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Design of Three-Tiered Sensor Networks with a Mobile Data Collector under Energy and Buffer Constraints

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Design of Three-Tiered Sensor Networks with a Mobile Data Collector under Energy and Buffer Constraints

by

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Declaration of Co-Authorship / Previous Publication

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

This thesis also incorporates the outcome of a joint research undertaken in collaboration with Ataul Bari under the supervision of professor Dr. Arunita Jaekel. The collaboration is covered in Chapter 3 and Chapter 4 of the thesis. In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author, and the contribution of co-authors was primarily through the provision of some key ideas and constructive criticism.

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Thesis Chapter	Publication title/full citation	Publication status
Chapter 3 *Chapter 4*	***Bari, A., Teng, D. and Jaekel, A.*** *2009. Optimal Relay Node Placement in Hierarchical Sensor Networks with a Mobile Data Collector. The 2nd International Workshop on Sensor Networks. ICCCN 2009 Workshop on Sensor Networks. (SN 2009)*	*accepted for publication*

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Abstract

A sensor network consists of a network with a large number of sensor nodes deployed around some phenomenon to gather information. Since the nature of sensor nodes is that their energy is limited, many techniques focus on addressing the problem of minimizing the energy consumption in order to extend the network lifetime. One approach is to deploy relay nodes. However, the requirement to transmit over large distances leads to a high rate of energy dissipation. Therefore, mobile data collectors are introduced to resolve this problem.

In this thesis, we present an Integer Linear Programming formulation that takes different parameters into consideration to determine an optimal relay node placement scheme in the network with a mobile data collector, which ensures that there is no data loss and the energy dissipation does not exceed a specified level. The simulation results show that our formulation can significantly extend the network lifetime and provide Quality of Service.

Dedication

To my parents, Deli Teng and Guihua Yu

For their endless understanding, supporting, encouragement

and LOVE

…

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First of all, I would like to express my gratitude to my advisor, Dr. Arunita Jaekel, for her encouragement, support and invaluable suggestions, without which I will not complete this research work.

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List of Abbreviations

WSN: Wireless Sensor Network

SN: Sensor Node

BS: Base Station

RN: Relay Node

RNP: Relay Node Placement

MDC: Mobile Data Collector

MBS: Mobile Base Station

QoS: Quality of Service

ILP: Integer Linear Programming

Chapter 1

Introduction

1.1 Motivation of Study

A wireless sensor network (WSN) consists of a network with a large number of sensor nodes (SNs) deployed around some phenomenon. As a cost-efficient approach for collecting real time data, it has been widely employed in many monitoring-based applications such as gathering data regarding highway traffic, battle field reconnaissance, and habitat monitoring of endangered animal species.

Since the nature of sensor nodes is that their energy is limited, many techniques focus on addressing the problem of minimizing the energy consumption in order to extend the lifetime of a sensor network. One approach is to deploy relay nodes (RNs), which are used to relay data generated by other sensor nodes. However, the requirement to transmit data over large distances leads to a high rate of energy dissipation.

Mobile data collectors (MDC) can be used to resolve this problem. They are mobile elements, which could move in the designated area to gather data. MDCs download the buffered data from sensor or relay nodes when they are in their direct transmission range and then forward them to a wireless access point. For multi-hop communication, using MDCs in sparse WSNs can reduce the relaying overhead for nodes near the base station (BS). Moreover, the nodes in the sensor networks no longer need to form a connected network. Therefore, it plays a critical role in improving the performance of sparse WSNs by using MDCs.

In this thesis, we focus on the relay node placement problem in sensor networks with a MDC. Specifically, we investigate the problem of minimizing the number of relay nodes required to meet specified coverage and lifetime requirements.

1.2 Problem to Solve

We consider a hierarchical, three-tiered wireless sensor network. The lower tier contains a set S of n sensor nodes, which are randomly deployed in the sensing area to collect data for target mission. A subset of a set R of m *potential* locations of relay nodes will constitute the middle tier network. Each relay node of this subset would act as a cluster head to gather data from sensor nodes in their corresponding clusters and buffered the collected data. Then a mobile data collector, lying in the upper tier of the network, visits those cluster heads along a fixed trajectory, downloads the buffered data and transmits them to the base station. Such a model reduces the energy dissipation of the relay nodes by relieving them of the burden of transmitting data over longer distances, thereby increasing the overall lifetime of the networks.

In this thesis, we address issues as followings:

1. Minimizing number of relay nodes (cluster heads) and figuring out their positions to form the middle tier network, satisfying pre-specified buffer and lifetime constraints;

2. Assigning sensor nodes to the clusters to make sure the buffer and the lifetime constraints are satisfied.

1.3 Our Solution Approach

We assume that the positions of the sensor nodes are known beforehand and the relay nodes can be deployed at the locations determined by our placement strategy. The set of *R* of potential locations for the relay nodes is given as an input and is generated by using a grid based approach [17].

We assume that sensor nodes generate data at the fix rate and a relay node uploads its buffered data only when it is visited by the MDC so that the transmit energy dissipation is reduced. In a network where sensor nodes continuously generate data and transmit them to relay nodes, and the relay nodes buffer the data until they can be uploaded into a MDC, the placement scheme must also ensure that no data is lost due to the buffer overflow of these relay nodes. Once the data are uploaded, a relay node empties its buffer so that the buffer can be reused to collect data until the next visit by the MDC.

Moreover, we limit the load on each relay node (and its corresponding energy dissipation rate) so that it is able to achieve the desired network *lifetime* [23] required by some applications.

It has been shown that the relay node placement problem is NP-hard [19]. We present an integrated Integer Linear Programming (ILP) formulation that takes into consideration the position of sensor nodes along their data generation rates, the relay nodes buffer size, the maximum allowable energy dissipation at a relay node and the speed of the MDC, and determines an optimal relay node placement scheme, which ensures that there is no data loss due to relay node buffer overflow and the energy dissipation does not exceed a specified level. By using the proposed ILP formulation, the number of relay nodes required to form the middle tier network is minimized.

We solve the ILP formulation by using CPLEX 9.1.

1.4 Contribution

The main contributions of this thesis are as follows:

1. We propose a new model for determining relay node placements (RNP), based on the trajectory of a MDC;
2. We present an ILP formulation that determines an optimal placement of relay nodes in hierarchical sensor networks with a MDC. Our proposed approach designs a network that meets specified coverage, buffer capacity and energy dissipation requirements;
3. We investigate the effect of different design parameters, such as the buffer size and the MDC speed on the network performance.

Our approach differs significantly from the existing approaches that exploit node mobility. The current techniques typically assume that the number and the positions of the nodes, to be visited by the MDC, are known beforehand. We do not make any such assumptions and determine the positions of the relay nodes to best meet the application requirements.

To our best knowledge, this is the first formulation that jointly optimizes buffer and energy-aware placement of relay nodes in hierarchical sensor networks with a MDC.

1.5 Thesis Organization

The thesis is organized in five chapters. Chapter 2 provides a survey of technologies used in WSNs with relay nodes or mobile elements. Chapter 3 presents the proposed ILP formulation for the relay node placement problem in WSNs with MDCs. Chapter 4 shows the experimental results and performance analysis. Finally, Chapter 5 concludes the thesis and points out some related future research directions.

Chapter 2

Review of Literature

2.1 Wireless Sensor Networks

A sensor network is a static ad hoc network with a large number of sensor nodes deployed around some phenomenon to gather data from the monitored area for a certain period of time [1]. The collected data are transmitted to central point, known as a base station or a sink, from where users can access the data, possibly through the internet, for further processing of the data and to extract useful information, depending on the type and nature of the application [3]. A general layout of a sensor network is shown in Figure 2.1 [3].

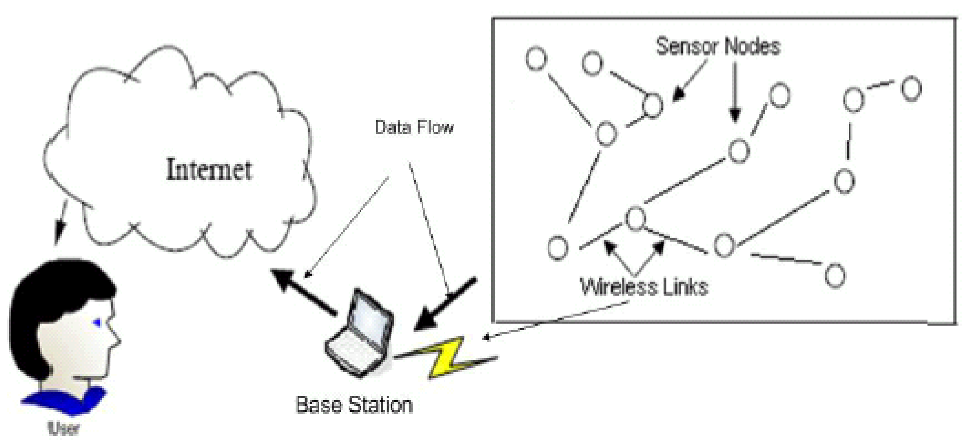

Figure 2.1 A general layout of a sensor network [3]

Unlike other wireless networks, such as wireless mesh network, the nodes in sensor networks are more resource limited, which means they have limited energy, processing and memory capability, and transmission range. However, they can be applied in real world easily with low cost. They have been widely employed in many monitoring-based applications such as environmental applications, which may range from tracking the movement of animals to forest fire detection and bio-complexity mapping of the environment; military applications, where manual operation is infeasible; and health applications, which are used to monitor the condition of patients, diagnostics and so on.

2.1.1 Sensor Nodes in Wireless Sensor Networks

A sensor node is equipped with sensing devices, low computational capacity processor, short-range wireless transmitter-receiver and power unit. In some models, sensor nodes also have location-finding devices to locate their positions, such as Global Positioning System (GPS) [12].

In the sensing devices of a sensor node, a group of sensors and actuators are contained to link the node to the outside world. Analog-to-digital converters (ADCs) are also included to convert analog signals into digital signals that can be passed to the processor. Then the microprocessor processes the signals and manages the procedures that enable the sensor node collaborate with the other nodes to execute the sensing tasks. Moreover, the microprocessor also controls the sensors and implements the communication protocols. It usually operates under various operation modes for power management purposes. The transmitter-receiver unit enables the sensor node to communicate with the network. It consists of a short range radio which works under four modes: transmit, receive, idle and sleep. Raghunathan et al. [53] state that completely shutting down the radio saves more energy than the idle mode in which no data are transmitted or received. The power unit, one of the most critical components of a sensor node, is usually equipped with lightweight batteries from where energy can be supplied to all the components of a sensor node [1].

Though sensor nodes can be deployed in target areas to gather useful data, there are some inherent limitations in sensor nodes. For instance, the memory and computing power of sensor nodes are limited. Therefore, the types of data processing algorithms on a sensor node and the size of intermediate results stored on the sensor node are restricted. Moreover, the transmission ranges of sensor nodes are also limited. Energy consumption is increased with the transmission ranges increasing. In addition, since the sensor nodes are equipped with lightweight batteries which often cannot be recharged or replaced economically or physically, the energy of sensor nodes are also limited. The energy constraint is considered as the biggest constraint in WSNs. Hence, it is critical to use the power efficiently to extend the network lifetime.

The deployment of sensor nodes can be pre-determined such as deploying sensor nodes in a building, or random such as throwing sensor nodes into monitoring areas. The random deployment is usually used in hostile territories where it is dangerous to operate or applications which do not require precise locations of sensor nodes. Since infrastructure may be not available in monitoring areas, sensor nodes which are deployed randomly should be able to self-configure and self-organize themselves to form a network before they monitor the target area.

2.1.2 Architecture of Wireless Sensor Networks

The architectures of WSNs can be classified into two categories: flat architecture and hierarchical architecture.

In the flat architecture, all sensor nodes are treated equally and assigned with the same functionality and play the same role. Sensor nodes collect data from the monitoring area and then transmit data to BS by single- or multi-hop. Figure 2.2 and 2.3 show single- and multi-hop communication of a flat architecture.

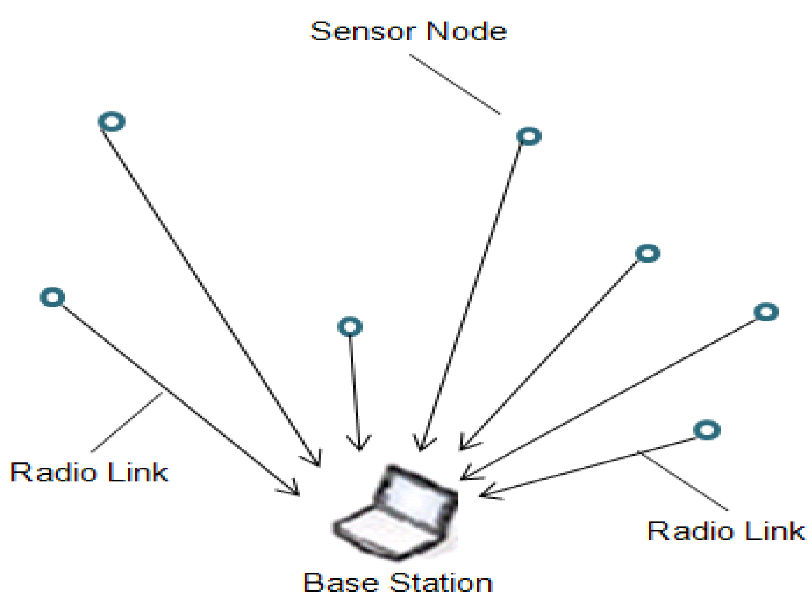

Figure 2.2 Single-hop communication of flat architecture

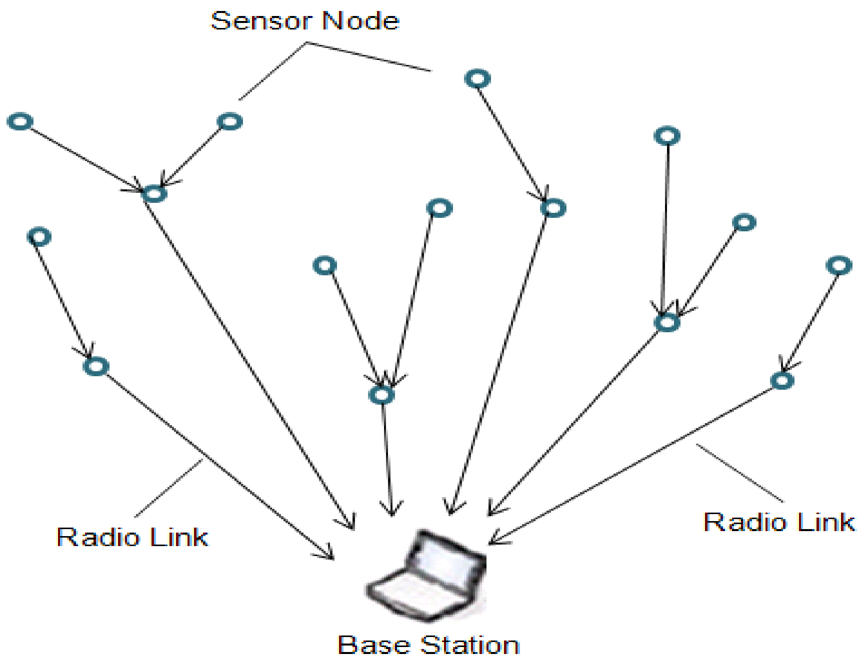

Figure 2.3 Multi-hop communication of flat architecture

In the hierarchical architecture, sensor nodes are grouped into distinct clusters. There are specific nodes, possibly with more capability than sensor nodes, used as the cluster heads. These cluster heads have the responsibility to gather data from the sensor nodes belonging to their respective clusters and forward these data to the BS. The cluster heads can communicate with BS by either single-hop or multi-hop. In the single-hop communication model, such as the models in [49] and [50], the cluster heads transmit data directly to BS which is located within one hop transmission range of cluster heads. On the other hand, in the multi-hop communication model, such as the models in [51], [52], [24], and [19], cluster heads not only forward data collected from their respective cluster, but also the data from other cluster heads. The single-hop communication model of hierarchical architecture is shown in Figure 2.4 (figure of multi-hop communication model is similar).

Compared with the flat architecture, hierarchical architectures can prolong the network lifetime and provide fault tolerance, scalability and efficient communication.

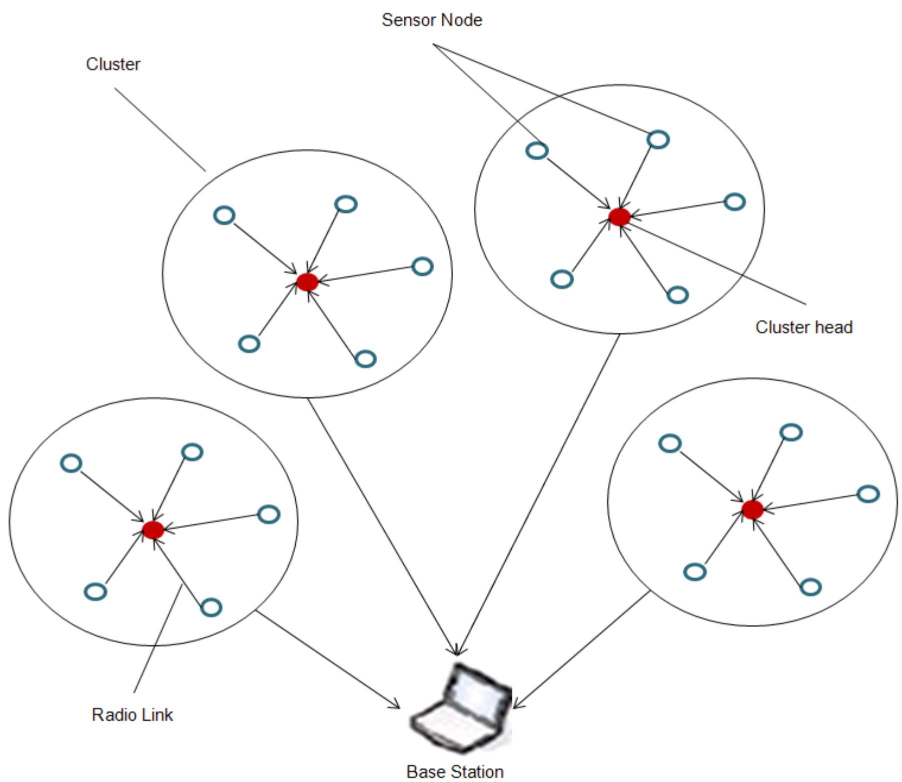

Figure 2.4 Single-hop communication of hierarchical architecture

2.1.3 Lifetime of Wireless Sensor Networks

The sensor networks are deployed in some areas to gather useful information over a certain period of time. The lifetime of a sensor network is defined as the time interval between which a certain amount crucial nodes deplete their battery, which results in either a routing hole [2] within the network or a disconnected network, or a network with insufficient coverage. [3]

In a flat sensor network, we can consider the lifetime as the period until the first nodes dies, or the last node dies, or a certain percent of nodes die. Zhang and Hou [4] state that α-lifetime of a sensor network can be taken as the length time interval during which at least α-portion of the target area can be continuously monitored, in other words, at least one node monitors a minimum of α-portion of the target area.

In a hierarchical sensor network, due to different functional roles in networks, the lifetime can be considered in terms of the lifetime of sensor nodes or the lifetime of cluster heads. Individual sensor nodes have limited impact on the network lifetime. Since when a sensor node dies, the network suffers from the lack of sensing by this single node. However, owing to the data redundancy existing in the network, this failed node will typically not result in significant data loss. On the contrary, the death of cluster heads affects the network lifetime more. That is because if a cluster head dies, all the sensor nodes belong to that cluster become inaccessible from other part of the network. Therefore, more attention should be paid to ensure sufficient lifetime of the cluster heads in hierarchical sensor networks.

2.1.4 Design Factors in Wireless Sensor Networks

Due to limitations of WSNs, such as the small sizes of sensor nodes, non-rechargeable energy resource, and limited computing power, many factors are taken into account when design a WSN which are as follows [1], [11]:

1. *Power Consumption*: since it is infeasible to replenish the power resources of sensor nodes, in order to extend the network lifetime, it is critical to reduce energy consumption.

2. *Fault Toleranc*e: due to lack of power, environmental interference or physical damage, nodes in WSNs may fail. This failure of sensor nodes should not influence the performance of entire WSN. Hence, the network should have the ability to sustain its functionalities without any interruption owing to node failures.

3. *Scalability*: the number of sensor nodes deployed in a sensor network may be extremely large. The new schemes or protocols should be able to handle such networks.

4. *Data Aggregation*: redundant data may be generated by sensor nodes. Instead of forwarding similar data received from multiple nodes, the redundant data should be aggregated and only one copy of data are transmitted. Thus, the energy consumption of transmitting data can be reduced.

5. *Connectivity*: the sensor networks should ensure each node in the networks can connect with other nodes.

6. *Coverage*: since the wireless sensing range of a sensor node is limited, each sensor node can only cover a certain physical area. Hence, sufficient sensor nodes should be deployed in the target area to ensure that the entire area is covered.

7. *Quality of Service (QoS)*: a trade-off exists between the quality of results and conservation of energy, especially for the applications in which maximizing the network lifetime is more critical than the quality of data sent. Therefore, energy-efficient approaches are needed to resolve this problem.

8. *Network Deployment in Ad Hoc Manner*: sensor nodes may be deployed in areas where no infrastructure is available. Hence, they should have the ability to self-configure and self-organize themselves to form a network.

9. *Unattended operation and no human intervention*: since it may be physically or economically impossible for any kind of human intervention after the deployment of the networks, it is important that sensor nodes can reconfigure themselves to adapt to changes in the networking conditions.

2.2 Relay Nodes in Wireless Sensor Networks

Gathering and transmitting data are basic functions of WSN. Direct transmission from SNs to BS is usually unavailable since BS is generally far away from SNs. In addition, with the distance between the SN and BS increasing, the energy consumption increases rapidly [17]. However, multi-hop communication can be used to address this problem. In this scenario, SNs share the burden of routing. That means that each SN needs to forward data generated by itself and other SNs. Therefore, nodes located near to the BS need to relay data at much higher rate than the ones located further away from the BS. This uneven energy dissipation among the SNs results in that the nodes located closer to the BS deplete their energy faster than the others.

Many approaches are proposed to address this problem. One of these approaches is to deploy a special type of node in WSNs named relay node, whose duty is relay data transmitted from SNs. Similar to sensor nodes, RNs are also battery-operated devices and have ability of wireless communication [3]. Some researchers, such as Dasgupta et al. [18], state that RNs should have the equal capabilities as SNs. While the others suggest that RNs should have more energy and larger communication range and higher data processing capability [3]. Tang et al. [19] also state that a RN can remove redundancy in data packets and extract useful data from SNs in its cluster, and then forward the new generated data to BS.

It has been shown [3] that use of relay nodes improves network lifetime, balanced data gathering, and fault tolerance during the data transmission.

2.2.1 Relay Nodes Placement Problem

It is a critical issue to find the location of relay nodes which act as clusters heads in a hierarchical sensor networks. The Relay Node Placement problem typically considers the following requirements [17]:

1. Each SN in WSN can communicate with at least one relay node;
2. The relay node network is connected;
3. The number of required relay nodes is minimized.

Suomela [19] claim that finding an optimal placement of relay nodes is NP-hard. In some cases, even finding the approximate solutions is NP-hard. Many researches focus on this issue for different objectives: maximizing the network lifetime, providing fault tolerance, balancing data gathering, achieving energy efficiency, maintaining network connectivity and so on. In the following section, we will review some literatures in detail.

2.2.2 Relay Nodes in Two-Tiered Architectures

In a two-tiered architecture, SNs compose the lower tier and RNs, acting as cluster heads, compose the upper one. SNs are grouped into cluster and transmit data to their respective cluster heads. The RN collects data from the SNs belong to its own cluster and then forward the data to the BS.

Gupta and Younis [21] and Pan et al. [23] are the first to present deployment of RNs in two-tiered WSN. In 2003, Gupta and Younis propose an algorithm to address the problem of load balancing in two-tiered WSN in [21] and another approach to resolve the issue of fault tolerance in two-tiered WSN in [22]. In the same year, Pan et al. [23] propose a two-tiered sensor network model to maximize network lifetime. Later, more researches have been done in this field.

In 2004, Falck et al. [5] address the problem of balancing data gathering in which the total amount of received data during the network lifetime is balanced against a requirement of providing sufficient coverage for all the SNs. They present a linear program formulation for this problem and show the optimal data routing. Moreover, they propose an incremental placement algorithm to find near optimal locations for the RNs. They claim that the proposed algorithm performs somewhat better than grid placement algorithm, but requires more computation.

Later in 2005, Tang et al. [19] consider the problem of minimizing the number of RNs in vast scale WSNs. They state that the RNP problem can be divided into two optimization problems: Connected Relay Node Single Cover (CRNSC) problem and 2-Connected Relay Node Double Cover (2CRNDC) problem in which for the sake of providing fault tolerance, each SN is able to connect at least two RNs. They propose two polynomial time approximation algorithms to resolve CRNSC problem and two approximation algorithms for 2CRNDC. They claim that the proposed algorithms can gain results close to those generated by optimal solutions.

Bari et al. [17] present two ILP formulations to find the optimal results of minimizing the number of RNs in WSNs. They also propose another ILP formulation to minimizing the number of RNs with specified performance guarantees in terms of coverage, connectivity and energy dissipation in [13].

Misra et al. [14] also address the problem of minimizing the number of RNs with certain connectivity and survivability constraints. They assume that RNs can be only located at a subset of candidate locations. In addition, they propose two frameworks of polynomial time approximation algorithms with O(1) approximation ratios for RNP connectivity problem and survivable network design problem (SNDP) respectively.

Hou et al. [24] consider the problem of energy provisioning (EP) in two-tiered WSNs. They present a mixed-integer nonlinear programming (MINLP) formulation for the joint problem of EP and RNP (EP-RNP). In addition, they propose a heuristic algorithm named Smart Pairing and Intelligent Disc Searching (SPINDS) in which a RN is located iteratively to a better location to extending the network lifetime.

Ergen and Varaiya [6] also address the problem of providing energy efficiency in WSNs with RNs. Specifically, they resolve the problem of figuring out optimal locations of RNs together with the optimal energy supplied to them, using a non-linear programming formulation.

In 2008, Guo et al. [16] propose an algorithm to jointly optimize the RNP problem and route assignment for two-tiered WSNs.

Eu et al. [15] introduce ambient energy harvesting technologies which can be used to supply energy for WSN instead of batteries. They state that WSNs Powered by Ambient Energy Harvesting (WSN-HEAP) can gain energy from the environment permanently and can work until the hardware failure of SNs.

2.3 Mobility in Wireless Sensor Networks

Ye et al. [2] first proposed a routing protocol named Two-Tier Data Dissemination (TTDD) in which the concept of mobility is presented to reduce the energy consumption and extend network lifetime. Subsequent research also focuses on exploiting mobility to collect data in a sensor network for different kinds of purposes [8], [30], [38], [40], [42], [43], [44], such as maximizing lifetime of WSN, increasing connectivity and capacity of WSN, providing fault tolerance, removing the relaying overhead of nodes near the base station, and assisting in security.

The existing research can be classified into three categories in terms of the properties of mobile elements: mobile base station-based solutions, mobile data collector-based solutions and rendezvous-based solutions [25].

2.3.1 Mobile Base Station-Based Solutions

Since sensor nodes in the vicinity of a base station normally run out of energy before others in a multi-hop communication model, the mobile base station (MBS) can be utilized to maintain the connectivity of WSN. Moreover, it addresses the problem of uneven energy consumption. In this scheme, the base station in WSN changes its location to collect data from sensor nodes during operation time. Data are buffered at senor nodes before they are transferred to the mobile base station.

In 2003, Kim et al. [9] propose a distributed self-organizing protocol named Scalable Energy-efficient Asynchronous Dissemination (SEAD) to forward data to MBS, in which near-optimal dissemination trees are build by considering the distance and the packet traffic rates among sensor nodes. They claim that compared to TTDD, Directed Diffusion (DD) [26], and Adaptive Demand-driven Multicast Routing (ADMR) [27], SEAD consumes less energy on creating and maintaining a dissemination tree to multiple MBSs.

Gandham et al. [8] state that employing multiple BSs can reduce or retain the hop count of each sensor node in WSN compared with utilizing single BS. Hence, energy consumption of per forwarded message is reduced. They propose an ILP program formulation to choose locations of multiple MBSs in which they assume that lifetime of

WSN is divided into equal periods and MBSs will be relocated at the start of each period. They also propose a flow-based routing protocol and four evaluation metrics.

For the purpose of prolonging the lifetime of WSN and increasing amount of data delivered during the lifetime in WSN, Azad and Chockalingam [30] also propose energy efficient low-complexity algorithms to choose locations of MBSs in which three algorithms are included: i) Top-K_{max} algorithm, ii) maximizing the minimum residual energy (Max-Min-RE) algorithm and iii) minimizing the residual energy (Max-Min-RE) algorithm. They claim that the proposed base station placement algorithms outperform single mobile BS and multiple static BSs. Moreover, they claim that the proposed algorithms can achieve the results which are close to optimal ones gained by using ILP formulation.

Jain and Vokkarane [31] also propose two base-station relocation policies, Centroid of Target Detecting Sensors (CTS) Policy and Centroid of Base Station Location (CBS) policy, to monitor energy-efficient target, in both of which a MBS is contained. They state that CTS relocate MBS to the geometric centroid of all sensor nodes which detect the target and CBS relocate MBS to the geometric centroid of the BS locations obtained over several time periods. They claim that CTS reduce energy consumption obviously for forwarding data to BS and increase network lifetime. They also claim that applying CBS, on the contrary, result in network lifetime decreased. Moreover, they claim that increasing the relocation energy threshold for moving the BS will also reduce the network lifetime.

A joint mobility and routing strategy is proposed by Luo and Hubaux [29] to extend lifetime of WSN. They first assume short path routing as the routing strategy and search for the optimal mobility strategy, then they search for a routing strategy which overcomes short path routing based on the optimal mobility strategy. They claim that the proposed strategy leads to 500% improvement in terms of lifetime of WSN compared with the case that base stations are static.

In [33], the problem of traffic overload is addressed. Pozzo and Tralli [33] introduce a model for offline estimation of traffic load distribution in WSN with single or multiple MBSs. Then they propose two different geographic forwarding strategies which are aware of traffic overload at each node and exploit channel and/or energy information.

Fodor and Vidacs [28] propose an effective routing protocol to balance the optimal routes and the number of messages used to update these routes, in which restricted flooding is used to update the locations of MBSs. They state that the proposed protocol can be used in the WSN with both single and multiple BSs. They also claim that the proposed protocol can achieve 95% energy gain compared with the basic protocol.

Zaslavsky and Freedman [32] analyze the performance of dense WSN by using MBSs. They state that deploying MBSs in the static WSN can improve QoS for the constant calls arrival rate.

2.3.2 Mobile Data Collector-Based Solutions

Sparse WSNs are used in some applications, such as monitoring traffic of a big city, battle field reconnaissance and habitat monitoring in large areas. For this kind of networks, connectivity is a critical problem need to be resolved. Though deploying RNs or using long-range communication interfaces can maintain network connectivity, it is not feasible due to economical reasons. The use of MDC is first introduced by Shah et al. [36] to address this problem in which MDC is referred as a data mule. A MDC is a mobile element, it could be a mobile robot or a vehicle equipped with a powerful transceiver and battery. It works like a MBS which moves in the designated area to gathers data. Sensor nodes collect data and buffer them until MDCs visit them. MDCs download the buffered data from sensor nodes when they are in their direct transmission range and then forward them to a wireless access point. Using MDCs in sparse WSNs reduce the relaying overhead of nodes near the base station. Moreover, the nodes in the sensor networks no longer need to form a connected network, since the MDCs can pick up the data they gathered.

Existing MDC-based solutions can be classified into three categories according to movement patterns of MDCs [37]: random mobility, in which MDCs move in random patterns, predictable mobility in which the movement patterns of MDCs are know beforehand, and controlled mobility in which the movement patterns of MDCs are controlled in real time.

In 2005, Jea et al. [10] introduce a single controlled data mule approach to collect data in which the data mule moves along straight line up and down. However, they state that the single data mule approach cannot handle large scale networks due to the buffered data overflow at SNs. Therefore, they use a multiple data-mules approach in which each mule is allocated to a designated area. However, they state that the number of SNs is uneven in those divided areas; buffered data can still overflow before the data mule downloads them. Hence, they propose a load balancing algorithm with multiple data mules used to gathering data. The proposed algorithm can be divided into five parts: initialization, leader election, load balancing, assignment, and data collection.

Jain et al. [45] also focus on the problem of providing energy efficient data collection in sparse WSNs. They present three-tiered mule architecture to exploit the presence of mobile nodes in WSN as forwarding agents. In addition, they discuss the performance metric involved in this architecture such as latency, data success ratio and communication energy. They also discuss the parameters of this architecture such as buffer size of SNs, data generation rate, movement pattern of mobile nodes and radio characteristics.

Anastasi et al. [44] also address the problem of providing energy-efficient and reliable data collection in sparse WSNs. They consider the joint impact of discovery (of a data mule) and data transfer protocols. They claim that a discovery protocol with a low duty cycle is efficient for most environmental monitoring applications. In addition, they claim that mobility pattern of data mules can decide whether a low duty circle is a convenient option for energy efficiency or not.

Zhao et al. [48] present mobility approaches while considering space-division multiple access (SDMA) technique to address the problem of data gathering in WSNs, particularly minimizing the length of a data gathering tour. They make an ILP formulation for the mobile data gathering with SDMA (MDG-SDMA) problem and prove that this problem is NP-hard. Moreover, they propose three heuristic algorithms named Maximum Compatible Pair (MCP) algorithm, Minimum Covering Spanning Tree (MCST) algorithm and Revenue-Based (RB) algorithm for the MDG-SDMA problem. They claim that the proposed algorithms can reduce the period of a data collecting tour by at least 35% in a sensor network where SNs are deployed densely compared with the one without using SDMA.

Ma and Yang [41] focus on minimizing the total time of a data gathering period which can be considered as a Single Hop Data Gathering Problem (SHDGP) in large scale WSN. They propose a heuristic algorithm for a single MDC and a data gathering scheme for multiple MDCs respectively. They claim that compared with a network with a stationary data collector or a network with a MDC which can only moves in straight lines, the proposed scheme can increase lifetime of WSN significantly.

Several mobility approaches are proposed to control the movement of sink nodes. However, they do not take the problem of coverage area into account. In 2007, Kamat et al. [40] propose an algorithm named optimized-Hilbert based on conventional Hilbert spacing-filling curves to address coverage problem. A powerful device called aggregation and forwarding node (AFN) is deployed as a mobile data collector in this scenario. Optimized-Hilbert provides mobility pattern of AFN in an area during AFN collecting data.

Based on their previous periodic, event-driven and query-based protocol (PEQ) [38], Boukerche and Pazzi [39] propose a data gathering protocol in which a MDC is deployed to broadcast beacons periodically. Sensor nodes which receive the beacons decide to join the MDC's cluster based on hop levels. All messages are exchanged locally within the cluster. The authors claim that the proposed protocol introduces no traffic or energy overhead, reduces packet delivery delay significantly and increases reliability.

Basagni et al. [47] explore ways to improve the performance of WSNs by using mobility. They investigate the performance of two WSN mobility paradigms: data MULEs solutions in which data routing is single hop and the movement pattern of mobile device is uncontrolled, and the solutions with multiple hops routing to a mobile sink in which the mobility is controllable.

In 2008, Ghassemian and Aghvami [46] identify improvements that can be gained by using mobility in sensor networks. They divide mobility into three levels: sensor lever mobility in which SNs are able to move and collect data, information level mobility in which the monitored object is mobile, and mobile relay level mobility in which a mobile data collector is used to gather data from SNs. In addition, they introduce models and metrics of mobility and effect of mobility on the protocol performance. They conclude that for the mobile relay level mobility, lower message delay, better energy efficiency and better scalability can be achieved.

For the sake of prolonging the lifetime of networks, Alsalih et al. [42] propose an ILP based placement scheme for multiple MDCs in Underwater Acoustic Sensor Networks (UASNs). UASNs is based on a 3D architecture in which data are transmitted from underwater SNs to the MDCs deployed anywhere on the surface of water.

Yang et al. [43] propose a protocol named Sensor-aided Overlay Deployment and Relocation (SODaR) to address the mobile device deployment problem in large scale sensor networks. They claim that SODaR is effective in terms of load balancing, message and movement overhead.

2.3.3 Rendezvous-Based Solutions

In rendezvous-based scenario, SNs forward their collected data to rendezvous points which are close to the path of mobile devices. Data are buffered at rendezvous points (RPs) until mobile devices visit and download them [25]. Therefore, rendezvous-based solutions can be classified as hybrid solutions between MBS and MDC solutions.

Little attention is paid in the literature in this field. In 2007, Xing et al. [34] state that data-intensive applications which need to collect high-bandwidth data under temporal constraints limited the use of mobile devices due to their low movement speed. Hence, they formulate the minimum-energy rendezvous planning (MERP) problem which aims to find a set of RPs visited by mobile devices within specified delay and minimum energy consumption requirements. Moreover, they propose two rendezvous planning algorithms: Rendezvous Planning with Constrained Path (RP-CP), which is used to find the optimal RPs when mobile devices move along the data routing tree and Rendezvous Planning with Unconstrained Path (RP-UG) which greedily chooses the RPs by consuming minimum energy. They also design a Rendezvous-based Data Collection protocol (RDC) to facilitate reliable data transmitted from RPs to mobile devices.

In a subsequent paper, the authors consider frequency-based multi-deadline rendezvous planning, in which the path of a mobile device is planned based on the sources with tight deadline, and schedule-based multi-deadline rendezvous planning [35]. They state that the frequency-based approach can be used in applications with only a few different deadlines in a network, but scheduled-based approach can used in applications with many deadlines in a network.

Chapter 3

Exploiting Node Mobility for Network Design with Performance Guarantees

3.1 Network Model

For our model, we consider a hierarchical, three-tiered wireless sensor network, where the lower tier consists of:

1. a set S of n sensor nodes, randomly distributed in the sensing area;
2. a set R of m potential locations of relay nodes, a subset of which will constitute the middle tier network. Each relay node of this subset would act as a cluster head;
3. one MDC, lying in the upper tier of the network.

Each sensor node in the lower tier collects data for target missions and forwards them to the cluster head, a relay node, of the cluster it belongs to. The cluster heads gather the data from sensor nodes in their respective clusters, and buffer them until a MDC visit them. Then the MDC downloads the buffered data and transmits them to the base station. Figure 3.1 and 3.2 show the physical and logical topologies for a three-tier WSN.

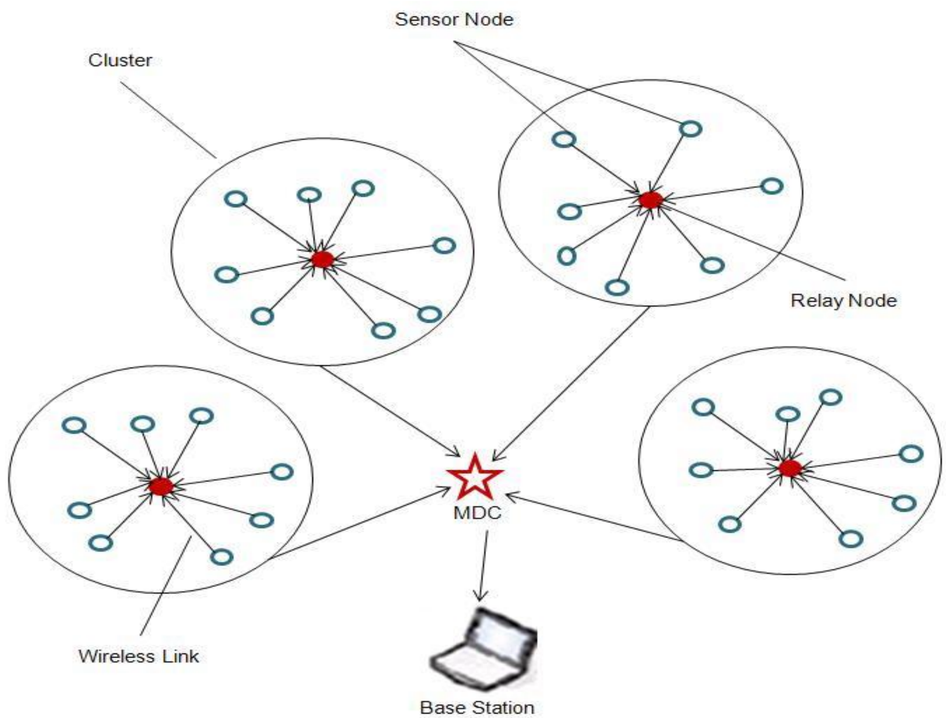

Figure 3.1 Physical topology of a three-tiered wireless sensor network

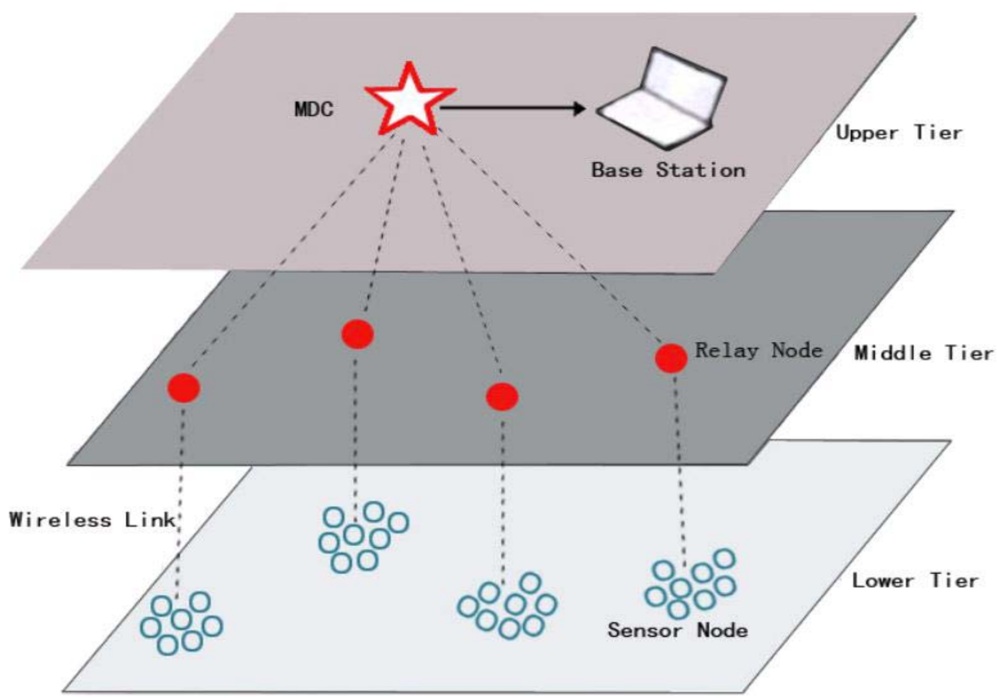

Figure 3.2 Logical topology of a three-tiered wireless sensor network

For each node, we assign it a unique label as follows:

1. For each sensor node, a label i, $1 \le i \le n$;
2. For each possible location of relay node, a lable j, $n+1 \le j \le n+m$;
3. For the mobile data collector, a label $n+m+1$.

A sensor node i is said to be *covered* by a relay node at location j (we shall refer to such relay node as simply j), if i can transmit its data directly to j. A sensor node i may be covered by more than one relay node. However, in our proposed formulation which designs the middle tier relay node network, we enforce that each sensor node belongs to exactly one cluster, C^j , corresponding to a relay node j.

Our objective is to jointly determine the followings:

1. Minimum number of relay nodes (cluster heads) and their positions, to form the middle tier network, satisfying pre-specified buffer and lifetime constraints;
2. The set of sensor nodes belonging to each cluster, so that the buffer and the lifetime constraints are satisfied.

We assume that the positions of the sensor nodes are known beforehand, or can be determined (e.g. using GPS), and the relay nodes can be placed at the locations determined by our placement strategy. This is feasible for many applications such as the monitoring of road condition, habitat and industrial environment. The proposed ILP formulation assumes that the set R of *potential* locations for the relay nodes is given as an input and is generated by using a grid based approach [17] in which an imaginary grid covers the entire sensing area. Depending on the number of potential locations of relay nodes in sensing network, the grid can be set as fine or as coarse as desired. The fine grid includes more potential locations and can achieve better solution typically. However, it increases the complexity of the formulation at the same time, hence the time required to obtain a solution is also increased.

The approaches of generating R will not influence the solutions obtained by using our ILP formulation. Other approaches, such as the P-position based approach given in [19], can also be used to generate R. In other words, once the set of potential locations is given, our ILP formulation can figure out the number and locations of the relay nodes to form the middle tire network while considering energy and buffer constraints.

We assume that a sensor node $i \in S$ continuously generates data at a fixed rate of b_i per unit time and transmits the data to the corresponding cluster head. The value of b_i, $i \in S$ can be the same for all sensor nodes, or may vary from sensor to sensor. In our experiments, we have set the same value of b_i for all sensor nodes.

We assume that the MDC visits each relay node j, which is included in the middle tier, periodically at fixed time intervals. The buffer of j is cleared at once after the data of j are transmitted to the MDC so that it can be reused to store data received from all $i \in C^j$ until the next visit of MDC. We also assume that a MDC is not power or buffer constrained, and being a mobile entity, a MDC can travel through the entire network. A relay node j transmits its buffered data only when the MDC is within a specified distance, $d_{j,\, n+m+1}$, from j. We assume that the MDC traverses the entire network at a constant speed following a predetermined trajectory, and it needs T_r unit time to complete the trajectory. That is, the time interval between any two successive visits by a MDC to a relay node j is known and is equal to Tr which is considered an input data for the proposed ILP formulation. The interval between successive visits should be small enough that no relay node suffers from buffer overflow.

3.2 Network Power Model

Akyildiz et al. [1] claim that the power consumption of a sensor node can be divided into three parts: sensing, communication, and data processing.

They state that the power consumption of sensing varies with the nature of applications. Monitoring constant events consumes more energy than monitoring sporadic events. They also state that the complexity of event detection impacts the energy consumption.

However, the dominant factor in power consumption of a sensor node is the power needed for data communication in which the energy for data transmission and reception is considered. In the first-order radio model [49], Heinzelman et al. state that receive (transmit) circuitry consumes α_1 *nJ/bit* (α_2 *nJ/bit*) of energy. The total energy to receive b bits is given by, $E_{Rx}(b) = \alpha_1 b$ while the total energy needed to transmit b bits over a distance d is given by $E_{Tx}(b,d) = \alpha_2 b + \beta b d^q$, where q is the path loss exponent, $2 \leq q \leq 4$ [49] and β is the amplifier energy to transmit unit bit of data over unit distance. In our experiments, we have used $\alpha_1 = \alpha_2 = 50$ *nJ/bit*, $\beta = 100$ $pJ/bit/m^2$ and the path-loss exponent $q = 2$.

Compared with the energy expenditure of communication between nodes, data processing consumes less energy. Hence, we only take the power expenditure of data communication into consideration in our formulation.

3.3 Notation Used

We define the following constants and variables as input in the ILP formulation.

Constants:

- n: The total number of sensor nodes, with each sensor node having a unique index i, $1 \leq i \leq n$.
- m: The total number of possible position of relay nodes, with each position having a unique index j, $n+1 \leq j \leq n+m$.
- $n + m + 1$: The index of the MDC.
- r_{max}: The transmission range of each sensor node.
- $d_{i,j}$: The Euclidean distance between node i and node j.
- α_2 (α_1): Energy coefficient for transmission (reception).
- β: Energy coefficient for amplifier.
- q: Path loss exponent.
- b_i: Number of bits generated by sensor node i in unit time.
- B: Buffer size of each relay node.
- T_r: Time required by the MDC between two successive visits at any relay node j.
- e_{max}: Maximum allowable energy dissipation (during the period T_r) of a relay node.
- C^j: The set of sensor nodes belonging to the cluster of relay node j.

Variables:

- $X_{i,j}$: Binary variable defined as follows:

$$X_{i,j} = \begin{cases} 1, \text{ if the sensor node } i \text{ selects relay node } j \text{ as its cluster head;} \\ 0, \text{ otherwise.} \end{cases}$$

- Y_j: Binary variable defined as follows:

$$Y_j = \begin{cases} 1, \text{ if relay node at location } j \text{ is included in the middle tier network;} \\ 0, \text{ otherwise.} \end{cases}$$

- R_j: Continuous variable indicating the total number of bits generated (during the period T_r) by the sensor nodes belonging to the cluster of the relay node j, C^j.

3.4 ILP Formulation for Placement of Relay Nodes

We design the middle tier network, i.e. the relay node network, using an ILP formulation in which the number of relay nodes is minimized while considering energy and buffer constraints. In the proposed ILP formulation, we ensure that each sensor node is covered by at least one relay node but belongs to only one cluster, and the data buffered at any relay node j, included in the middle tier, is not lost due to buffer overflow between two successive visits to j by the MDC. We present our formulation as follows:

$$\text{Minimize} \sum_{j=n+1}^{n+m} Y_j \qquad (1)$$

Equation (1) is the objective function, which minimizes the number of relay nodes in the middle tier while satisfying the buffer and energy dissipation constraints.

$$X_{i,j} \cdot d_{i,j} \le r_{\max}, \forall i, 1 \le i \le n; \forall j, n+1 \le j \le n+m \quad (2)$$

Constraint (2) enforces the restriction that a sensor node can communicate with a relay node only when the relay node is within the transmission range of the sensor node.

$$Y_j \ge X_{i,j}, \forall i, 1 \le i \le n; \forall j, n+1 \le j \le n+m \quad (3)$$

Constraint (3) ensures that if a relay node j is chosen as a cluster head by one or more sensor nodes, then j must be included in the set of relay nodes, selected to form the middle tier network. On the contrary, if a relay node j is not chosen as a cluster head by any sensor node, normally, it should not be included in the middle tier network. This is not specifically enforced by any constraint, but is taken care of by the objective function, which will set $Y_j = 0$, if this does not violate any other constraints.

$$\sum_{j=n+1}^{n+m} X_{i,j} = 1, \forall i, 1 \le i \le n \quad (4)$$

Constraint (4) guarantees that each sensor node belongs to exactly one cluster and transmits data to the relay node which is selected as the cluster head of its cluster.

$$R_j = T_r \cdot \sum_{i=1}^{n} bi \cdot X_{i,j}, \forall j, n+1 \leq j \leq n+m \qquad (5)$$

Constraint (5) calculates the total number of bits buffered in relay node j during the interval T_r, by summing the data transmitted to it from all sensor nodes belonging to the cluster C^j and then multiplying the summation by the interval T_r.

$$R_j \leq B, \forall j, n+1 \leq j \leq n+m \qquad (6)$$

Constraint (6) guarantees that if a relay node j is included in the middle tier network, the total bits buffered at j during the interval T_r will not exceed the buffer size of the relay node, B.

$$\alpha_1 \cdot R_j + \alpha_2 \cdot R_j + \beta \cdot R_j \cdot d^q_{j,n+m+1} \leq e_{\max}, \forall j, n+1 \leq j \leq n+m \qquad (7)$$

Constraint (7) computes the total energy dissipated by a relay node, which can be divided into three parts: the revive energy, $\alpha_1 \cdot R_j$; the transmit electronics energy, $\alpha_2 \cdot R_j$; and the transmit amplifier energy, $\beta \cdot R_j \cdot d^q_{j,n+m+1}$. This constraint ensures that the total energy dissipated by a relay node does not exceed e_{max} during the interval T_r.

We note that the number of relay nodes selected using our formulation is typically higher than the minimum number of relay nodes that would be required (to satisfy coverage requirements only) without considering any buffer or energy restrictions. The extra nodes are used to maintain the buffer requirements and/or to achieve the desired network lifetime, and are included in the topology only if necessary.

Chapter 4

Computational Experiment Results

4.1 Experiment Setup

We have used an experimental setup similar to [19], where the sensor nodes are randomly distributed over a $200 \times 280 m^2$ area. We assume that the communication range of each sensor node is assumed to be $r_{max} = 40m$ and the value of both energy coefficient for transmission and reception, α_2 and α_1, is $50 nJ/bit$. Moreover, we set the amplifier energy to transmit unit bit of data over unit distance to be $\beta = 100 pJ/bit/m^2$ and the path-loss exponent, $q = 2$. All relay nodes are assumed to have same initial energy of 5 J and all sensor node are assumed to generates data at a rate of 100 bits/unit-time, i.e., $b_i = 100, \forall i, 1 \leq i \leq n$.

4.2 Data Description

We have simulated our scheme with different number of sensor nodes, ranging from 100—600. For each size of the sensor node networks, we randomly generate 10 different sets for the locations of the sensor nodes in the network, and compute the results using each set. The results reported in the tables and figures in this chapter reflect the averages of all the different runs for each network size. We use a grid based approach mentioned in last chapter to compute the initial potential positions of the relay nodes. We varied the number of potential relay node locations from 48 (for coarse grid) to 165 (fine grid), which are indicated as 48-Grid, 88-Grid and 165-Grid in the following discussions of our results. The network model of 48-Grid is shown in Figure 4.1 (the ones of 88-Grid and 165-Grid are similar).

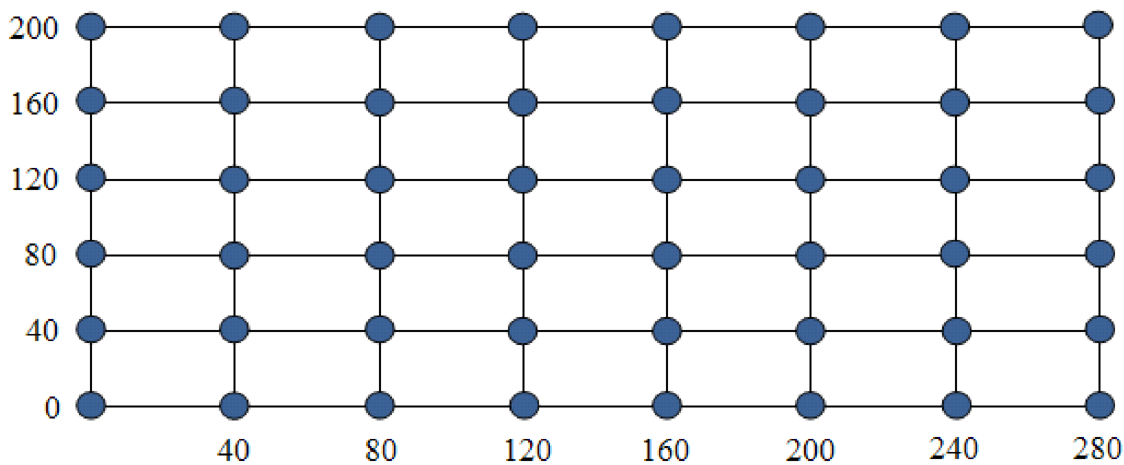

Figure 4.1 48-Grid Sensor Network Model

4.3 Experiment Parameters and Results

In this section, we show the simulation results of our formulation. We run different sets of experiments by setting different values for the parameters in terms of the buffer size of relay nodes (B), the interval of two successive visits by MDC (T_r), the maximum energy dissipation of relay nodes (e_{max}) and the distance between a relay node and the MDC ($d_{j,\ m+n+1}$). In all cases, our objective is to minimize the number of relay nodes required to form the middle tier relay node network, while maintaining a specified buffer capacity constraint and a maximum energy dissipation constraint.

4.3.1 Experimental Results of Varying *B*

Table 4.1 (Table 4.2) compares the number of relay nodes required to form the middle tier, on networks with 100—300 (400—600) sensor nodes, while the buffer size of relay nodes is varied from 15 Mb—8 Mb (30 Mb—18 Mb). For these sets of simulations, we relaxed the energy constraint (by setting $e_{max} = \infty$) to observe the effect of buffer size on the required number of relay nodes. We set the time interval between any two consecutive visits by the MDC to a relay node as 10 time-units, i.e., $T_r = 10$.

	Placement	Buffer Size *B*			
# Sensors	Scheme	15 Mb	12 Mb	10 Mb	8 Mb
100	48-Grid	16.0	16.0	16.1	16.5
	88-Grid	13.8	14.2	14.3	14.8
	165-Grid	12.1	12.3	12.5	13.8
200	48-Grid	20.7	21.2	22.0	25.9
	88-Grid	17.2	18.3	20.8	25.3
	165-Grid	15.8	17.0	20.1	25.0
300	48-Grid	23.1	26.0	30.4	38.0
	88-Grid	21.0	25.3	30.0	38.0
	165-Grid	20.1	25.0	30.0	38.0

Table 4.1 Number of relay nodes required under various placement schemes and buffer sizes, on networks with 100—300 sensor nodes.

	Placement	Buffer Size B			
# Sensors	Scheme	30 Mb	25 Mb	20 Mb	18 Mb
400	48-Grid	23.1	23.1	23.2	23.8
	88-Grid	19.3	19.5	21.1	23.0
	165-Grid	16.1	17.1	20.4	23.0
500	48-Grid	23.7	23.7	26.1	28.3
	88-Grid	19.9	21.1	25.4	28.1
	165-Grid	17.7	20.1	25.0	28.0
600	48-Grid	24.0	25.3	30.6	34.0
	88-Grid	21.6	24.7	30.2	34.0
	165-Grid	20.1	24.0	30.0	34.0

Table 4.2 Number of relay nodes required under various placement schemes and buffer sizes, on networks with 400－600 sensor nodes.

It is clear from the tables that in the different schemes which contain the same number of sensor nodes, the number of required relay nodes is increased with the buffer size B decreasing, which is as expected. However, in each table, we can see that when the size of network is small, the required number of relay nodes does not change much while varying the buffer size constraint. For example, for the 48-Grid schemes, the required number of relay nodes is varied from 16.0 to 16.5 and from 23.1 to 23.8 in the network with 100 and 400 sensor nodes respectively. This indicates that for such networks, the number of relay nodes is primarily determined by the *coverage* requirements. Hence, the buffer size has relatively little impact on the number of relay nodes required.

However, we can see that as the number of sensor nodes (and hence the amount of data generated) increases, the variations gap of the number of required relay nodes between the schemes with the lowest and highest buffer size is raised. This indicates that for such networks, the buffer size plays a critical role in minimizing the number of relay nodes.

Moreover, the tables show that when the number of sensor nodes and buffer size B do not vary, the number of required relay nodes is decreased with increased number of potential relay node positions. We note that the quality of the solutions is improved with larger number of potential locations of the relay node.

4.3.2 Experimental Results of Varying T_r

In this section, we study the effect of different values of T_r on the number of required relay nodes. We use the sets of 400–600 sensor nodes for these simulations and fix the buffer size B as 20 Mb and $e_{max} = \infty$. The value of T_r is varied from 7－10. Results are shown in Table 4.3 in detail.

Figure 4.2 demonstrates that how the number of required relay nodes changes with different sensor node size networks, on the grid setting 165-Grid (results with other grid settings follow a similar pattern). On the other hand, Figure 4.3 shows how the number of required relay nodes changes with different grid settings, on networks with 500 sensor nodes (results with the networks with other sizes are similar).

	Placement	T_r			
# Sensors	Scheme	7	8	9	10
400	48-Grid	23.1	23.1	23.1	23.2
	88-Grid	19.3	19.5	20.0	21.2
	165-Grid	16.7	17.1	19.0	20.4
500	48-Grid	23.7	23.7	24.5	26.1
	88-Grid	20.1	21.1	23.3	25.4
	165-Grid	18.5	20.1	23.0	25.0
600	48-Grid	24.1	25.3	28.0	30.6
	88-Grid	22.3	24.8	28.0	30.2
	165-Grid	22.0	24.0	28.0	30.0

Table 4.3 Number of relay nodes required under variation of T_r and placement schemes, on networks with 400—600 sensor nodes.

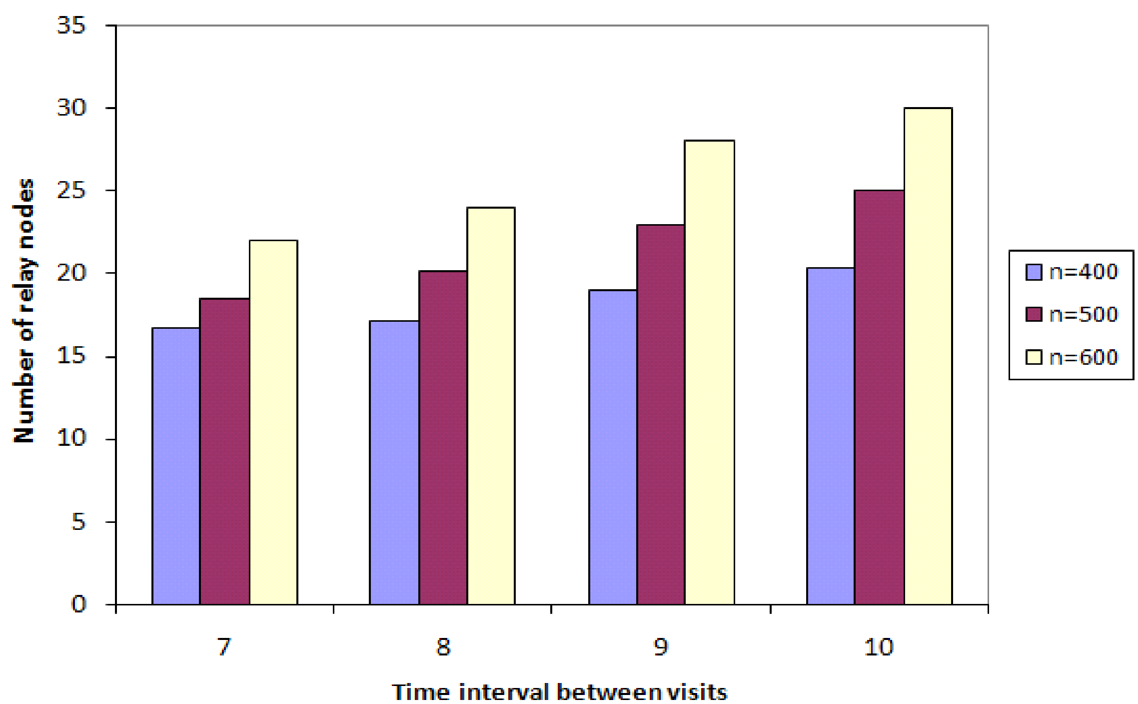

Figure 4.2 Variation of the number of relay nodes with the variation of T_r, under various network sizes for the grid setting 165-Grid.

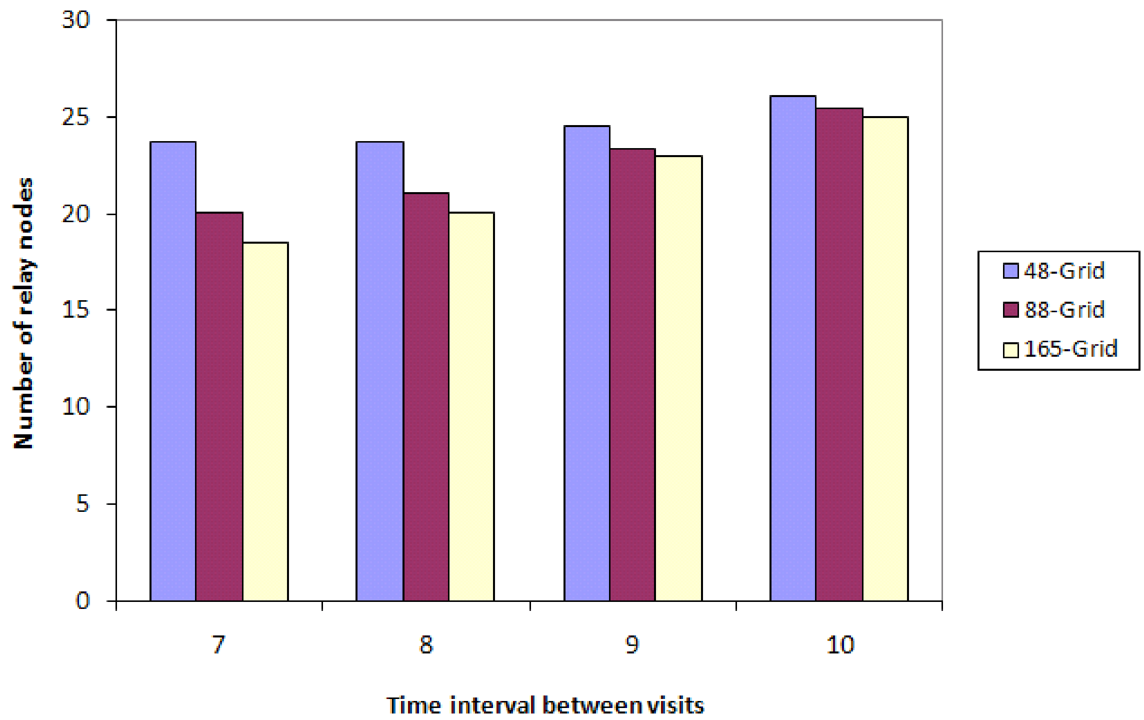

Figure 4.3 Variation of the number of relay nodes with the variation of T_r, under various grid settings for 500 sensor nodes network.

From the Table 4.3 and Figure 4.2, it is clear that in the same network schemes which have the same number of sensor nodes and potential relay nodes, the number of required relay nodes is increased with the value of T_r increasing. This is because that the total amount of data buffered at relay nodes is increased when the time interval between two visits of MDC increased. However, the buffer size of relay nodes is still restricted. Therefore, more relay nodes are needed to make sure no data are lost. They also show that for the same grid setting, such as 48-Grid, 88-Grid and 165-Grid, with the number of sensor nodes increasing and T_r unchanging, the required number of relay nodes is increased.

Moreover, Table 4.3 and Figure 4.3 show that when the number of sensor nodes and T_r are not changed, the number of required relay nodes decreases with increasing number of potential relay node positions.

Furthermore, from the table and figures, we can see that the finer grid produces better results in all cases.

4.3.3 Experimental Results of Varying e_{max}

In this section, we do the experiments with different values of e_{max}. We use the sets of 400–600 sensor nodes for these simulations and set the buffer size to be B = 20 Mb and T_r = 10. The value of is e_{max} varied from 1.90E6–2.30E6. Figure 4.4 shows the number of relay nodes required to form the middle tier under different energy settings.

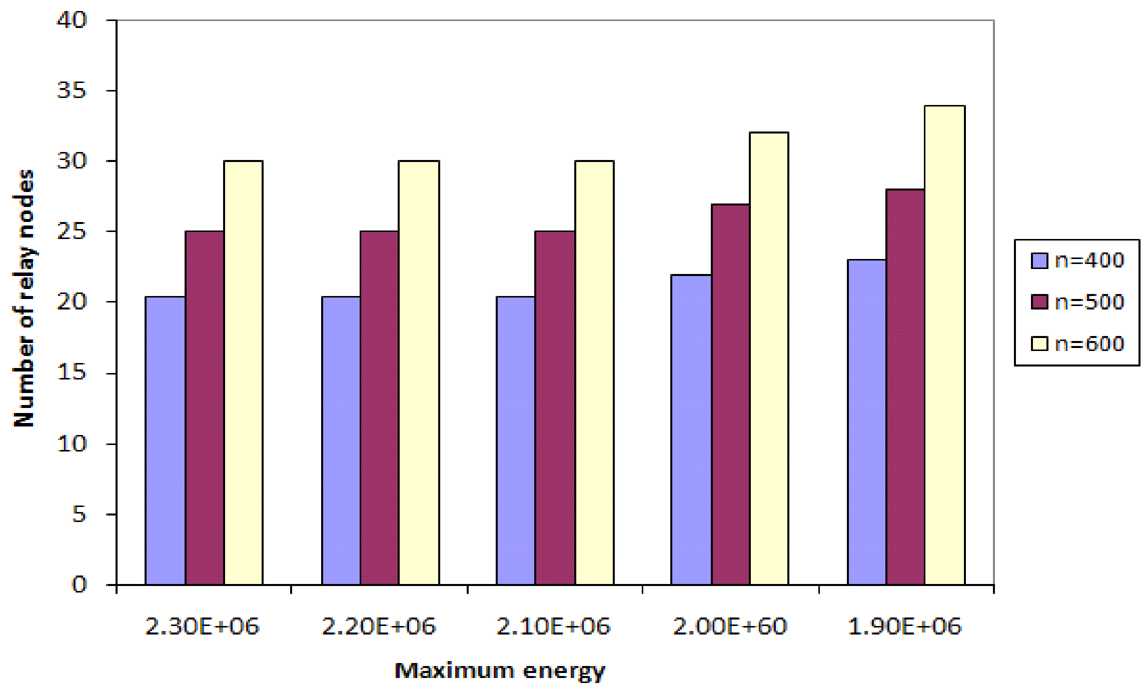

Figure 4.4 Variation of the number of relay nodes with the variation of e_{max}, under various network sizes for the grid setting 165-Grid.

As expected, the required number of relay nodes increases as the value of e_{max} becomes more constrained; however, the rate of increase is not very high.

This leads to an interesting observation that by allowing only a few extra relay nodes, the network lifetimes (measured using *N-of-N* metric [23], where the network survives until the first relay node dies) can be significantly improved, which is shown in Figure 4.5.

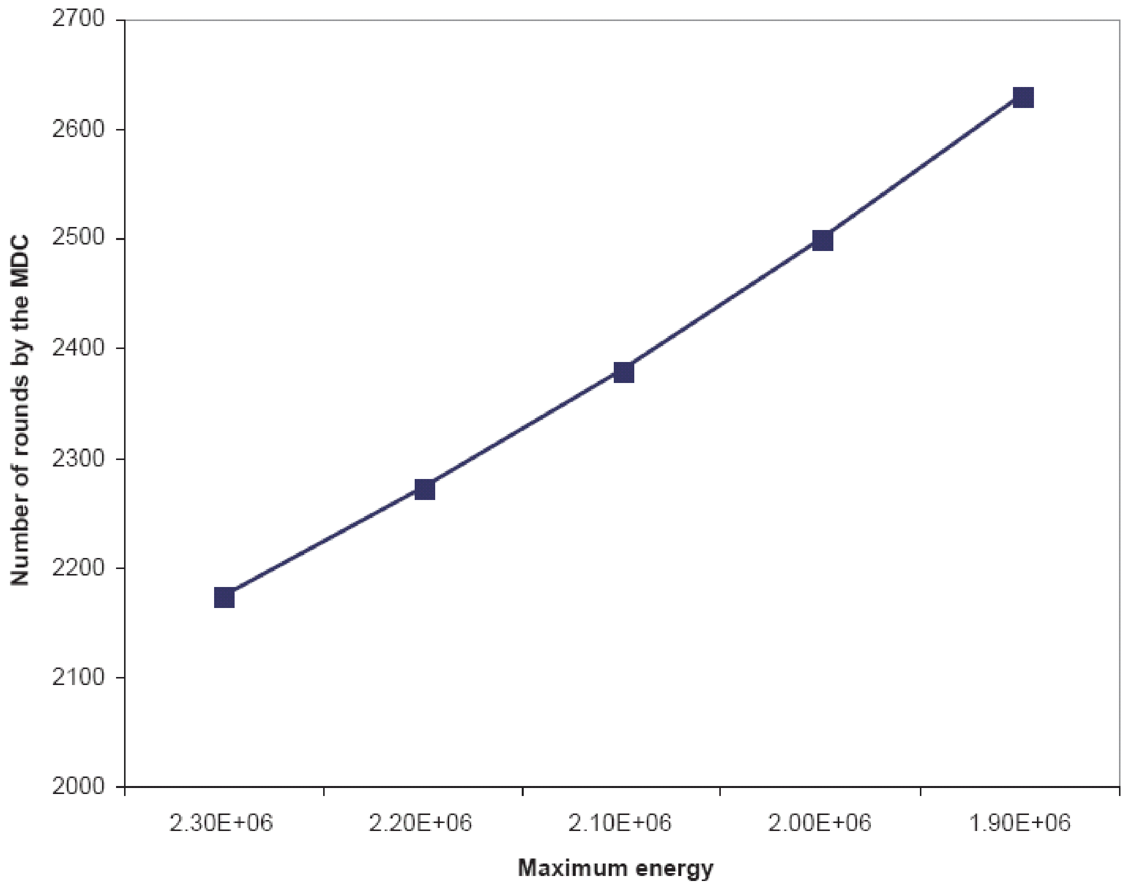

Figure 4.5 Number of rounds of data gathering by the MDC, achieved by adjusting the maximum energy dissipation levels.

4.3.4 Experimental Results of Varying $d_{j,\, m+n+1}$

In this section, we study the effect of $d_{j,\, m+n+1}$, the transmission distance from a relay node *j* to the closest point of the MDC trajectory, on the number of required relay nodes to form the middle tier network under different energy settings. We use the sets of 400–600 sensor nodes for these simulations and set the buffer size B = 20 Mb and T_r = 10. The value of e_{max} is varied from 1.90E6–2.30E6 and the value of *d* is 1, 8, 12, and 20. Figure 4.6 and 4.7 show the results in detail.

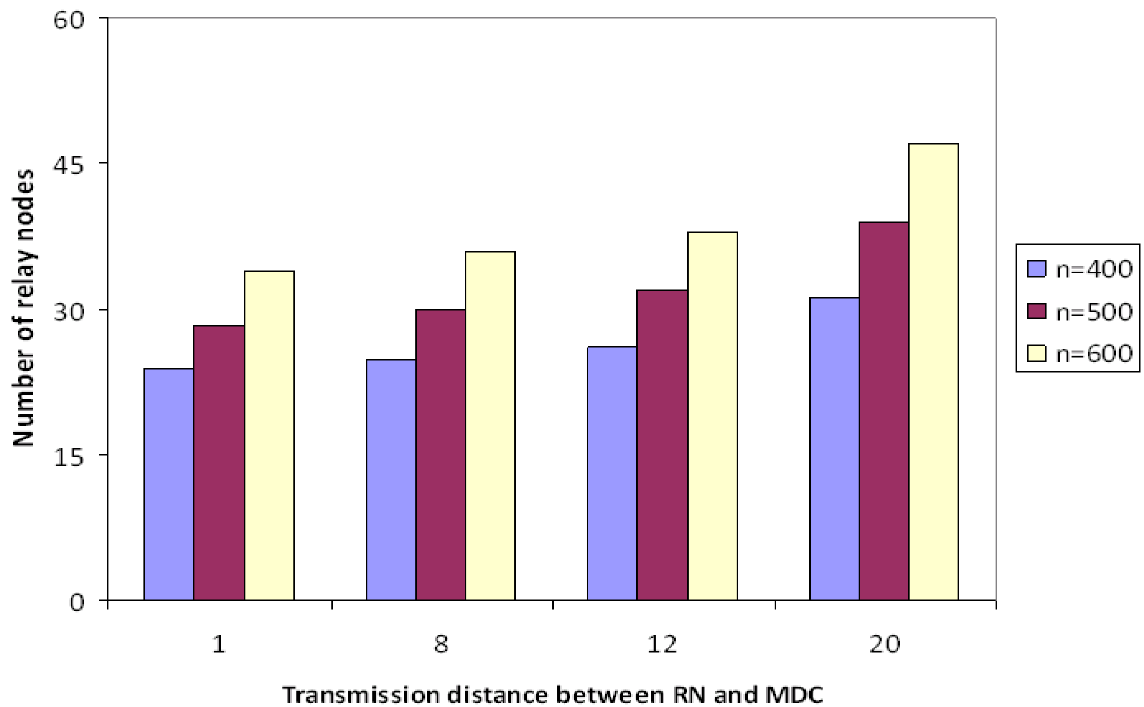

Figure 4.6 Variation of the number of relay nodes with the variation of $d_{j,\ m+n+1}$, under various network sizes for the grid setting 48-Grid.

With e_{max} = 1.9E6 and various value of $d_{j,\ m+n+1}$, Figure 4.6 shows that how the number of required relay nodes changes with different sensor node size networks, on the grid setting 48-Grid. We note that as $d_{j,\ m+n+1}$ increases, more relay nodes are required to maintain the energy dissipation levels below the specified level. Figure 4.7 shows the results on the grid setting 88-Grid (results with other value of e_{max} and grid setting 165-Grid follow a similar pattern).

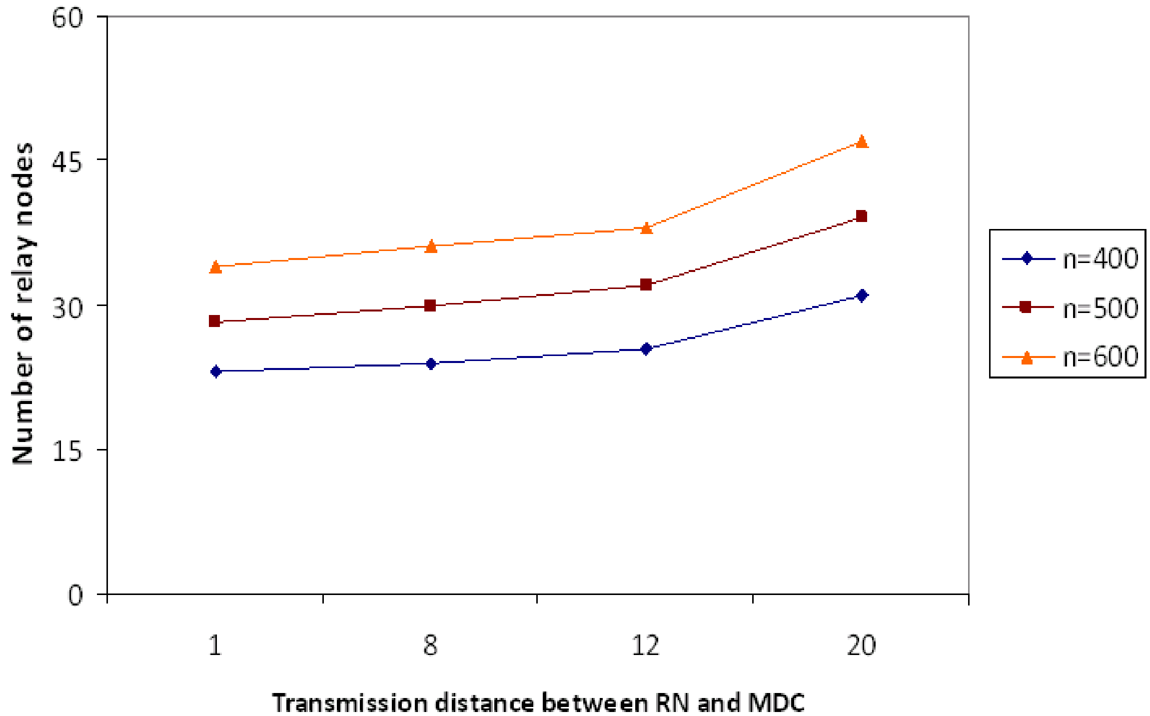

Figure 4.7 Variation of the number of relay nodes with the variation of $d_{j,\ m+n+1}$, under various network sizes for the grid setting 88-Grid.

As expected, the number of required relay nodes increases with the number of sensor and values of $d_{j,\ m+n+1}$ increasing. This is because the relay nodes consume more energy when transmission distance from the relay node to the MDC is increased. However, the maximum allowable energy dissipation of a relay node is restricted. Hence, more relay nodes are needed to share the load.

4.3.5 Summary of Experimental Results

In this chapter, we have shown the simulation results of our ILP formulation. Experimental results show that our ILP formulation can choose the minimum number of relay nodes which form the middle tier network by considering followings:

1. Constraints on buffer size and energy dissipation of a relay node;
2. Time interval visited by MDC;
3. Transmission distance between relay nodes and MDC.

The simulation results show that for small size networks, the buffer size of a relay node has relatively little impact on the number of relay nodes required which is primarily determined by the *coverage* requirements. On the contrary, for larger networks, the buffer size plays a critical role in minimizing the number of relay nodes.

Moreover, for the sake of making sure no data is lost, more relay nodes are required to provide QoS when the time interval between two visits of MDC or the transmission distance from the relay nodes to the MDC is increased. In addition, when the energy dissipation is more constrained, the network lifetime can be improved significantly by adding a few more relay nodes.

Chapter 5

Conclusion

5.1 Conclusions

In this thesis, we have proposed a new formulation that, given a set of potential locations, optimally determines the minimum number of relay nodes, along with their locations, in a hierarchical sensor network, which includes a MDC that visits the relay nodes and downloads information. The placement is done in such a way that:

1. Each sensor node is covered by at least 1 relay node;
2. No relay node suffers from the buffer overflow;
3. No relay node dissipates energy higher than a specified rate.

We have investigated the effect of different design parameters, such as the buffer size of a relay node and the speed of the MDC, on the network performance. The simulation results demonstrate that our approach can significantly increase the network lifetime, as well as, can provide QoS by ensuring that no data are lost due to the buffer overflow, by strategically placing a few additional relay nodes. We show that our ILP is able to generate optimal solutions for networks with hundreds of sensor nodes.

5.2 Future Work

As a future work, we are currently working on developing an approach that can compute an optimal trajectory, to be followed by the MDC. Moreover, we will take fault tolerance into consideration.

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APPENDIX A: Experimental Results in Tables

When B = 20000, T_r = 10, e_{max} is varied from 1.9E6 to 2.3E6, the number of required relay nodes in various network sizes and grids:

	Placement	e_{max}				
# Sensors	Scheme	2.3E6	2.2E6	2.1E6	2.0E6	1.9E6
400	48-Grid	23.2	23.2	23.2	23.5	23.8
	88-Grid	21.1	21.1	21.1	22.0	23.0
	165-Grid	20.4	20.4	20.4	22.0	23.0
500	48-Grid	26.1	26.1	26.1	27.1	28.3
	88-Grid	25.4	25.4	25.4	27.0	28.1
	165-Grid	25.0	25.0	25.0	27.0	28.0
600	48-Grid	30.5	30.5	30.5	32.0	34.0
	88-Grid	30.2	30.2	30.2	32.0	34.0
	165-Grid	30.0	30.0	30.0	32.0	34.0

When B = 20000, T_r = 10, e_{max} = 1.9E6, and the value of $d_{j,m+n+1}$ is 1, 8, 12 and 20, the number of required relay nodes in various network sizes and grids:

	Placement	D			
# Sensors	Scheme	1	8	12	20
400	48-Grid	23.8	24.8	26.0	31.1
	88-Grid	23.0	24.0	25.5	31.0
	165-Grid	23.0	24.0	25.2	31.0
500	48-Grid	28.3	30.0	32.0	39.0
	88-Grid	28.1	30.0	32.0	39.0
	165-Grid	28.0	30.0	32.0	39.0
600	48-Grid	34.0	36.0	38.0	47.0
	88-Grid	34.0	36.0	38.0	47.0
	165-Grid	34.0	36.0	38.0	47.0

When B = 20000, T_r = 10, e_{max} = 2.0E6, and the value of $d_{j,m+n+1}$ is 1, 8, 12 and 20, the number of required relay nodes in various network sizes and grids:

	Placement	*d*			
# Sensors	Scheme	1	8	12	20
400	48-Grid	23.5	23.8	24.8	29.1
	88-Grid	22.0	23.0	24.0	29.0
	165-Grid	22.0	23.0	24.0	29.0
500	48-Grid	27.1	28.3	31.1	36.1
	88-Grid	27.0	28.1	31.0	36.0
	165-Grid	27.0	28.0	31.0	36.0
600	48-Grid	32.0	34.0	36.0	43.0
	88-Grid	32.0	34.0	36.0	43.0
	165-Grid	32.0	34.0	36.0	43.0

When B = 20000, T_r = 10, e_{max} = 2.1E6, and the value of $d_{j,m+n+1}$ is 1, 8, 12 and 20, the number of required relay nodes in various network sizes and grids:

	Placement	*d*			
# Sensors	Scheme	1	8	12	20
400	48-Grid	23.2	23.5	23.8	27.4
	88-Grid	21.1	22.0	23.0	27.0
	165-Grid	20.4	22.0	23.0	27.0
500	48-Grid	26.1	27.1	28.3	34.0
	88-Grid	25.4	27.0	28.1	34.0
	165-Grid	25.0	27.0	28.0	34.0
600	48-Grid	30.6	32.0	34.0	40.0
	88-Grid	30.2	32.0	34.0	40.0
	165-Grid	30.0	32.0	34.0	40.0

When B = 20000, T_r = 10, e_{max} = 2.2E6, and the value of $d_{j,m+n+1}$ is 1, 8, 12 and 20, the number of required relay nodes in various network sizes and grids:

	Placement	*d*			
# Sensors	Scheme	1	8	12	20
400	48-Grid	23.2	23.2	23.5	27.4
	88-Grid	21.1	21.1	22.0	27.0
	165-Grid	20.4	20.4	22.0	27.0
500	48-Grid	26.1	26.1	27.1	34.0
	88-Grid	25.4	25.4	27.0	34.0
	165-Grid	25.0	25.0	27.0	34.0
600	48-Grid	30.5	30.5	32.0	40.0
	88-Grid	30.2	30.1	32.0	40.0
	165-Grid	30.0	30.0	32.0	40.0

When B = 20000, T_r = 10, e_{max} = 2.3E6, and the value of $d_{j,m+n+1}$ is 1, 8, 12 and 20, the number of required relay nodes in various network sizes and grids:

	Placement	*d*			
# Sensors	Scheme	1	8	12	20
400	48-Grid	23.2	23.2	23.2	26.0
	88-Grid	21.1	21.1	21.1	25.5
	165-Grid	20.4	20.4	20.4	25.2
500	48-Grid	26.1	26.1	26.1	32.0
	88-Grid	25.4	25.4	25.4	32.0
	165-Grid	25.0	25.0	25.0	32.0
600	48-Grid	30.6	30.6	30.6	38.0
	88-Grid	30.2	30.2	30.2	38.0
	165-Grid	30.0	30.0	30.0	38.0

APPENDIX B: Sample Experiment Results Generated by CPLEX

There are 600 sensor nodes and 48 relay nodes in this sensor network.

The buffer size of relay nodes is 20000.0.

The ratio of the duration of time of each round is 10.

The value of emax is 1900000.0.

The value of d is 8.

The indexes of used relay nodes are as follows: 602 603 605 607 608 609 610 611 612 613 615 616 617 618 619 620 621 623 624 625 627 628 629 631 632 633 635 636 637 638 639 640 642 644 647 648

The total number of relay nodes is: 36.

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