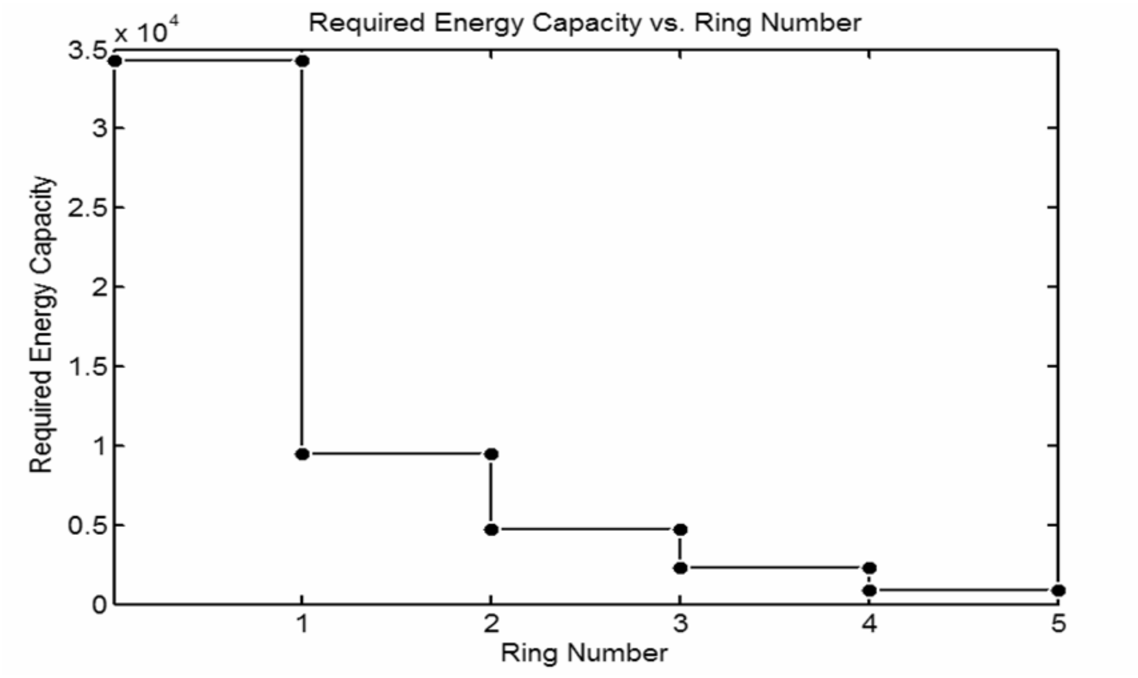

Figure 3.1. Energy capacity requirement in different rings

the network is then 22520 units, which means 40 per cent increase in the total network cost.

Table 3.2 also shows the suitable battery types, chosen from the list in [64], with capacities close to the calculated capacities. However, the batteries with calculated energy capacities might not be available or due to physical limitations it might not be possible to equip the nodes with such batteries. Especially due to the size limitations in wireless sensor network nodes, using heavy, voluminous batteries is impractical. Furthermore, as the size of the monitored area increases, the energy requirement of the nodes in the central rings becomes larger. As an example, in order to cover a circular area with radius 1000 m and using the same parameters as before, except for a budget of 75000 units, the necessary battery capacity for each ring is presented in Table 3.3.

At this point another version of this problem emerges: If there are a number of different discrete capacity nodes available to choose from, how can we decide on the number of nodes for each type, which leads to the maximum lifetime with the minimum cost.

Table 3.3. Battery capacities of nodes

Ring No	Battery Capacity (kJ)
1	188.78
2	54.43
3	30.16
4	19.38
5	13.68
6	9.68
7	6.80
8	4.56
9	2.69
10	1.10

3.2. Maximum Lifetime Heterogeneous Discrete Battery Capacity Solution

3.2.1. Introduction

Wireless sensor nodes impose restrictions on the energy resources to be used on them. Since wireless sensor nodes are envisioned to be cheap and small devices, it is more likely that battery dimensions and hence the battery capacities must be small in size. Taking into account that such batteries have some discrete capacities, we should find the combination of battery capacities chosen from a set of distinct capacity types, which produces the maximum lifetime with the minimum cost.

We solve this problem on the similar lines to the previous solution. We deploy sensor nodes in concentric ring shape areas as before and decide on the number of each type of nodes we use.

3.2.2. Network Lifetime Optimization with Discrete Battery Capacities

We can use Inequality 3.1 in order to find the minimum number of nodes required for coverage and connection. The minimum number of total nodes, n_h, to cover the whole area, which has a radius a_h, can be found using the following inequality

$$\frac{n_h}{\log(\frac{n_h}{\varepsilon})} \geq \frac{a_h^2}{R^2} \tag{3.12}$$

Inside each ring, the innermost sensor nodes bear the highest load. As a result, these critical nodes exhaust their batteries earlier than the other nodes in the ring. Therefore, the lifetime of these critical nodes affects the network lifetime. In order to determine the lifetime of these critical nodes, we assume that critical nodes are located in the innermost sub-ring with thickness R. Accordingly; we calculate the number of critical nodes in each ring nc_i as follows:

$$\begin{aligned} \frac{nc_i}{\log(\frac{nc_i}{\varepsilon})} &\geq \frac{(a_{i-1}+R)^2 - a_{i-1}^2}{R^2} \\ &\geq 1 + \frac{2a_{i-1}}{R}(i = 1, 2...h) \end{aligned} \tag{3.13}$$

The minimum number of nodes, n_i, required to satisfy coverage and connection in each ring can be found with Inequality 3.1.

The number of packets that a critical node in Ring i has to relay in a data collection period (s_i) is calculated as follows:

$$s_i = \frac{n_h - \sum\limits_{j=1}^{i-1} n_j}{nc_i} \tag{3.14}$$

The total average energy spent by a critical node in Ring i during one periodic data gathering cycle (P_i) can be found using Equation (3.4). Moreover, the lifetime T_i of a critical node in Ring i is calculated using Equation (3.5). Consequently, the

Table 3.4. Discrete battery capacities

Ring No	Battery Capacity (kJ)	Number and Type of Battery
1	31.32	2 AA
2	12.96	2 AAA
3	6.75	2 AAAA

lifetime equation for each ring is as follows ($n_0 = 0$):

$$T_i = \frac{E_i}{l\left[(v+\mu R^k)+(2v+\mu R^k)\left(\frac{n_h-\sum_{j=1}^{i-1} n_j}{nc_i}\right)\right]}, (\ i = 1, 2 \ldots h) \tag{3.15}$$

In order to obtain the maximum lifetime with the minimum cost, we should equate the lifetimes of these critical nodes to each other. Using these equations, we determine the inner radii of each ring, a_i.

3.2.3. Demonstrative Example

We apply the formulation to a sample case and present the result. We cover an area 500 m in radius using three different battery capacity sensor node types. We use common systems parameters introduced in Table 3.1. Furthermore discrete battery capacities, chosen from the table in [64] are listed in Table 3.4.

After the necessary calculations, deployment parameters shown in Table 3.5 are obtained.

Using the discrete battery capacity node types in Table 3.3, the minimum cost - maximum lifetime solution yields 0.87 million cycles of lifetime with 19772 units of cost. If we compare these results to the previously obtained results in Section 3.1.4, we conclude that discrete battery capacity usage results in suboptimal network lifetimes. This is due to the fact that, we provide larger energy capacities than needed for the

Table 3.5. Deployment parameters

Ring No	Inner Radius (m)	Number of Nodes
1	0	7
2	65	17
3	145	230

nodes when the ring sizes increase. As a consequence, we waste certain amount of money, which could otherwise be used in increasing the network lifetime by deploying some extra nodes as we mention in the following sections.

3.2.4. Partial Conclusions

Efficient distribution of the total energy sources in a wireless sensor network increases the lifetime of the network. Energy consumption among nodes in a wireless sensor network is not balanced; hence, providing a homogeneous battery capacity to all nodes results in early deaths among heavily loaded nodes closer to the sink, which designate the end of the network lifetime. Consequently, a large amount of energy left in other nodes is wasted. We showed that, using concentric ring deployment strategy and assigning energy capacities to meet the energy consumptions results in a very significant increase in the network lifetime.

3.3. Maximum Lifetime Nonuniform Node Density Solution

3.3.1. Introduction

Considering the limited battery capacities of sensor nodes, wireless sensor networks can be deployed with a large number of sensors in order to use redundancy to increase system reliability and network lifetime. We propose that, the node densities of each region in a dense network can be arranged such that, the number of nodes in each region turn out to be proportional to the energy drainage in each region. Such an arrangement in node distribution, results in an efficient distribution of resources, which remedies the subdued network lifetime caused by uneven life spans encountered in different regions of the network.

Since the relaying load increases with decreasing distance to the sink, in order to balance the energy consumption rate, the population should also be higher with decreasing distance to the sink with this deployment. Note that, we increase the density not for data collection purposes, but for data relaying purposes. That is, in order to capture the concerned event in the area, a minimum number of nodes are necessary but not more. We assume that, the extra nodes have a duty of just relaying the data from outer nodes and they do not generate data unnecessarily.

3.3.2. Network Lifetime Optimization with Variable Node Densities

We use single battery capacity node in this deployment scheme. The total cost of single type of sensor nodes with capacity E is as follows:

$$C = \sum_{i=1}^{h} n_i(\alpha + \beta E) \tag{3.16}$$

We assume that, the number of statistics generated in an area during a period of time is proportional to the area size. Therefore, the number of necessary nodes to collect these statistics should be proportional to the area size. In the concentric ring approach, if each ring thickness is chosen equally as R, the area covered by i^{th} ring becomes $2i$-1 times the area of the first ring, so is the generated packet amounts. An ideal sensor node allocation scheme should be designed such that all the energy units are utilized equally resulting in reduced wastage due to residual energies.

Next, we derive a node allocation scheme which equalizes the individual disconnection times T_i. Let g be the number of data packets generated in the first ring. Then, the number of data packets generated in Ring i is ($2i$-1)g. The nodes in Ring i have to transmit both the packets generated in Ring i and also the packets generated in

Rings from $i+1$ to h. Therefore necessary number of nodes in each ring is calculated as follows:

$$n_i = \sum_{j=i}^{h} (2j-1)g \tag{3.17}$$

Moreover, we should consider coverage and connection criteria in each ring. Since we increase the node densities starting from the outermost ring, Ring h, if the number of nodes in Ring h satisfies the coverage and connection conditions, we ensure that others also do readily. Therefore, the minimum number of nodes in Ring h, n_h, can be calculated using the following inequality:

$$\begin{aligned} \frac{n_h}{\log(\frac{n_h}{\varepsilon})} &\geq \frac{a_h^2 - a_{h-1}^2}{R^2} \\ &\geq\ 2h-1 \end{aligned} \tag{3.18}$$

Relay nodes bear heavier loads, since they have to both receive and transmit packets of the other nodes; on the other hand, sensing nodes just transmit their packets. Therefore, relay nodes deplete their batteries earlier than sensing nodes. Accordingly, the lifetime equation for each ring is equal to the lifetime of a relay node:

$$T_i = \frac{E}{l(2v+\mu R^k)}, (\ i = 1,\ 2 \ldots h) \tag{3.19}$$

We distribute the wireless sensor nodes with nonuniform node densities in order to proportionally distribute the overall load on the wireless sensor nodes equally. We deploy the nodes in concentric rings with thickness R. Besides, we use single type of sensor nodes with battery capacities given as E. We should determine the number of nodes in each ring in order to obtain the maximum attainable lifetime with nonuniform node densities. Based on this; we may formulate the problem as follows:

Problem P_2:

Maximize $T = \min\ (T_i)\ (i = 1, 2...h,)$

subject to

$$n_i = \sum_{j=i}^{h} (2j - 1)g \tag{3.20}$$

$$\frac{n_h}{\log(\frac{n_h}{\varepsilon})} \geq 2h - 1\ (i = 1, 2...h) \tag{3.21}$$

$$T_i = \frac{E}{l(2v + \mu R^k)}, (\ i = 1,\ 2 \ldots h) \tag{3.22}$$

In this problem formulation, Inequality (3.20) checks for the necessary node numbers in each ring to satisfy the maximum lifetime density distribution. The Inequality (3.21) imposes coverage and connectivity conditions on minimum number of nodes in Ring h. Equality (3.22) ensures that each node in the network has the same lifetime and no residual energy is left in the network after the end of the network lifetime.

3.3.3. Maximum Lifetime Solution

If we put the minimum number of nodes for $n_h$found with Inequality (3.21) into Equation (3.20) we obtain g. Furthermore, total number of nodes in the network (n_{tot}) is found by summing the node numbers given by Equation (3.20) as follows:

$$\begin{aligned} n_{tot} &= \sum_{i=1}^{h} n_i \\ &= \sum_{i=1}^{h} \sum_{j=i}^{h} (2j - 1)g \\ &= \frac{h(h + 1)(4h - 1)}{6} g \end{aligned} \tag{3.23}$$

Substituting E in Equation (3.22) we find the network lifetime. Furthermore, putting total number of nodes in Equality (2.7), we find the total cost of the nodes.

3.3.4. Demonstrative Example

We apply the obtained solution to a sample case and present the results in this section. We use the same common parameters as in Table 3.1. We cover a circular shaped area with 500 m radius; therefore there exists five rings with 100 m thickness. Moreover we use 0.87 kJ battery capacity nodes, which is the same capacity nodes used in Ring five in Section 3.1.3. The number of nodes in each ring is calculated as shown in Table 3.6.

The total cost of the solution is 62720 units. On the other hand, the network lifetime is 0.9 million cycles. Compared to heterogeneous battery capacity solution, we obtain shorter lifetime with higher total cost. This is due to the fact that we use sensor nodes mostly for relaying purposes and we do not make use of them in sensing operations. Furthermore, in addition to the battery cost in the heterogeneous battery capacity solution, there is also cost of extra sensor nodes in this solution.

If the same total number of nodes is deployed with homogeneous density the network lifetime drops to 36126 cycles. This shows that nonuniform node density solution is a better choice for dense wireless sensor networks.

As seen in Table 3.6, very high number of nodes in small area rings causes significant interference. We use topology control in order to eliminate this ill-behavior in the next section.

3.4. Nonuniform Node Density Solution with Topology Control

3.4.1. Introduction

Nonuniform node density solution discussed in Section 3.3 creates a congestion problem, because as the distance to the sink decreases, required node densities increase. As a result of close interaction, interference problems arise. Moreover, for coverage purposes, it is unnecessary that all the deployed nodes operate in active mode at the

Table 3.6. Number of nodes for nonuniform density solution

Ring No	Number of Nodes
1	225
2	216
3	189
4	144
5	81

same time. The redundancy could be exploited for the creation of a periodic active node selection scheme.

We use topology control in order to control the number of active nodes. Topology control algorithms introduced in our literature survey section could be used for choosing the coverage preserving active node sets. Topology control algorithms find a connected coverage set of wireless sensor nodes and the number of active nodes in this set is tried to be minimized in order to obtain a cost effective solution. Just before an active node set deplete their batteries, all nodes wake up and run the topology control algorithm. As a result, new set of nodes are selected according to such algorithms and become active. This periodic active sensor node set selection scheme runs until the number of living node is not sufficient to form a connected coverage set anymore.

With such deployment strategy, the full capacity of the network could be utilized and this efficiency in energy usage results in considerable lifetime increase. Furthermore, the energy overhead of running the topology control algorithm is reported to be as low as one per cent in [46].

3.4.2. Network Lifetime Optimization Problem with Variable Node Densities

We deploy nodes in concentric ring regions with varying densities. In each ring, at any moment, only the minimum number of nodes required to cover the ring area is active. The minimum number of nodes to cover a ring is found with Equation (3.1).

The time period starting when a node becomes active and ending when it depletes its battery, constitutes its lifetime. Small extra time which passes during the short course of algorithm run is negligible. The connectivity and coverage in the network is destroyed when not enough nodes exists to reconstruct a covering set. The network lifetime is then, the compound lifespan of sets which became active before the sensor network failure.

Therefore, we can write the lifetime equation as the multiplication of number of active sets in Ring i (c_i), with the average node lifetime in Ring i. We use the same capacity (E) batteries in all nodes. Then, the cumulative lifetime of the nodes in Ring i is:

$$T_i = \frac{c_i E}{l\left[(v+\mu R^k) + (2v+\mu R^k)\left(\frac{\sum_{j=2}^{h} n_j}{n_i}\right)\right]}, (\ i = 1,\ 2 \ldots h\text{ - }1), \text{ and } T_h = \frac{E}{l(v+\mu R^k)} \tag{3.24}$$

The cumulative lifespan of all the active node sets should be equal to each other on average, in order that no sensor node energy is wasted. Therefore, we can write the following equality:

$$\frac{c_1 E}{l\left[(v+\mu R^k) + (2v+\mu R^k)\left(\frac{\sum_{j=2}^{h} n_j}{n_1}\right)\right]} = \frac{c_2 E}{l\left[(v+\mu R^k) + (2v+\mu R^k)\left(\frac{\sum_{j=3}^{h} n_j}{n_2}\right)\right]} \cdots$$
$$= \frac{E}{l(v+\mu R^k)} = T \tag{3.25}$$

We should determine the distribution of number of nodes in each ring, which results in the maximum attainable lifetime. We may formulate our problem as follows:

Problem P_3:

Maximize $T = \min\,(T_i)\ (i = 1, 2...h,)$

subject to

$$\frac{n_i}{\log(\frac{n_i}{\varepsilon})} \geq \frac{a_i^2 - a_{i-1}^2}{R^2}\ (i = 1, 2...h)\ , \tag{3.26}$$

$$\frac{c_1 E}{l\left[(v + \mu R^k) + (2v + \mu R^k)\left(\frac{\sum_{j=2}^{h} n_j}{n_1}\right)\right]} = \frac{c_2 E}{l\left[(v + \mu R^k) + (2v + \mu R^k)\left(\frac{\sum_{j=3}^{h} n_j}{n_2}\right)\right]} \cdots$$

$$= \frac{E}{l(v + \mu R^k)} = T \tag{3.27}$$

In this problem formulation, Inequality (3.26) checks that only the minimum number of nodes necessary for coverage is active at any time. The equalities in (3.27) mandates that no useless nodes exists in the network and lifetime of the network is equal to the maximum lifetime of the network, which cannot be any longer than the lifetime of nodes in the outmost ring.

3.4.3. Maximum Lifetime Solution

The nodes in each ring should have a distance to each other such that their loads are virtually the same. Therefore we choose ring thickness as the value of communication radius, R. In this case the minimum number of active nodes in each ring is:

$$\frac{n_i}{\log(\frac{n_i}{\varepsilon})} \geq \frac{i^2 R^2 - (i-1)^2 R^2}{R^2}$$
$$\geq 2i - 1\ (i = 1, 2...h) \tag{3.28}$$

If we put the minimum number of nodes found with Inequality (3.28) in Equation (3.27), only unknowns which are the number of sets of active nodes in each ring (c_i)

Table 3.7. Number of nodes and battery capacities

Ring No	Number of Nodes	Number of Active Sets
1	294	42
2	288	12
3	252	6
4	186	3
5	81	1

can be solved easily.

3.4.4. Demonstrative Example

We apply the obtained solution to a sample case and present the results in this section. The communication model parameters and the packet length are the same as the ones used in simulations in [60]. The common parameters are in Table 3.1.

We cover a circular shaped area with 500 m radius; therefore there exists five rings with 100 m thickness. We use 0.87 kJ capacity batteries in this case. The number of nodes and the number of active sets in each ring is calculated as shown in Table 3.7.

As can be seen from Figure 3.2, node density variation matches the relaying load for each ring. Moreover, note that Figure 3.1 and Figure 3.2 show similar trends through rings.

The calculated lifetime of the network is 1.16 million cycles in this case. Total cost of the network is 78000 units. With the same number of total nodes deployed uniformly, the network lifetime would be 0.17 million cycles. Nonuniform deployment offers a hundred fold increase in the network lifetime compared to uniform deployment.

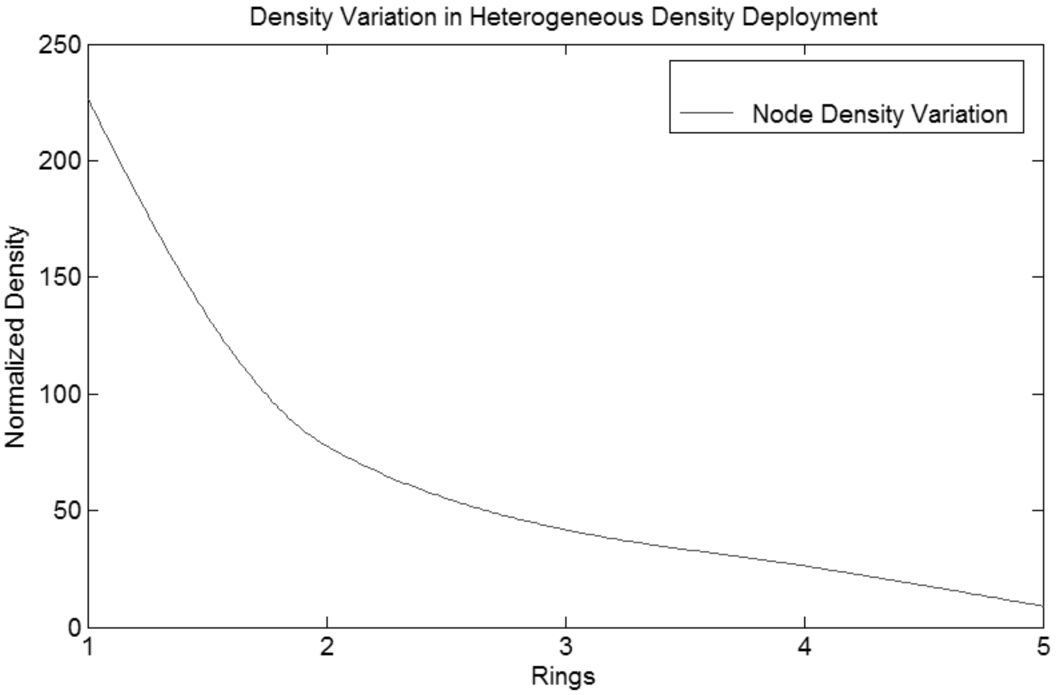

Figure 3.2. The node density variation with heterogeneous density deployment

Compared to the results in Section 3.3, we see that the topology control is much more efficient. As a result of using sensor nodes both for data capturing and transmission, the lifetime of the network slightly increases, compared to the nonuniform density scheme without topology control. Furthermore data interference problem is solved with topology control.

3.5. Partial Conclusions

Wireless sensor networks suffer from unbalanced load distribution in the network. As a result of this fact, if sensor nodes are deployed homogeneously, nodes closer to the sink tend to become extinct in early phases of the network operation. Moreover, they limit the network lifetime by breaking connectivity. We have shown that non-uniformly assigning different node densities to each concentric ring alleviates the problem and lead to a substantial improvement in the network lifetime. For dense networks, uniform deployment is not even an option compared to nonuniform deployment case.

Compared to the nonuniform deployment solution proposed for densely deployed sensor networks, heterogeneous battery capacity solution offers the same network lifetimes with less network costs. This efficiency is mainly due to the fact that, heterogeneous battery capacity solution doesn't lead to any increase in the total sensor hardware costs, as opposed to the nonuniform deployment solution. We only need to increase the total battery capacities in each region, in order to balance the energy consumptions throughout the network. However, with nonuniform deployment solution, we also increase the number of nodes in each region which results in extra hardware cost. The difference between the total costs of these two solutions is the hardware costs of the extra relay nodes in the densely deployed network. With even a small portion of the extra hardware cost added in nonuniform deployment solution, heterogeneous battery capacity solution achieves a big improvement in the network lifetime.

4. PERFORMANCE EVALUATION

4.1. Introduction

We simulated the proposed deployment schemes on OPNET Modeler network simulator. In our experiments we observed how the performance of the deployment schemes varies. We have evaluated the performance of each scheme based on the network lifetime of the network. This chapter presents the performance evaluation modeling details, as well as the comparison of obtained performance metrics for different deployment schemes.

4.2. Modeling Environment and Modeling Details

The proposed system was modeled and simulated on OPNET Modeler using the wireless module. For simplicity, we assume a perfect MAC layer; therefore, only energy consumption is due to packet transmissions and no packet retransmission occurs for packet collisions. We use a minimum cost forwarding protocol similar to the one introduced in [65]. This routing scheme finds the minimum transmission cost path from each node to the sink. Since transmission energy depends on transmission distance primarily, this routing scheme is similar to shortest path routing. The protocol is composed of two phases.

When the initial setup phase starts, the sink node broadcasts packets with incrementally increasing transmission powers starting from the minimum transmission power up to the maximum transmission power. For each transmitted packet, the sink node calculates the packet path cost as the sum of its own path cost, which is zero, plus the calculated energy loss due to the transmission of the packet. Upon receiving a packet, a node checks if the transmission power value in the packet is greater than the calculated transmission energy required to send this packet to the sink, which means that the source is in a distance that the receiver node can hear. If it is, the packet path cost is compared to the current next hop node cost, which has an initial value of infinity. If the cost path in the packet is smaller than the current next hop node cost, receiver node modifies its current next hop node cost with the cost value in the packet and its next hop node with the source of the packet. Moreover, it starts broadcasting packets with increasing transmission powers as the sink node did and this process is diffused. At the end of the phase, each node knows its next hop node towards the sink.

In the second phase, nodes simulate periodical data transmissions. When a node transmits a packet to its next hop node, it indicates its next hop node as the intended destination in the packets it transmits. Then, the receiving nodes check if they are the intended receiver and relay or discard the packet accordingly. After a packet transmission, nodes update their energy reserves according to the energy model, we introduced. If at a moments, the energy of a node drops to zero; the node is assumed to be dead and stops forwarding packets. Therefore, the nodes, for which this node is their next hope, disconnect. At this point no further routing update take place. The lifetime of the network is taken as the time when the network becomes completely disconnected.

4.2.1. Network Topology

Monitored area in our experiments is a circular area with 500 m in radius. We deploy the sensor nodes in concentric ring areas. The communication radius is 100 m; therefore, there are five rings in this deployment scenario. We place the sensor nodes uniformly in these rings. After calculating the necessary number of nodes to cover each ring, using the formulation given in Chapter 4, we obtain the following node numbers given in Table 4.1.

After we calculated the coordinates of each sensor node relative to the sink node, we placed these sensor nodes in the respective rings and run the routing algorithm. Then, we obtained the following topology and routing graph given in Figure 4.2.

Note that due to the nature of the routing algorithm, the relaying load for nodes in the same ring is not equal to each other. That is, seven nodes in the first ring have

Table 4.1. The minimum number of nodes for each

Ring No	Number of Nodes
1	7
2	24
3	42
4	62
5	81

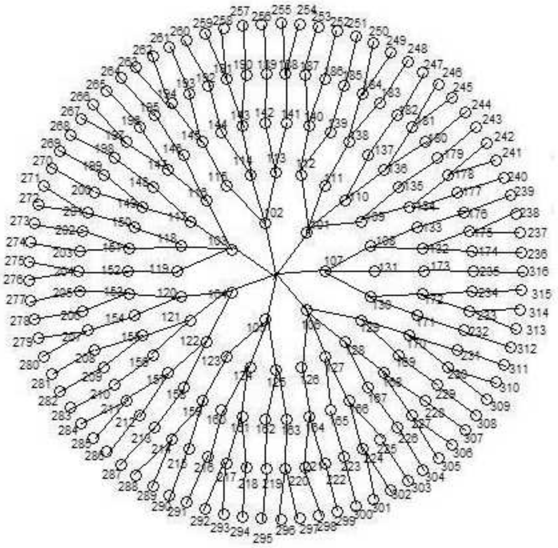

Figure 4.1. Network topology and routing graph

to share the loads of 24 nodes in the second ring. Since the next hope node for each node is determined when the routing algorithm runs and it doesn't change dynamically, some nodes bears three nodes' load from the second ring and some other bears four nodes' load. As a result of this, although the heterogeneous battery capacity solution allocates battery capacities in order to attain a global death for every node, still there are slight variations between the lifetime of nodes in a ring.

Table 4.2. Battery capacities of nodes

Ring No	Battery Capacity (J)
1	10.57
2	3.37
3	1.75
4	0.87
5	0.28

4.2.2. System Parameters

We use the common system parameters given in Table 3.1, but differing from the system parameters in Table 3.1, path loss exponent is taken as two and energy to run the power amplifier, μ is taken as 10 pJ / bit / m^2in our simulations. Doing this we idealized the channel characteristics and surrounding environment. Moreover, due to the time considerations, the nodes in each ring are assigned small initial energies as shown in Table 4.2.

4.2.3. Homogeneous Battery Capacity Case

For this experiment, we assigned each node in the network homogeneously 10.57 J battery capacities, the same energy as a node in the first ring in the heterogeneous case. Due to the high relaying load, sensor nodes in the first ring consume their battery capacities much earlier than the others. As we show in Figure 4.2, when the nodes in the first ring consumed their energy at the end of 60 simulation hours, the nodes in other rings maintain most of their initial energy reserves. But since the nodes in the first ring no longer forwards the packets, the network becomes disconnected very early. Since replacing the batteries of the nodes is impractical most of the time in wireless sensor networks, this excess energy in a large number of nodes becomes wasted.

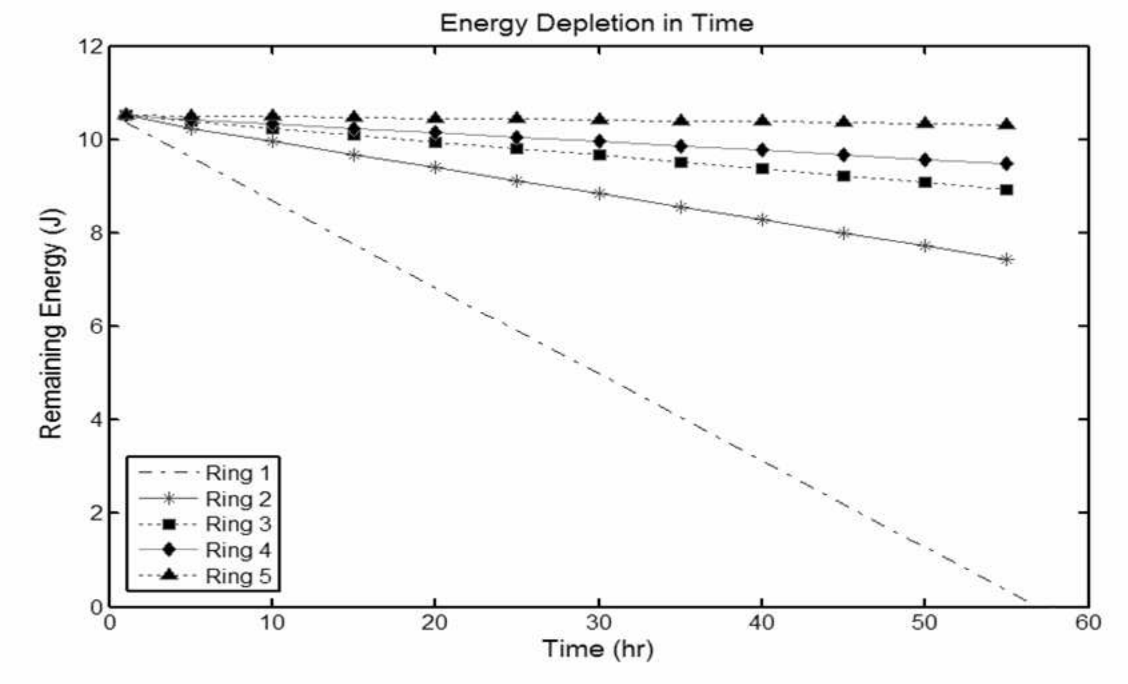

Figure 4.2. In homogenous case when the energy of the nodes in the first ring end, other nodes keep most of their initial energies

In order to alleviate this ill behavior, we deploy the sensor nodes with heterogeneous battery capacities in the next section.

In the second case, the battery capacities shown in Table 4.2 are used and the network is simulated. The same network lifetime of 60 simulation hours as the previous case is achieved. Since the battery capacities are proportional to the forwarding load for each ring in this case, when the nodes in the first ring disappear, the other nodes also use up their battery capacities. Moreover as seen in Figure 4.3, since the nodes in each ring consume their energies at about the same time, no energy is wasted in the network.

4.2.4. Heterogeneous Battery Capacity Case

This saving in energy is equal to about 40 per cent costs saving as stated in the sample results. With the same cost as the heterogeneous case the nodes might be assigned a battery power of 1.37 J homogeneously. The simulated lifetime for this

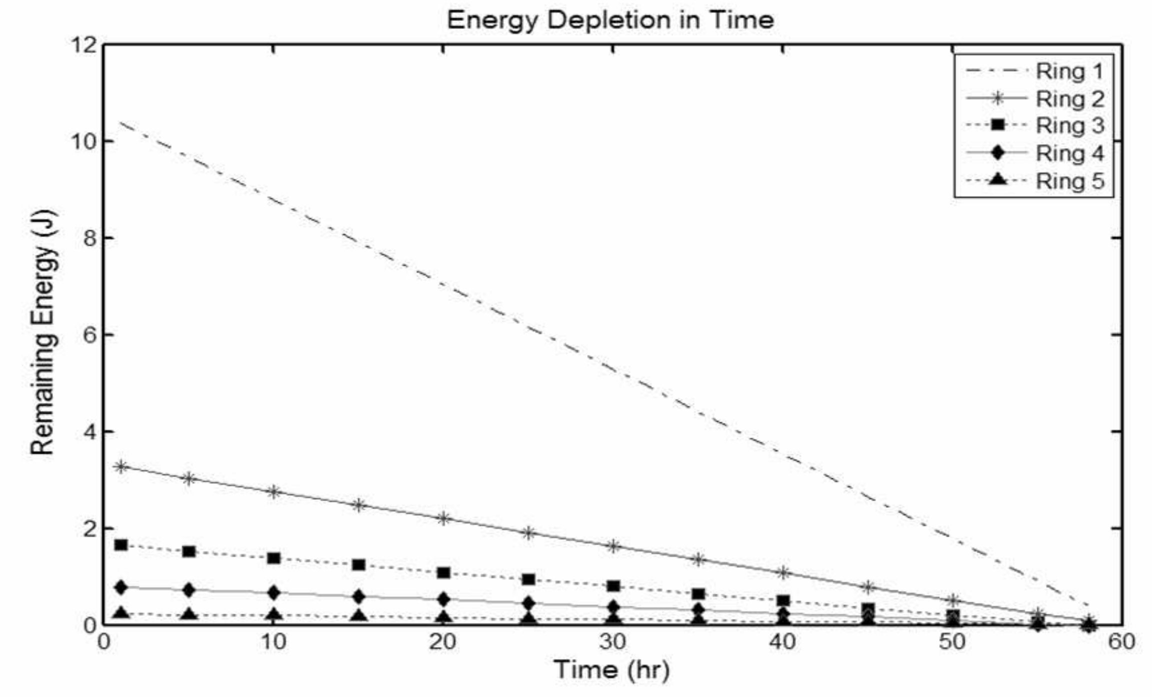

Figure 4.3. Using heterogeneous energy capacity, the nodes in each ring complete their useful lifetimes almost at the same time

case is about seven hours. In this case, our strategy provides about seven times longer system lifetime compared to the homogeneous case using the same budget.

The total network resources are mostly wasted in homogenous wireless sensor networks. Figure 4.4 depicts the variation in the total network energy in time for homogeneous and heterogeneous network cases. This figure emphasizes the necessity to use heterogeneous deployment schemes.

Figure 4.5 shows the lifetime variations across different total network energy reserves. In the heterogeneous network, total energy is shared between nodes in a way that, it is used most economically. As a result, as seen in Figure 4.5, with the same total network energy, the heterogeneous capacity network outperforms the homogeneous capacity network.

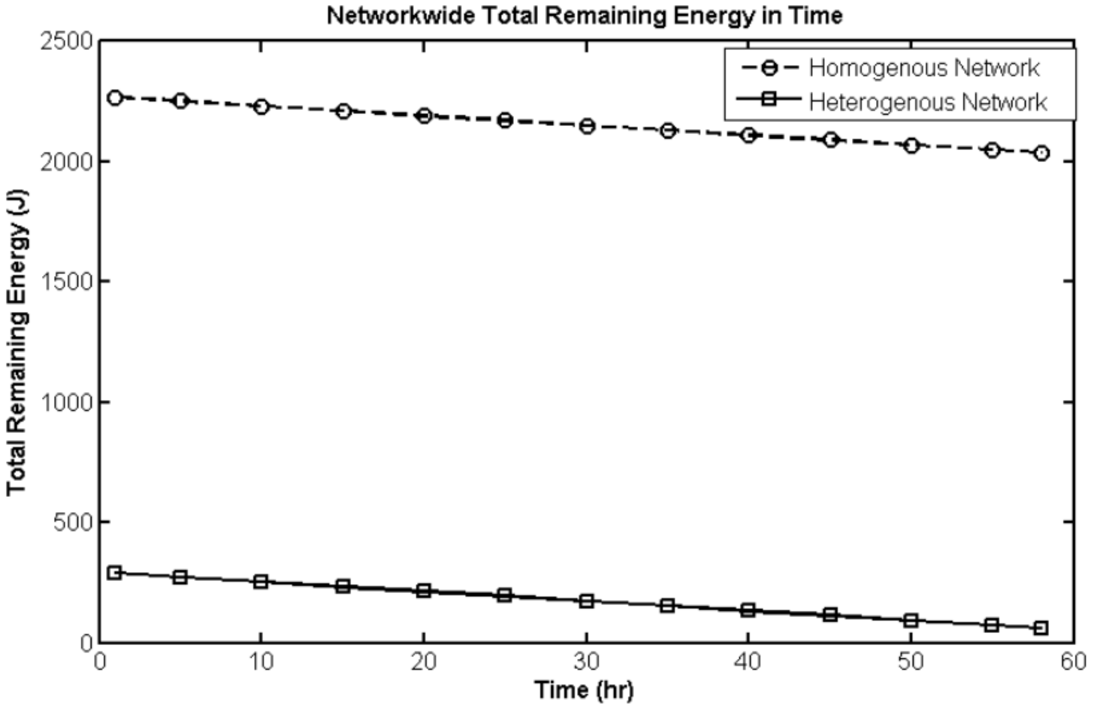

Figure 4.4. Total network resources are used efficiently in heterogeneous wireless sensor network compared to homogeneous wireless sensor network

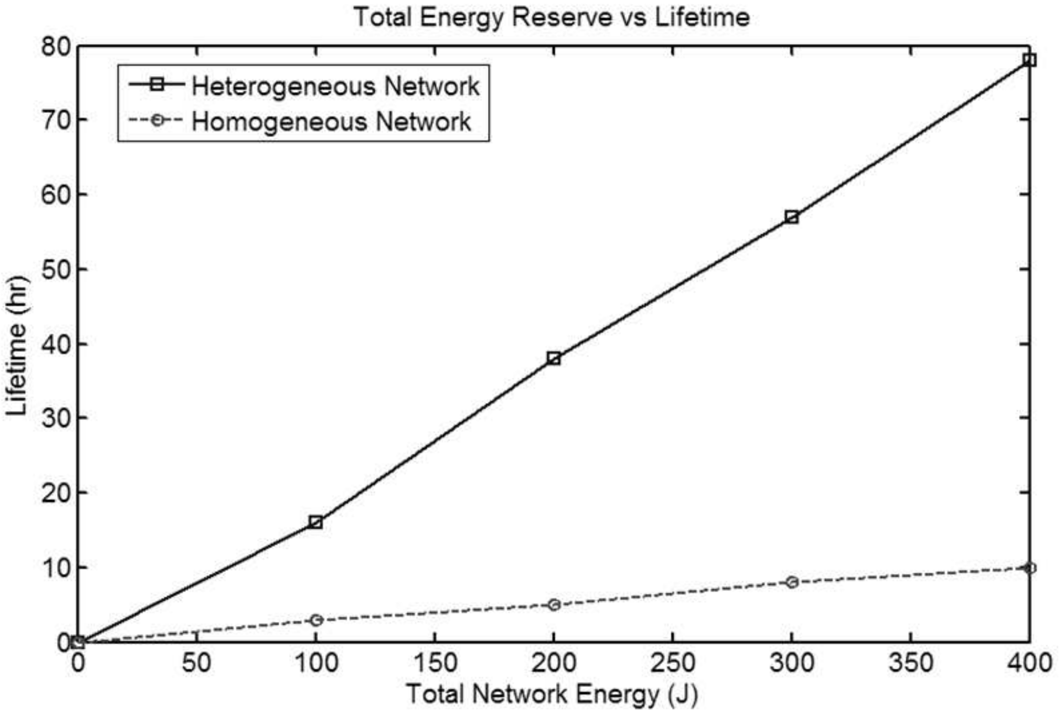

Figure 4.5. Since total energy reserve is used efficiently in the heterogeneous network case, much longer system lifetimes are possible compared to the homogeneous case

4.2.5. Dependency on the Monitored Area Size

As the monitored area size increase, the number of rings also increases. As a result, difference between the necessary battery capacities in the innermost ring and the outermost ring grows. The capacity requirement of inner rings might be so high that, it may not be possible to equip these nodes with such heavy and expensive batteries.

4.2.6. Dependency on Node Density

In this section, we study the effect of increasing the density of the network (while keeping the network size constant) on the lifetime of the network. We expect the density to have no influence on the network lifetime as long as it remains uniform. The reason behind this prediction is that as long as the density is uniform, the number of nodes in each ring will increase in the same rate, and hence, the forwarding load of each node does not change.

5. CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

The most important performance criterion of wireless sensor networks is the network lifetime, since wireless sensor networks are required to operate for the maximum time with their available battery power budgets. Due to the limited battery capacities of sensor nodes, energy efficient network design has utmost importance. Homogeneous wireless sensor network deployments have inefficiencies in the distribution of system resources. Many-to-one connection characteristic of the wireless sensor networks causes an unbalanced relaying load distribution among the sensor nodes. Accordingly, the energy consumption rates are also unbalanced.

Homogeneous allocation of system resources creates an unfair treatment to the nodes which are closer to the sink and hence, they consume their battery powers earlier than the other nodes. As they disappear, not only uncovered regions form, but also the number of disconnected nodes grows rapidly with the loss of these nodes. This defines the early end of lifetime for the network. The remaining big portion of network resources is simply wasted. The waste of network resources results in increase in total costs and decrease in network lifetime. In order to alleviate this ill-behavior, we studied the heterogeneous deployment solutions in this work.

Heterogeneous wireless sensor network deployment strategies, which we propose allocate network resources proportional to the relaying load of nodes in each region. Consequently, the energy consumption rate of nodes in different portions of the network balances. The created balance in energy consumption rates leads to an almost simultaneous deaths throughout the network. Therefore, near full capacity of the network could be utilized. The reward is, six to seven folds increase in the network lifetime. We evaluated two efficient heterogeneous deployment strategies in this thesis.

In order to analyze the heterogeneous deployment strategies, we assume that nodes are deployed in concentric ring areas. Therefore, nodes in each ring bear the same relaying load and should have the same battery capacities or node densities. We require that nodes in each ring should have almost the same lifetime in order to use the network resources the most efficiently.

Using heterogeneous battery capacity nodes, we showed that it is possible to use full capacity of the network. We showed that homogeneous battery capacity deployment causes a big amount of waste in terms of the total network energy. On the other hand, using heterogeneous battery capacity nodes, we can achieve the maximum lifetime of the network which is about six times longer than the same cost homogeneous battery capacity solution.

Furthermore, we showed that, with heterogeneous battery capacity solution, discrete battery capacity nodes could also be used. The network lifetime increases also for this case compared to the homogeneous battery capacity deployment. However, compared to the optimal solution obtained by calculating the battery capacities according to the available budget, discrete battery capacity usage offers a suboptimal network lifetime. This is due to the fact that, with discrete battery capacity usage, we create new sub-problems in the rings with thickness larger than the communication radius.

With densely deployed nodes, redundancy is exploited in order to increase performance. Similar to the heterogeneous battery capacity solution, our aim is balance the loads on each sensor node. With uniform density deployment, the regions close to the sink are bottleneck regions and cause an early network death. We increase the node density the distance to the sink decreases, since the relaying load increases in the same way. As the node density increase, tightly packed sensor nodes causes severe interference problems. In order to get rid of this unwanted behavior, topology control algorithms can be used. With topology control, only the necessary number of nodes to ensure the connectivity and coverage operate in active mode at any time. The excess nodes are operated in passive mode and after the deaths of active nodes, a new set of nodes are selected and form the active set using topology control algorithms. Using nonuniform densities for each region with densities matching up with the relaying load in that region, we showed that the maximum lifetime of the network can be accomplished. The nonuniform density deployment offers up to six times longer network lifetimes according to our analysis.

5.2. Future Works

Heterogeneous deployment schemes offer an efficient distribution of total energy sources in a wireless sensor network and results in a significant increase in the network lifetime. Heterogeneous battery capacity usage strategy and nonuniform density solutions can be considered jointly in order to obtain better performance and scalability. Moreover, proposed schemes can be used in addition to other power conservation schemes, like MAC layer power saving techniques and power aware routing algorithms proposed in the literature.

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