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Relay Node Placement and Trajectory Computation of Mobile Data Collectors in Wireless Sensor Networks

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Relay Node Placement and Trajectory Computation of Mobile Data Collectors in
Wireless Sensor Networks

by

Fangyun Luo

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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 Dr. Ataul Bari under the supervision of Dr. Arunita Jaekel. The collaboration is covered in Chapter 3, Chapter 4 and Chapter 5 of the thesis. In all cases, the key ideas, primary contributions, experimental design, 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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II.   Declaration of Previous Publication

This thesis includes some materials from one original paper that has been previously published as follows:

Table 1 Previous Publication

Thesis Chapter	Publication title/full citation	Publication status
Chapter 3 Chapter4	*Bari, A., Luo, F., Froese,W. and Jaekel, A. 2010. Optimal Relay Node Placement and Trajectory Computation in Sensor Networks with Mobile Data Collector. Ad Hoc Networks (2010), 400-415.*	*published*

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ABSTRACT

Recent research has shown that introducing mobile data collectors (MDC) can significantly improve the performance of wireless sensor networks. There are important design problems in this area, such as determining the number and positions of relay nodes, determining their buffer capacities to ensure there is no data loss, and calculating a suitable trajectory for MDC(s).

In this thesis, we first propose an integrated integer linear program (ILP) formulation that calculates the optimal number and positions of the relay nodes with the requisite buffer capacities. We then present two algorithms for calculating the trajectory of the MDC, based on the locations and the load of each individual relay node, in a way that minimizes the energy dissipation of the relay nodes. Our simulation results demonstrate that our approach is feasible for networks with hundreds of sensor nodes and leads to significant improvements compared to conventional data communication strategies.

DEDICATION

To all the people who help me through the way of making this achievement, especially to my wife (Mary Chen), my son (Shawn Luo) and my sisters.

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The research work presented in this thesis received help from many people. First of all, I would like to take this opportunity to express my gratitude to my supervisor, Dr. Arunita Jaekel. Without her advice, guidance and encouragement, this research work would not have been completed.

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INTRODUCTION

1.1 Wireless Sensor Networks

A basic wireless sensor network (WSN) consists of a number of sensor nodes (SN), which are usually deployed to measure/detect intended physical phenomena within a geographical area, and a base station (BS), which serves as a central repository to collect sensed data from all sensor nodes in the sensing area.

Sensor nodes, which are tiny, low-cost, low-power, and multifunctional sensing devices, in wireless sensor networks combine technological advances in sensing, computation, communication and operate in a cooperative manner to achieve the objective of deployment.

The base station is an access point, at which the user can access the data remotely, either directly or through internet. It is usually located at a fixed position and is not power constrained (e.g. plugged to a wall outlet).
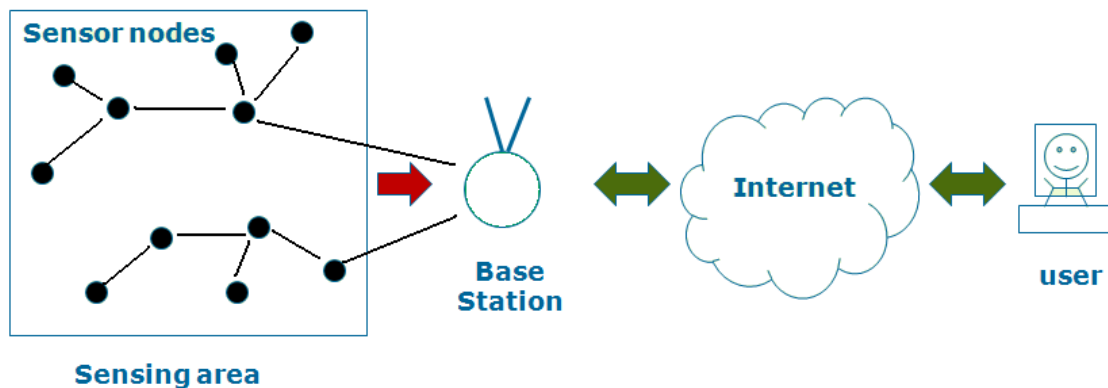
Figure 1. 1 A general layout of a wireless sensor network

As shown in Figure1.1, a wireless sensor network is usually deployed within a geographical area (called sensing area shown as a rectangle border), where there are some

physical phenomena to be measured/monitored. Sensor nodes (shown as black dots) are distributed inside the sensing area in order to achieve the sensing task effectively and accurately. When sensor nodes obtain data from sensing their respective vicinities, they send the data continuously or periodically to the base station (shown as circle with antenna) directly or following an appropriate routing path (shown as solid lines). A base station, on the other hand, is responsible for processing, analyzing and extracting meaningful information from the collected data to provide an entire view of the sensing area being detected.

Factors, such as tiny in dimension, unattended operation and cost concerns, pose restrictions in the designated capabilities of sensor nodes. Some major limitations that constrain the functionality of sensor nodes include [1], [2] and [3]:

- *Limited transmission range:* The built-in communication unit of a sensor node has limited radio transmission range.

- *Limited power supply*: A sensor node is usually powered by a small battery. In wireless sensor networks, recharging or exchanging the batteries of sensor nodes is generally considered too costly to carry out. Therefore, once the limited energy of the battery is completely dissipated, a sensing device will be out of operation and lose its functionality [1] and [3].

Presented with such challenges, two major concerns in the design of sensor networks are scalability and energy conservation [2]. Scalability requires sensor networks to be adaptive to frequent changes in operating conditions which include, for example, addition/removal of sensor nodes in a network or the scale variation of the sensing area. Given initial energy supply, a sensor node can only be functional for a fairly short period

of time if it is operating at a large data transmission rate over long distance. Therefore, an energy-aware network design is directly related to the lifetime of the network.

1.1.1 Hierarchical Two-Tiered Wireless Sensor Networks

To address the above mentioned issues, hierarchical two-tiered wireless sensor networks have been proposed in recent years. In traditional two-tiered architecture, as shown in Figure 1.2, individual sensor nodes (shown as green dots) are partitioned into clusters (enclosed in a dashed circle) and transmit their data to their respective cluster heads (shown as red squares). The cluster head collects data from all the sensor nodes in its own cluster and transmit the data to the base station [4] and [5], using an appropriate routing scheme (*single-hop* or *multi-hop*). Each sensor node belongs to only one cluster and sends sensed data directly to its cluster head instead of the base station [6].
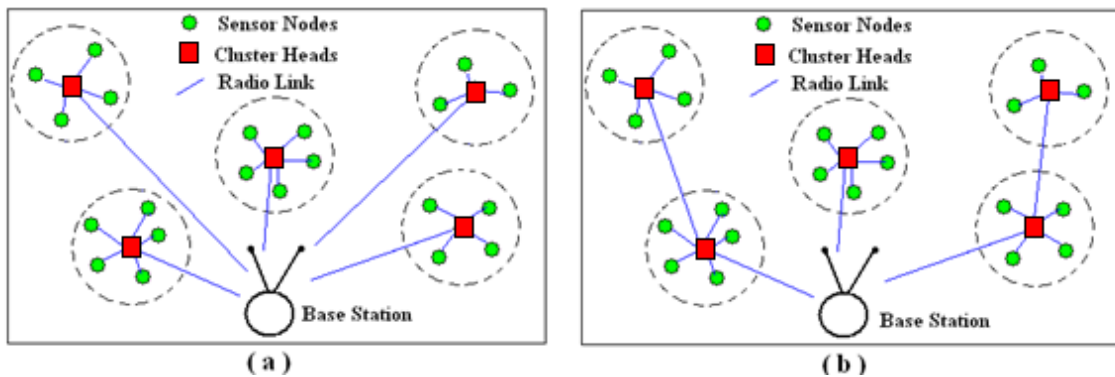
Figure 1. 2 General layout of a hierarchical sensor network. (a) The data routed by single-hop, (b) The data routed by multi-hop

Since the cluster heads are required to transmit large amounts of data over longer distances, compared to individual sensor nodes, the use of specialized nodes for cluster heads has gained considerable support in recent years [2], [4], [7] and [8]. These specialized nodes, often called *relay nodes* (RN), are typically equipped with enhanced capabilities in terms of energy provisioning, buffer capacities and transmission ranges.

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The resulting architecture, where a large number of low-power, sensor nodes with limited capabilities form the lower tier and relatively fewer relay nodes with enhanced capabilities form the upper tier, has been shown to improve network performance in a number of areas including network lifetime, load-balanced routing and fault-tolerance [2], [4], [5], [7], [9] and [10].

The lifetime of the two-tier architecture network is primarily determined by the lifetime of the upper tier relay nodes network. Each relay node is responsible for receiving (and possibly aggregating) the data from all sensor nodes in its cluster and then transmitting the data to (or towards) the base station, using either *single-hop* or *multi-hop* paths [5], [6] and [8]. The energy dissipation of the relay nodes increases rapidly with the distance between the sender and the receiver, and has a significant impact on the lifetime of the network. A number of energy-aware routing strategies have been proposed to extend the lifetime of the relay node network [5], [6] and [8]. However, such strategies are of limited use for relay nodes that are far away from other nodes and must therefore transmit over a large distance, or for nodes near the base station that must transmit data from many other nodes, in case of multi-hop routing. In addition, for sparse networks it is even possible that no feasible routing scheme exists, since the distance to the nearest neighbour may be greater than the radio transmission range of a relay node.

1.1.2 Hierarchical Three-Tier Architecture of WSNs

A number of recent papers have shown that the use of some mobile nodes or mobile data collectors (MDC) can significantly improve the performance of a network in terms of lifetime, coverage, and connectivity [11], and techniques for effectively utilizing the unique capabilities of mobile nodes have been attracting increasing research attention

in the past few years [12], [13], [14], [15], [16], [17] and [18]. In this thesis, we consider a network model that extends the traditional two-tier architecture, as shown in Figure 1.3, by adding a third tier consisting of one (or possibly more) mobile data collector(s) (MDC), above the relay node network (which now constitutes the middle tier). The MDC, which is not power constrained, visits all relay nodes in the middle tier, following a fixed trajectory [11], collects data from them, and delivers the collected data to the base station. Thus, the relay nodes are relieved from the burden of "routing" data towards the base station, possibly over long distances, resulting in considerable energy savings at these nodes.
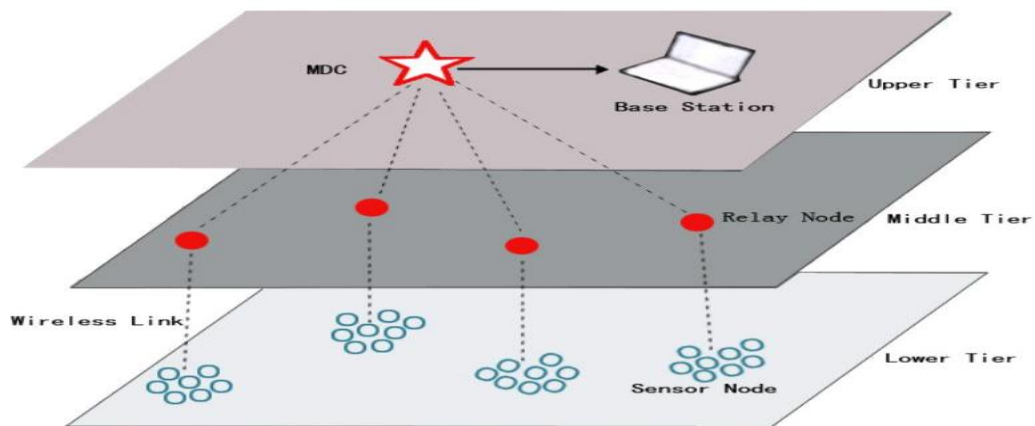
Figure 1. 3 Logical topology of a three-tiered wireless sensor network [19]

1.2 Motivation

In three-tier wireless sensor networks, we assume that the lower-tier sensor nodes have already been deployed and the number and locations of these sensor nodes have been determined by the monitoring needs of the specific application. Relay nodes are used as cluster heads to form the middle tier network, and MDC(s) and base station form the upper tier. There are two important issues in designing the middle and top tiers of the network, which need to be considered:

1. The placement strategy of relay nodes in the middle tier

2. The computation of the trajectory for the MDC(s) in the top tier.

The placement strategy is responsible for finding the locations of the relay nodes constituting the middle tier, such that each sensor node is covered by at least one relay node (i.e. there is at least one relay node within the transmission range of each sensor node), and the number of the relay nodes is minimized, known as relay node placement problem. It has been proven in [20] that finding the optimal placement of relay nodes in sensor networks is NP-hard. Since MDC periodically collects data from the relay nodes，it is necessary to consider the buffer size of relay nodes, such that the data generated by the lower tier sensor nodes can be stored at the relay nodes and delivered to the MDC without any loss of data (i.e. without buffer overflow).

The lifetime of a sensor network is typically determined by the battery power of the "critical node(s)" in the network [1] and [6]. Therefore, it is extremely important to devise strategies that extend the lifetime of the wireless sensor network as a whole. The relay nodes, although provisioned with higher power, are also battery operated. As the transmission energy dissipation increases rapidly with the distance between the source and the destination nodes [6], the suitable trajectory of MDC has a significant impact on the network lifetime.

1.3 Objective of Study and Contribution

When designing the middle tier of the network (consisting on relay nodes), it is essential to ensure that:

- There is adequate coverage, i.e. each sensor node can communicate with at least one relay node.

- The overall cost (in terms of the number of nodes and the buffer requirements) is reduced as much as possible.

Unlike previous approaches, in this thesis we present a technique for jointly optimizing both placement and buffer size of relay nodes in three-tier wireless sensor networks. The proposed approach not only designs a network that meets the coverage and connectivity requirements, but also minimizes the buffer size of relay nodes, such that there is no buffer overflow. Once the positions and loads of the relay nodes have been determined, the proposed algorithm is used for calculating the trajectory of the MDC, such that the energy dissipation of the relay nodes due to data transmission is minimized. The main contributions of this thesis are as follows:

1. We propose an ILP formulation that, given a set of potential locations of relay nodes in a network, optimally solves the relay node placement problem. Our formulation also computes the buffer requirements for the relay nodes, so that data generated by the lower tier sensor nodes can be stored at the relay nodes and delivered to the MDC without any loss of data (i.e. without buffer overflow).

2. We also provide a modification of our ILP that, given the maximum number of relay nodes to be used in the middle tier, finds the locations of the relay nodes and minimizes their buffer requirements.

3. We present an algorithms for calculating the trajectory of the MDC (either along a straight line, or in a circular path), such that the energy dissipation of the relay nodes due to data transmission is minimized.

In our model, we have used a centralized approach for computing the optimal relay node positions and routing schedule. This is applicable for networks where the relay nodes can be positioned accurately and nodes are mostly stationary after deployment. A centralized approach has been adopted in a number of recent papers [10] and [21], and also can be used in different application areas, such as habitat monitoring, environment monitoring, building monitoring, or surveillance [22] and [23].

1.4 Organization of Thesis

The remainder of this thesis is organized as follows. In Chapter 2, we briefly review the basic architecture of sensor networks, and the use of node mobility in such networks. In Chapters 3 and 4, we present our ILP formulation for optimal relay node placement and the algorithms for trajectory computation respectively. We discuss and analyze our experimental results in Chapter 5, and conclude with a critical summary and some directions for future work in Chapter 6.

CHAPTER II

REVIEW OF LITERATURE

2.1 Sensor Nodes in Wireless Sensor Network(WSN)

The research and development of wireless sensor networks were initially motivated by the military applications such as battlefield surveillance. The Distributed Sensor Network (DSN) program, initiated by the Defence Advanced Research Project Agency (DARPA) in the late 70's, symbolizes the modern research on sensor networks.

Wireless sensor network is resultant of research advancements from various areas such as sensing, communication and computing (including both hardware and software). A wireless sensor network consists of spatially distributed sensor nodes to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutions [24] and [25], and to cooperatively transmit their data through the network to a central point, known a base station or a sink. From the base station 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 [26]. The recent technological advances in the field of micro-electro-mechanical system (MEMS) have made the development of tiny, low-powered and multifunctional sensing devices technically and economically feasible [24] and [27]. The devices, known sensor nodes, are resource limited, such as limited energy, processing and memory capability, and transmission range. Although the capability of an individual sensor node is limited, sensor networks are able to perform complex sensing tasks through the collaborative effort of a large number of deployed sensor nodes. They have been widely employed in many monitoring-based applications. For example, a sensor network can be used for

measuring the humidity or the temperature of a certain region, for tracking some objects, as well as for monitoring habitats, battle fields, human health conditions or nuclear radiation levels [24].

2.1.1 Sensor Nodes and Deployment

Sensor nodes are underlying building blocks of sensor networks. A typical sensor node, as shown in Figure 2.1, which is simplified from [24], is usually equipped with a sensing unit for measuring the intentional target (e.g. temperature, humidity, pressure and object- presence/absence etc.). After sensing its vicinity, the raw data generated by a sensing unit is generally in an analogous format which is not computer-readable; therefore, an analog-to-digital convertor (ADC) is normally required to transform the analog data into digital format which, in turn, is further processed by a processing unit. The resultant data from a processing unit is cached into the local memory and when it comes the turn for a sensor node to transmit, the cached data is sent out by the radio communication unit following a pre-established routing path to base station.
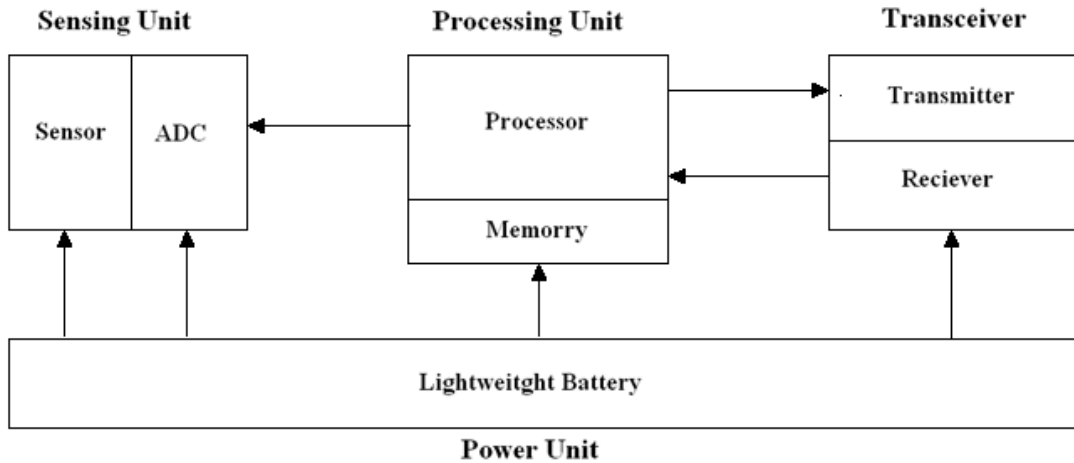
Figure 2. 1 Components of a sensor node

Sensor nodes in the network are normally deployed inside or very close to the phenomenon, so that the sensing task can be carried out effectively. Positioning sensor nodes within a sensing field can be executed either in a pre-determined fashion or they can be randomly distributed. The pre-determined placement of sensor nodes applies to situations where it is possible to know the actual location of sensor nodes prior to the deployment of the network (e.g. deployment of sensor network in factories or in the bodies of human/animals). However, in certain cases, especially when working in hostile environment such as battle field or poisoned region, randomly deploying sensor nodes is more practical (e.g. deployment of sensor nodes by dropping them from helicopter/airplane or delivering them in artillery shell or missiles) [24] and [25]. The capability of random deployment requires self-organized routing schemes and distributed-network algorithms to be incorporated in sensor networks, which are relatively complex. However, it is the power of random deployment, which makes sensor networks suitable for applying in hostile territories as well as in disaster-relief operations.

2.1.2 Model of Sensor Networks

Sensor networks, according to their internal architecture, can be broadly classified into two categories known as flat sensor networks and hierarchical sensor networks respectively. In flat sensor networks, all sensor nodes are assigned the same roles. They are responsible for not only sensing the environment, but also forwarding the sensed data or relaying other sensor node's data to the base station.

Unlike flat sensor networks, hierarchical sensor networks (also known as two-tiered sensor networks) separate sensing and routing tasks into two different tiers. As mentioned in Sec. 1.1.1, sensor nodes which are dedicated to the sensing task lie in the

lower tier and are grouped into various clusters identified by an assigned cluster head. Each sensor node usually belongs to only one cluster and communicates directly to its cluster head, instead of the base station. All cluster heads, lying in the upper tier, collect sensed data from their respective clusters and form a network among themselves in order to send the collected data to the base station. Compared to flat architecture, hierarchical model achieves advantages in various design objectives: energy conservation, data aggregation, load balancing and connectivity. For example, in two-tier hierarchical architecture, sensor nodes in the lower tier are relived from the burden of routing and forwarding, which reduces the energy consumption of these nodes. Because of these mentioned advantages, hierarchical architecture has gained increased popularity in the research and development of sensor networks.

2.1.3 Power Model of Sensor Networks

Energy is considered as one of the most precious resources since it is generally infeasible to recharge/replace batteries within sensor nodes. In order to deal with the energy consumption, it is necessary to have an approach so that the energy dissipated at each sensor node becomes measurable. In the literature [6], the most commonly employed approach is known as first-order radio model depicted in Figure 2.2, which is simplified from [6].
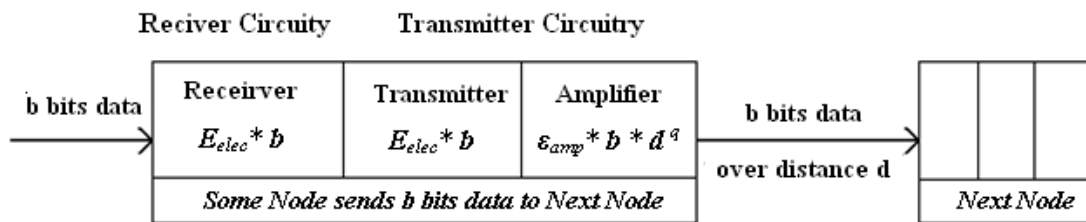
Figure 2. 2 First order radio model of a sensor node

According to this model, energy consumed at one sensor node, from receiving to transmitting b bit data over the distance d to next node, is divided into two parts: the receiver circuitry consumption and the transmitter circuitry consumption respectively. First part, in the Figure 2.2, E_{elec} is amount of energy consumed by the receiver circuitry for receiving per bit of data. The total amount of energy consumed in receiver circuitry is measured as ($E_{elec} * b$) joule for receiving a b-bit data. That is, $E_R (b) = E_{elec} * b$, where E_{Rx} is the total energy consumed in receiver circuitry.

Second part, energy consumed at the transmitter circuitry can be expressed in two terms. The first term is the amount of energy consumed by the transmitter, which is calculated similarly by the above expression, ($E_{elec} * b$) joule. The second term, however, is the amount of energy consumed by the amplifier for the signal transmission over space with distance d. ε_{amp} is the energy consumed by the amplifier for transmitting 1 bit of data over one unit distance. The energy loss over distance d is taken care by the term d^q, where q is the path loss exponent, $2 < q < 4$, for free space and for short to medium-range radio communication [1]. The amount of data consumed in the amplifier is calculated as ($\varepsilon_{amp} * b * d^q$) joule to amplify b bit data over distance d. So the amount of total energy consumed in transmitter circuitry is calculated as ($E_{elec} * b + \varepsilon_{amp} * b * d^q$) joule for transmitting a b bit data. That is, $E_T (b, d) = E_{elec} * b + \varepsilon_{amp} * b * d^q$, where $E_T (b, d)$ is the total energy consumed in transmitter circuitry.

As shown in Figure 2.2, by using first-radio model, the total energy consumption at a sensor node for communicating b bit data over distance d can be expressed as the following equation:

$$E_{total} = E_T\,(b,\,d) + E_R\,(b) = E_{elec}* b + \varepsilon_{amp}* b * d^q$$

2.2 Relay Nodes in Sensor Networks

In a sensor network, the main task of relay nodes is to relay data that they receive from other nodes (sensor nodes or relay nodes) in the network [28]. The introduction of a small number of relay nodes in a wireless sensor network can improve the network performance in a number of ways [29], [30], [31], [4], [1], [10], [32], [20]. Researchers have shown that the use of relay nodes lead to better performance of the network, in terms of the lifetime, data gathering, connectivity, and fault tolerance.

2.2.1 Relay Nodes in Flat Sensor Networks

Relay nodes have been proposed for the flat architecture as well as for the hierarchical architecture. Figure 2.3 gives an example showing how the appropriate deployment of relay nodes can reduce the burden from the sensor nodes that would otherwise be heavily loaded.
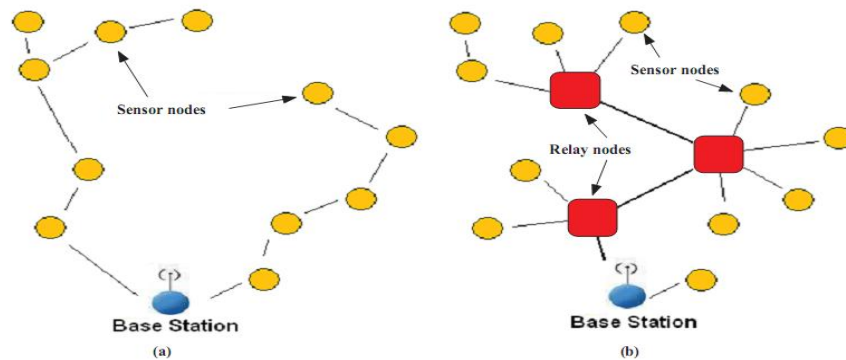
Figure 2. 3 Use of relay nodes in flat sensor network architecture [28]

In the flat sensor network architecture, shown in Figure 2.3, the sensor nodes located close to the base station are overloaded due to the data they receive from other

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sensor nodes. After introducing three relay nodes in the same network, the burden of the overloaded nodes, which are located close to the base station, have been relieved.

2.2.2 Relay Nodes in Hierarchical Sensor Networks

In a hierarchical sensor network, shown in Figure 1.2, relay nodes were first considered in [1] and [4]. In [1], the authors consider a two-tiered sensor network model, where the sensor nodes form the lower-tier, the relay nodes plus the base stations form the upper-tier. They focus on maximizing the network lifetime by arranging the base station(s), and by optimal inter-aggregation node relaying. In their approach, the sensor nodes form clusters and send their readings directly to the respective relay nodes. In [4], the authors address the issue of load balancing in an energy-constrained sensor network and propose an algorithm for clustering the sensor nodes around some relay nodes, which were equipped with higher energy and acted as cluster heads.

The use of relay nodes in hierarchical sensor network architectures has also been proposed in a number of recent papers [10], [33], [34] and [35]. In [10], the authors consider the "geometric deficiencies" of the network and propose an approach for additional energy provisioning to the existing nodes and deploying relay nodes in a two-tiered sensor network containing Aggregation and Forwarding Nodes and relay nodes. The objective is to prolong the lifetime of the network. In [33], energy-efficient storage architecture in multi-tier sensor networks is investigated. In [34], authors proposed a tenet architecture for tiered sensor networks that can be used to simplify application development and to reuse *mote-tier* software. In [35] a genetic algorithm is used to jointly solve a multi-objective problem: *balanced energy consumption* and *minimized total energy consumption.*

2.3 Relay Nodes Placement and Clustering

The placement problem of relay nodes in flat architectures is considered in [29]，

[31]，[32] and [36]. In [29] , the authors focus on placing a minimum number of relay

nodes to ensure that the resulting network is connected. They consider a class of sensors,

where the location of the sensor nodes are pre-determined, and modeled the problem

based on the well known *Steiner minimum tree with minimum number of Steiner points*

and bounded edge length [37] problem. They propose two approximation algorithms. In

[31], the authors focus on maximizing the lifetime of a sensor network, under the

constraint that each point in the sensing region is covered by at least one sensor node. In

their model, any node can assume the role of a sensor node or a relay node. They propose

an algorithm for finding the location of nodes, along with their roles, to achieve this

objective. In [32], the authors address the placement problem of the sensor nodes, the

relay nodes and the base stations, and propose a number of ILP formulations to achieve

different objectives, such as: a) Minimizing the number of sensor nodes to be deployed

while maintaining the coverage and the connectivity, b) minimizing the cost and the

energy consumption, and c) maximizing the lifetime. In [36], the authors formulate the

relay node placement problem, with the objective of maximizing the lifetime of the

network, as a nonlinear program and propose an approximation algorithm. The general

problem of finding an optimal placement of relay nodes is NP-hard, even finding

approximate solutions is NP-hard in some cases [20].

2.3.1 Relay Nodes Placement

In wireless sensor networks using relay nodes as cluster heads, the location of a

cluster head is the location of the corresponding relay node. The placement of the relay

nodes, in such a network, must ensure that each sensor node belonging to the network must be able to communicate with at least one relay node [28].

Since relay nodes are more powerful and expensive, compared to sensor nodes, it is desirable that the number of relay nodes be minimized, while ensuring that all the sensor nodes are covered by at least one relay node. The *relay node placement problem* is to find the minimum number of relay nodes and the locations of the relay nodes in a sensor network, so that each sensor node is covered by at least one relay node. Assuming omni-directional transmission by the sensor nodes, the placement can be seen as the problem of covering the area corresponding to the network, using a minimum number of discs having equal radius, where the radius of each disc is the transmission range of a sensor node, assuming that each sensor node has the same transmission range. This problem is similar to the well known Minimum Geometric Disk Cover problem which is known to be NP-hard [2] and [38].

Figure 2.4 shows the significance of the placement strategy of relay nodes in a network. Figure 2.4(a) shows that setting four relay nodes at locations A, B, C and D cannot cover all sensor nodes within the area bounded by the square ABCD (it is obvious to leave some sensor node uncovered in the shaded region). The radius of the circle around the relay nodes (discs) are the transmission range of the sensor nodes. Hence, the discs area are covered by these relay nodes. On the other hand, Figure 2.4(b) shows how four relay nodes can be placed at locations w, x, y and z so that entire region can be covered. The same number of discs of same size can result in different amount of coverage depending on the placement of the relay nodes. That is why solving the problem of *relay node placement* is valuable.
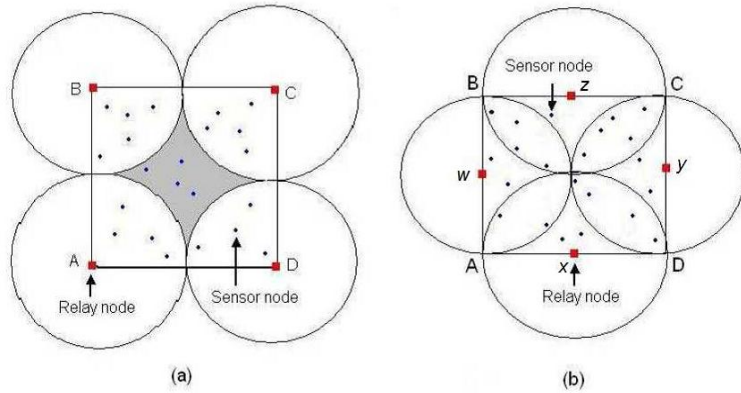
Figure 2. 4 An example of the relay node placement problem [39]

The problem of relay node placement in hierarchical sensor network architecture has been addressed in [1], [2] and [10]. Pan et al. [1] propose strategies that maximize the topological lifetime of a wireless sensor network by arranging the relay nodes, and finding the optimal location of the base station(s). Tang et al. [2] considered a hierarchical network architecture, where the entire region is divided into cells, and an optimal solution is determined for each cell. The authors consider relay node networks, with each cell having a length $2 \cdot r_{max} \cdot l$, where l is an integer and r_{max} is the communication range of each sensor node. The P-positions for a pair of sensor nodes at locations x and y are defined as the point(s) of intersection (if any) of two circles of radius r_{max} with centers at x and y in the same cell. An optimal placement of relay nodes for each cell is computed from the set, P, of P-positions for all pairs of sensor nodes within the cell, by checking all subsets of P of size four or less. Their method requires that the transmission range of the relay nodes, d_{max} must be at least $4 \cdot r_{max}$. Hou et al. [10] spent their research effort in prolonging the lifetime of hierarchical, cluster-based sensor networks in which the upper tier contains relay nodes (refered to as *Aggregation and Forwarding Nodes (AFN)*). The authors focus on prolonging the lifetime of sensor

networks with energy provisioning to the existing nodes and deploying relay nodes within the networks. In the paper, a mixed integer linear program (MILP) formulation and a heuristic are proposed to solve the problem.

2.3.2 Clustering in Wireless Sensor Networks

Clustering in a sensor network deals with the problem of partitioning the entire network into a number of distinct clusters, such that each sensor node belongs to a single cluster and one node in each cluster is designated to act as the cluster head. Cluster heads are responsible for gathering the data from their own clusters and routing the collected data towards the base station [28]. Efficient clustering in sensor networks contributes to the improvement of overall system performance, including scalability, network lifetime, and efficient energy utilization [40].
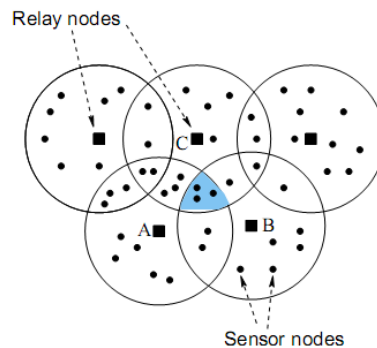
Figure 2. 5 Sensor nodes in overlapping coverage area [28]

The clustering problem for relay nodes is illustrated in Figure 2.5, where the sensor nodes in the shaded region, overlapping coverage area, can be assigned to any one of clusters A, B or C. Depending on the routing scheme of relay nodes A, B and C, one assignment may be more advantageous than the others. The goal of a load balanced clustering algorithm is to assign each sensor node to an appropriate cluster in a way that extends the lifetime of the network.

The clustering and the routing schemes are addressed for two-tiered networks in a number of recent papers, including those in [4], [5], [7], [8], [9] and [41]. Bari et al. [4] focus on load balanced clustering and propose a heuristic solution for the problem. Fault tolerant clustering is addressed in [9]. Yarvis et al. [41] investigate the problem of maximizing network lifetime by appropriately placing nodes which are not energy constrained (e.g., connected to a wall outlet). The works in [5], [7] and [8] focus on clustering and routing schemes that maximize the network lifetime. The aforementioned approaches assume that the number and positions of the relay nodes are given.

2.4 Mobility in Wireless Sensor Networks

Gandham et al. [12] first introduced the concept of using mobile sinks to balance the energy dissipation of all sensors by using multiple mobile base stations to prolong the lifetime of WSNs [12]. Their approach balances the energy dissipation of the sensors' in the neighbourhood of the base station. Subsequent research also focuses on exploiting mobility to collect data in a sensor network for different kinds of purposes [13], [14], [15], [16], [17], [18], [42], [43], [44] and [45], such as maximizing lifetime of WSN, increasing connectivity of WSN and providing fault tolerance.

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 [46].

2.4.1 Mobile Base Station-Based Solutions

Heinzelman et al. [3] have demonstrated, through simulations on static WSN, that sensor nodes in the vicinity of a base station drain their energy faster than other nodes in a multi-hop network. Mobile base station (MBS) can be utilized to address this problem

of uneven energy consumption. Moreover, mobility can also be used to maintain the connectivity of the WSN. In this scheme, the base station in WSN changes its location to collect data from sensor nodes during their operational lifetime. Data are buffered at senor nodes before they are transferred to the mobile base station.

The method proposed by Gandham et al. In [12] used Integer Linear Program (ILP) to determine new locations for base stations and ensured energy-efficient routing during each round, in which the lifetime is spit into equal periods of time. Since sensor nodes which are one-hop away from a base station are changed by moving base stations to new locations, balanced energy dissipation of sensors is achieved. Therefore, multiple mobile base stations, which might be required to move periodically, prolong the network lifetime.

Considering that the complexity of the optimal ILP solution for multiple mobile base stations by Gandham et al. is high. Azad et al. [42] proposed energy efficient low-complexity algorithms to determine locations of the base station. These algorithms includes: 1) Top-Kmax algorithm, 2) algorithm of maximizing the minimum residual energy (Max-Min-RE), and 3) algorithm of Minimizing the Residual Energy Difference (MinDiff-RE). Unlike previous algorithms, where some nodes still have significant unutilized energy when the network dies, the proposed approach ensures balanced energy dissipation so that all nodes deplete their energy around the same time.

Ma et al. [47] introduced the characteristic distance (d_{char}) for analyzing the optimization of sink velocity. They compromise between sink-sensor meeting delay and message delivery delay, which optimize the delay of message delivery and the energy consumption by increasing the number of mobile sinks with an optimal velocity. Mendis

et al. [48] applied Particle Swarm Optimization (PSO) for the placement of the sink and deriving the optimum movement path followed by sink node within the sensor field to achieve efficient energy management and longer lifetime of WSN with maximum field.

In Jea et al. [13], multiple mobile base stations, which move in parallel straight paths, are considered, and it is shown that such mobility can achieve scalability and load-balancing. In Luo et al. [14], the authors focus on optimal data collection, and propose a protocol that extends the lifetime of the network. Their approach takes into account both the base station mobility and the multi-hop routing.

2.4.2 Mobile Data Collector-Based Solutions

Sparse wireless sensor networks are used in some applications, such as monitoring a big battle area or habitat monitoring in large areas. In this situation, connectivity of networks is a critical problem. Deploying relay nodes with long transmission range to maintain network connectivity is not feasible due to economical reasons. The use of mobile data collector (MDC) is introduced to address this problem. In this kind of WSNs, sensor nodes generate data and store them in their buffers. When the MDC visits a sensors node and is in its direct transmission range, the sensor node can transmit the data in its buffers to the MDC. The MDC, in turn, relays the data to the base station. Existing MDC-based solutions can use random mobility, predictable mobility, and controlled mobility.

In [16], a three-tiered network is considered where mobile data collectors, lie in the middle-tier, move randomly within the network and pick-up data from the sensor nodes. A sensor node transmits data only when a MDC enters the direct communication range of the node. A Partitioning Based Scheduling (PBS) heuristic for computing the

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trajectory of the MDC is used in [18], where the focus is to reduce sensor buffer overflow. The authors have proposed a solution that has two parts. In the first part, nodes are partitioned into groups based on their locations and the data generation rates. Then, a node visiting schedule is generated within a group. Finally, the solutions of these groups are combined to obtain the final path of the MDC. In [17], the authors propose a queuing theory based mathematical model that analyzes the performance and trade-offs of the three-tier architecture.

2.4.3 Rendezvous-Based Solutions

Xing et al. [49] proposed two algorithms to find a set of rendezvous points (RPs) that can be visited by mobile elements (MEs) within a required delay, while the network energy consumed in transmitting data from sources to RPs is minimized. The first algorithm (Rendezvous Planning with Constrained ME Path) finds the optimal RPs when MEs move along the data routing tree. The second one (Rendezvous Planning with Unconstrained ME Path) finds RPs with good ratios of network energy saving to ME travel distance. They also designed the Rendezvous-based Data Collection (RDC) protocol which facilitates reliable data transfers at RPs.

In rendezvous-based scenario, sensor nodes could send their data to rendezvous points, which are on the path of MDC or closer to the path. Once the MDC visits the rendezvous points (RPs), the corresponding sensor nodes send their data to the MDC. Therefore, rendezvous-based solutions lead to improvements in the performance of a wireless sensor network.

In a hierarchical sensor network architecture, using higher powered relay nodes as cluster heads, which utilizes a MDC to collect data from the cluster heads has been

discussed in [44], [45]. The objective, in both works, is a new way to extend the overall lifetime of the network from rendezvous-based solution. Bari et al. [44] proposed an ILP formulation, which optimally selects the relay nodes, from a set of potential relay nodes positions, such that i) the number of relay nodes are minimal, and ii) the length of the trajectory of the MDC is as short as possible. Bari et al. [45] focus on reducing the length of the trajectory of the MDC, by allowing the MDC to visit the neighbourhood of each relay nodes, instead of visiting their exact locations.

CHAPTER III

DESIGNING THE MIDDLE TIER OF THE SENSOR NETWORK

3.1 Network Model

We consider a three-tiered wireless sensor network, where the lower-tier consists of a set S of n sensor nodes, i.e.,$/ S / = n$. We assume that the deployment of the sensor nodes has been implemented to ensure appropriate coverage of the sensing area, so the number and positions of the sensor nodes are known beforehand and given as input to our formulation.

There are two possible scenarios for determining the positions of the relay nodes and the sensor nodes as follows:

Case i) Nodes are either placed at specified locations (determined by a suitable placement strategy.

Case ii) The locations of the nodes are determined after placement, e.g. using a GPS system.

The average expected data rate for each relay node is assumed to be known in advance. The data rate need not be uniform, but can vary from node to node.

We consider a set R_m of m potential locations of relay nodes, i.e., $/ R_m / = m$. A subset R of R_m will constitute the middle-tier network. Each element of R would act as a cluster head. Let C^j be the set of sensor nodes belonging to the cluster of relay node j. We also consider a MDC, lying in the upper-tier of the network. The MDC visits all relay nodes in R, collects their data, and delivers the data to the base station. Each relay node has a buffer size B. We assign, to each node, a unique label as follows:

i) for each sensor node, a label i, $1 \leq i \leq n$,

ii) for each possible location of the relay nodes, a label j; $n < j \leq n + m$, and

iii) for the MDC, a label $n + m + 1$.

A sensor node $i \in S$ is said to be *covered* by a relay node at location j (we shall refer to such relay node as relay node j), if and only if i can transmit its data directly to j. A sensor node i may be covered by more than one relay node, however, our objective is to design the relay node network such that each sensor node belongs to exactly one cluster, C^j, corresponding to a relay node j. In other words,

- $C^1 \cup C^2 \cup \ldots C^j \cup \ldots C^n = S$ and

- $C^i \cap C^j = \emptyset, for\ i \neq j.$

Our proposed formulation determines the minimum number and the positions of the relay nodes, to be selected as the cluster heads, to form the middle tier network, and assign sensor nodes to clusters such that the relay nodes buffer requirements are minimized.

We assume that the positions of the sensor nodes are known (or can be determined, e.g. using GPS), and the relay nodes can be placed at the computed locations. This approach is feasible for many applications (e.g., monitoring industrial environments, road condition, and habitat). We have used a grid based approach [50] to generate $\boldsymbol{R_m}$, **the set of *potential* relay node positions**. However, our ILP formulation does not depend on how $\boldsymbol{R_m}$ is generated and other approaches such as approach given in [2] can easily be used.

We consider that a sensor node $i \in S$ generates data at a rate of b_i bits per unit time, and transmits to the corresponding cluster head. The value of b_i; $\forall i \in S$ can either be the same, or may vary. In our model, each relay node j, receives data from the sensor

nodes belonging to its own cluster C^j, and buffers them until j can transmit buffered data to the MDC, while it is visiting j. Data buffering is essential for applications where it is important not to lose any data generated by the sensor nodes. In our model, the MDC visits each relay node j, periodically, at fixed time intervals. Once a relay node j transmits its data to the MDC, its buffer is cleared and can be reused to store new data until the next visit by the MDC. A relay node j transmits its buffered data only when the MDC is closest to j, in its trajectory. The MDC traverses 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 T_r.

3.2 Network Power Model

The power needed for data communication is the dominant factor in power consumption in wireless sensor networks. We consider the first-order radio model [6] to account for the energy consumption due to communication where the receive (transmit) circuitry consumes α_1 *nJ/bit* (α_2 *nJ/bit*) of energy since the power model works a sensor node as well as a relay node.

The total energy needs to receive b bits is given by

$$E_{Rx}\ (b)\ =\ \alpha_1 b\ ,$$

where α_1 is the receive circuitry consumes (*nJ/bit*),

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 α_2 is the transmit circuitry consumes (*nJ/bit*),

q is the *path loss exponent*, $2 \leqslant q \leqslant 4$,

β is the amplifier energy to transmit unit bit of data over unit distance ($pJ/bit/m^2$).

In our experiments, we have used $\alpha_1 = \alpha_2 = 50$ nJ/bit, $\beta = 100$ $pJ/bit/m^2$ and the path-loss exponent $q = 2$ [6].

3.3 Network Lifetime

A number of different metrics have been used in the literature to measure the lifetime of a sensor network. These are:

- N-of-N lifetime: The mission fails if any relay/gateway node dies,

- K-of-N lifetime: The mission survives if a minimum of K relay/gateway nodes are alive) and

- m-in-K-of-N lifetime: The mission survives if all m supporting nodes and overall a minimum of K relay/gateway nodes are alive.

For this thesis, we have used N-of-N lifetime in our experimental setup. Assuming equal initial energy provisioning in each relay node, the lifetime of the network is defined by the ratio of the initial energy (E_{init}) to the maximum energy (E_{max}) dissipated by any relay node in a round, i.e.: $Lifetime = \lfloor E_{init} / E_{max} \rfloor$.

In this situation, it is much more important to minimize the energy dissipation (E_{max}) of the *most heavily loaded* relay node, than to decrease the average energy dissipation. This is exactly the goal of our trajectory computation algorithm, discussed in Chapter 4.

3.4 Notation Used for ILP Formulation

In our formulation, we define the following constants as input:

- n: The total number of sensor nodes, with each sensor node having a unique label i, $1 \leqslant i \leqslant n$.

- m: The total number of possible positions of relay nodes, each position having a unique label j, $n + 1 \leqslant j \leqslant n + m$.

- j: The relay node at location j, $n + 1 \leqslant j \leqslant n + m$.

- $n + m + 1$: The label of the MDC.

- r_{max}: The transmission range of each sensor node.

- $d_{i,j}$: The Euclidean distance between node i and node j.

- b_i: Number of bits generated by sensor node i in unit time.

- C^j: The set of sensor nodes belonging to the cluster of relay node j.

- W_1, W_2: Positive constants that determine the relative importance of minimizing the number of relay nodes and the buffer size of relay nodes.

- T_r: Time required by the MDC between two successive visits at any relay node j.

- y_{max}: Maximum allowable number of relay nodes.

We also define the following 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:

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

- 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.

- B_{max}: A Continuous variable representing the maximum allowable buffer size, so that $R_j \leqslant B_{max}, \forall j, n{+}1 \leqslant j \leqslant n{+}m$.

3.5 ILP Formulation for Minimizing the Number of Relay Nodes (ILP1)

In this section, we propose our ILP formulation. Our formulation

i) ensures that each sensor node is covered by at least 1 relay node,

ii) minimized the number of relay nodes, and

iii) minimize the maximum buffer capacity of any relay node j, to be included in the middle tier, as a secondary objective.

Using the notations discussed in section 3.3, we present our formulation as follows:

$$\textbf{Minimize} \quad W_1 \cdot \sum_{j=n+1}^{n+m} Y_j + W_2 \cdot B_{max} \tag{1}$$

Equation (1) is the objective function for the formulation, and consists of two terms. The primary goal (represented by the first term) is to minimize the total number of relay nodes used to form the middle-tier network. As mentioned earlier, a relay node j is included in the middle tier (i.e., $Y_j = 1$), only if j selected as a cluster head by at least one sensor node i. Therefore, by counting the number of relay nodes selected to be the cluster heads, we can determine the number of relay nodes being used in the middle-tier network. This is exactly the value calculated by the first term in the objective function. The second term is used to minimize the maximum buffer capacity of the relay nodes, which are the

secondary objectives. By choosing appropriate values for W_1 and W_2, we can select the relative importance of the two objectives being minimized. For example, if we set $W_2 = 0$, then the only parameter we are interested in minimizing is the number of relay nodes.

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

Constraint (2) specifies that a sensor node can communicate with a relay node j, only if j is within the transmission range of the sensor node. In other words, a sensor node i can transmit data to a relay node j, only if the distance between the sensor node i and the relay node j is less than the transmission range r_{max} of the sensor node i.

$$Y_j \geq X_{i,j} \qquad \forall i, 1 \leq i \leq n, \forall j, n+1 \leq j \leq n+m \qquad (3)$$

The relay node at location j must be included in the middle tier network, if it is selected as a possible cluster head by at least one sensor node i. Constraint (3) ensures that if a relay node j is chosen as a cluster head by one or more sensor nodes, then the relay node 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.

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

Constraint (4) requires that each sensor node belongs to exactly one cluster and transmits its data to the relay node that is selected to be the cluster head of its cluster. In other words, a sensor node can transmit data to exactly one relay node.

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

Constraint (5) calculates the total number of bits, R_j, buffered in relay node j during the interval T_r, by summing the data transmitted to it from all the sensor nodes belonging to the cluster C^j and then multiplying this value by the interval T_r. If a relay node j is selected to be included in the middle tier and a sensor node i belongs to its cluster C^j, then $X_{i,j} = 1$, and the data from sensor i contributes to the total data collected at node j.

$$R_j \le B_{max} \qquad \forall j, n + 1 \le j \le n + m \qquad (6)$$

Constraint (6) ensures that if a relay node j is selected, then the total bits buffered at the relay node j during the interval T_r do not exceed the buffer size B_{max}. Finally, the left hand side of constraint (6) is the total amount of bits buffered at the relay node j during the interval Tr. The right hand side B_{max}, of constraint (6), must be greater than or equal to the maximum of the amount of bits buffered by the relay nodes. Since the objective function is to minimize B_{max}, constraint (6) forces B_{max} to be the maximum buffer capacity required by any relay node, that is, the total amount of data to be buffered by any relay node in one round of data gathering cannot exceed B_{max}.

3.6 ILP Formulation for Minimizing the Buffer Size of Relay Nodes (ILP2)

The ILP formulation given in Section 3.5 minimizes the total number of relay nodes required to form the upper-tier network, and considers the buffer size as a secondary objective. This gives the lower bound for the number of relay nodes. However, it some cases, the total number of relay nodes may be given, and the problem is to find

out the placement of the given number of relay nodes such that the maximum size of the buffer is minimized. This can be easily achieved by the following modification of the ILP1.

$$\textbf{Minimize} \quad B_{max} \tag{7}$$

Subject to:

$$X_{i,j} \cdot d_{i,j} \leq r_{max} \qquad \forall i, 1 \leq i \leq n, \forall j, n+1 \leq j \leq n+m \tag{8}$$

$$Y_j \geq X_{i,j} \qquad \forall i, 1 \leq i \leq n, \forall j, n+1 \leq j \leq n+m \tag{9}$$

$$\sum_{j=n+1}^{n+m} X_{i,j} = 1 \qquad \forall i, 1 \leq i \leq n \tag{10}$$

$$R_j = T_r \cdot \sum_{i=1}^{n} b_i \cdot X_{i,j} \qquad \forall i, 1 \leq i \leq n, \forall j, n+1 \leq j \leq n+m \tag{11}$$

$$R_j \leq B_{max} \qquad \forall j, n+1 \leq j \leq n+m \tag{12}$$

$$\sum_{j=n+1}^{n+m} Y_j \leq y_{max} \qquad \forall j, n+1 \leq j \leq n+m \tag{13}$$

Equation (7) is the objective function that minimizes the maximum buffer capacity requirement of any relay node. Constraints (8) – (12) are analogous to the corresponding constraints in ILP1. Constraint (13) enforces the limit on the maximum number of relay nodes, that is, maximum number of relay nodes cannot exceeds y_{max}.

3.7 Conclusions

In this Chapter, we focus on a new formulation that, given a set of potential locations of relay nodes, optimally determines the number and locations of relay nodes that constitute the middle tier of the network. The relay node placement problem is solved in a way that ensures full coverage of the sensing are, with a minimum number of

nodes. Our formulation also determines the requisite buffer capacity needed at each node, so that data can be stored without buffer overflow, between successive visits by the MDC. We also present a modified ILP formulation that minimizes the maximum buffer size of the relay nodes, without exceeding the maximum allowable number of nodes.

CHAPTER IV

TRAJECTORY COMPUTATION FOR THE MDC

In this chapter, we present two heuristic approaches to compute the trajectory for the MDC, such that the maximum energy dissipated by any relay node is minimized. A number of papers have considered the use of complex trajectories, where the MDC visits each node individually [18], [44] and [45]. However, our goal is to use a very simple trajectory that can be easily traversed by the MDC. So, we consider the case where the MDC travels back and forth along a straight line, or along the circumference of a circle. A straight line trajectory has been shown to be a practical and useful option for mobile nodes in [13], and circular trajectories have been used to improve network lifetime in [51], [52]

4.1 Linear Trajectory Computation

Given the positions and the expected loads of the relay nodes, our approach finds a straight line which is followed by the MDC as the path to collect the data from the relay nodes, such that the energy dissipation by the relay nodes are minimized. We noted that the energy minimization can be accounted as the sum of the energy dissipated by the relay nodes. In such case, any standard weighted-regression analysis method can be applied to compute the best fitting trajectory. However, in our network model, if any relay node depletes power, then all sensor nodes belonging to the relay node become inaccessible, and the network may fail to meet the reliability standard. In this case, to extend the lifetime, it is important to minimize the maximum energy dissipated by any relay node in the network. We propose a simple approach that can be used to compute a

straight line trajectory that minimizes the maximum energy (E_{max}) dissipated by any relay node in the network.

4.1.1 Find Optimal Horizontal Trajectory (Algorithm-I)

Let **R** be the set of relay nodes, where each relay node is given a unique label j, 1 $\leq j \leq$ |**R**|. Also, let the coordinate (j_x, j_y) specify the position of relay node j, $\forall j \in$ **R**.
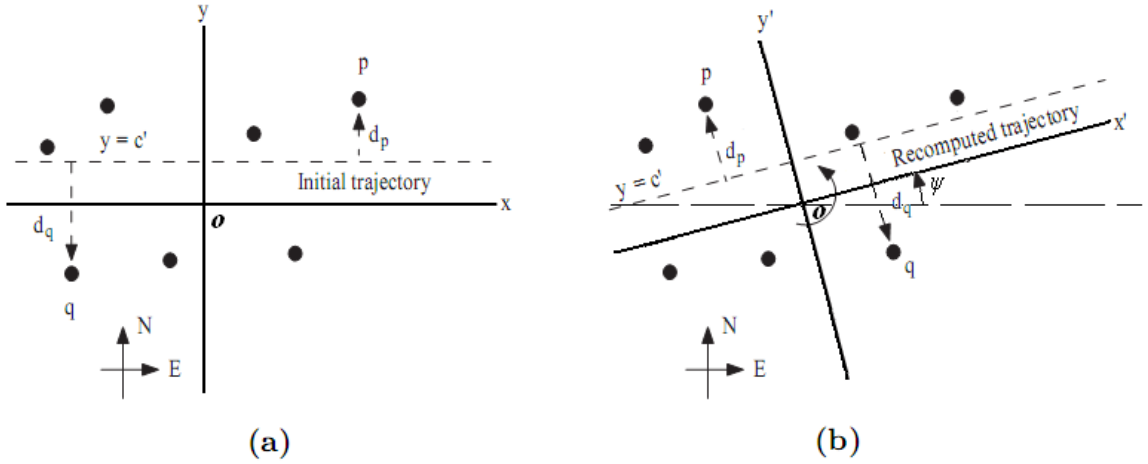
Figure 4. 1 Computation of the (a) initial trajectory, (b) improved trajectory by rotating the orientation of the axis.

We start by assuming that, given the area of the network, the trajectory is a horizontal line. Let the line be given by the equation $y = c$, where c is a constant. We set the initial value of c as the midpoint of the y-coordinate values of the uppermost and the lowermost relay nodes in the network. Since a relay node j transmits to the MDC when the MDC is closest to j, the transmission distance of j is the vertical distance (i.e., y-axis distance) of j, projected on the trajectory line $y = c$. Using this initial trajectory, we find the relay node p (q) that dissipates the maximum amount of energy by transmitting the data $B_p(B_q)$ to MDC which is on the trajectory, among all nodes located in the above (below) the initial line. To minimize the maximum energy of the relay nodes, we need to

find a new value c', $q_y \leq c' \leq p_y$, for the constant c', so that the energy dissipation of nodes p and q is balanced (Figure 4.1(a)).

We achieve this by setting the energy dissipation of nodes p and q (computed using the model discussed in Section 3.2), corresponding to the trajectory $y = c'$, as equal. Let the vertical distances of the node p and the node q, from the new trajectory $y = c'$ be d_p and d_q, respectively. Also, let the vertical distance between nodes p and q be λ. Then we have:

$$d_p^2 - \gamma d_q^2 = \xi \qquad (14)$$

$$d_p + d_q = \lambda \qquad (15)$$

where $\gamma = \frac{B_q}{B_p}$, and $\xi = \frac{1}{\beta}(\alpha_1 + \alpha_2)(\gamma - 1)$. The values of α_1, α_2 and β are obtained from network power model discussed in Section 3.2. We obtain the new value of $c'(= q_y + d_q)$ by solving the above two equations.

Algorithm-I is to find optimal linear trajectory in original reference frame. The pseudo code is showed on following steps:

(1) Input R a set of relay node with coordinate (j_x, j_y) and weight B_j

(2) Set a line $y = c$, which c is midpoint of the uppermost and lowermost relay nodes position

(3) Calculate and find the relay nodes p (q) with maximum amount of energy dissipating above (below) the line $y = c$.

(4) Calculate $y = c'$, $q_y \leq c' \leq p_y$ by solving below equations:

$$\begin{cases} d_p^2 - \gamma d_q^2 = \xi \\ d_p + d_q = \lambda \end{cases}$$

where $\gamma = \frac{B_q}{B_p}$, and $\xi = \frac{1}{\beta}(\alpha_1 + \alpha_2)(\gamma + 1)$. We obtain $c'(= q_y + d_q)$

(5) Recheck if the relay nodes p (q) dissipates maximum amount of energy above (below) the line $y = c'$. If yes, the line $y = c'$ is the trajectory for MDC, otherwise, set some other relay node to p (q) which dissipates maximum amount of energy above (below) the line $y = c'$. Then go step (4) to re-calculate the new $y = c'$.

(6) Output $y = c'$, which is the optimal linear trajectory of MDC in original reference frame.

4.1.2 Find the Overall Optimal Linear Trajectory (Algorithm-II)

Based on the actual layout of the networking area and the distribution of the sensor nodes, a different orientation, rather than strictly horizontal, for the trajectory may be beneficial. Once we obtain the initial trajectory, we compute the best orientation of the trajectory by rotating it in the range $0° \sim 180°$. We rotate the line by a small angle ψ, at a time, and get a new orientation, as shown in Figure 4.1(b). At each orientation, we recomputed the value of E_{max}, using the approach described above. After the rotation is complete, we select the orientation that gives the minimum among all orientations. As shown in the Section 5.2, this rotation can substantially improve the solution, based on the actual layout of the network.

Algorithm-II is to find final optimal linear trajectory by rotating the reference frame from $0°$ to $180°$. The pseudo code is showed on following steps:

(1) Input $\boldsymbol{R}$ a set of relay node with coordinate (j_x, j_y) and weight B_j

(2) Transfer the original coordinate system to new system by rotating each small angle ψ , which can be set any value depending on the computational precision

(3) Call Algorithm-I to obtain $y = c'$.

(4) Add angle ψ, *and* repeat (2)~(3) to obtain minimum amount of energy dissipation for some Φ and corresponding line.

(5) Convert the line $y = c'$ in the rotated coordinate system to the line $y = a\,x + b$ in original coordinate system by calculating a and b.

(6) Output $y = a\,x + b$ which is the final optimal linear trajectory of MDC.

4.2 Circular Trajectory Computation

The linear trajectories of MDC are particularly useful for narrow, rectangular, or elongated sensing areas. However, in general, the sensing regions are often more accurately approximated by regular polygons, or circular areas. In such cases, a circular trajectory within the sensing area would lead to more energy-efficient implementations. In this section, we present our algorithm for computing a circular trajectory for the MDC that minimizes the maximum energy (E_{max}) of any relay node in the network, given the positions and the expected loads of the relay nodes. A circular trajectory is defined by the following two parameters:

- The co-ordinates of the centre of the circle, and

- The radius of the circle.

In the remainder of this section, we first present a simplified heuristic, which assumes that the co-ordinates of the centre are given, and simply computes the radius of the circular trajectory to be followed by the MDC. Then, we present a more generalized algorithm that computes both the radius and the centre of the circular trajectory.

4.2.1 Find Optimal Circular Trajectory with Fixed Center (Algorithm-C1)

Let R be the set of relay nodes, where each relay node is given a unique label j, $1 \leq j \leq |R|$, and let the coordinate (j_x, j_y) specify the position of relay node j, $\forall j \in R$.

Algorithm-C1 is a modification of Algorithm-I, where the MDC follows a circular trajectory expressed as (c (x_0, y_0), r). Here, c (x_0, y_0) is the center of the circle, which is already specified and r is the radius of the circle, which will be determined by the algorithm. Given a circle, center c (x_0, y_0) and an initial radius r_0 in the network area, we find the relay node p (q) that dissipates the maximum amount of energy by transmitting the data B_p (B_q) to MDC which is on the trajectory, among all nodes located in the outside (inside) of the initial line. As in Algorithm-I, in order to minimize the maximum energy of the relay nodes, we need to find a new value r', $r_q \le r' \le r_p$, for the r', (as shown in Figure 4.2), so that the energy dissipation of nodes p and q is balanced.
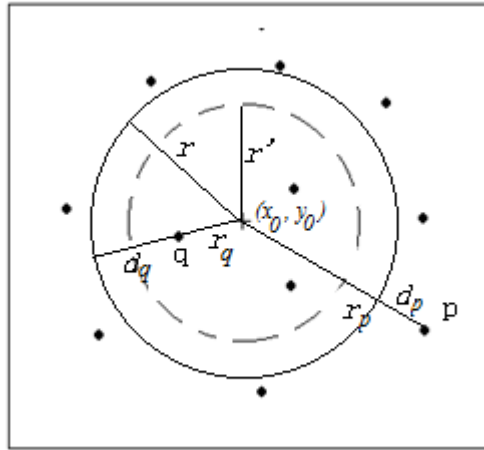
Figure 4. 2 Computing optimal circular trajectory with fixed center.

We achieve this by setting the energy dissipation of nodes p and q corresponding to the circle (c (x_0, y_0), r'), as equal. Let the perpendicular distances of the node p and the node q, from the new circle (c (x_0, y_0), r') be d_p and d_q, respectively, and $d_p + d_q = \lambda$. Then, we obtain the new value of $r'(= r_q + d_q)$ by solving the above equations (14) and (15).

The pseudo code for Algorithm-C1is outlined below:

(1) Input R a set of relay node with coordinate (j_x, j_y) and weight B_j , *also c* (x_0, y_0).

(2) Set a circle (c (x_0, y_0), r_0), where r_0 is midpoint of the farthest and nearest relay nodes from center c (x_0, y_0).

(3) Calculate and find the relay node p *(q)* with maximum amount of energy dissipating outside (inside) the line circle (c (x_0, y_0), r_0).

(4) Calculate the radius of the circle (c (x_0, y_0), r'), $r_q \leq r' \leq r_p$ by solving below equations:

$$\begin{cases} d_p^2 - \gamma d_q^2 = \xi \\ d_p + d_q = \lambda \end{cases}$$

where $\gamma = \frac{B_q}{B_p}$, and $\xi = \frac{1}{\beta}(\alpha_1 + \alpha_2)(\gamma + 1)$. We obtain $r'(= r_q + d_q)$.

(5) Check if the relay nodes p *(q)* dissipates maximum amount of energy outside (inside) the circle (c (x_0, y_0).

   a) If yes, the circle (c (x_0, y_0) r') is the circular trajectory for MDC.

   b) Else, determine new relay node to p *(q)* which dissipates maximum amount of

   energy outside (inside) the updated circle (c (x_0, y_0), r'), and go back to step (4).

(6) Output the circle (c (x_0, y_0), r'), which is the optimal circular trajectory of MDC with the center c (x_0, y_0), that minimizes E_{max}.

4.2.2 Find Optimal Circular Trajectory (Algorithm-C2)

If the relay nodes are uniformly distributed in the sensing area, then a circular trajectory centred near the middle of the sensing field is usually a good choice. However, for uneven node distributions, or in cases where there is a relatively large variation in the loads of the relay nodes, it may be beneficial to select a different centre for the circular trajectory. Algorithm-C2 is is simply an iterative process that selects different potential

centres for the trajectory, and calculates the optimal radius (by calling Algorithm-C1) corresponding to each centre. Finally, it selects the trajectory that leads to the lowest value of E_{max}, among all the potential trajectories that have been examined.

In order to determine the set of potential positions that can be used as the centres of circular paths in Algorithm-C2, we first divide the sensing area using horizontal and vertical grid lines. The intersection of the grid lines are then selected as potential centres, as shown in Figure 4.3. The size of grids can be set, based on the level of accuracy required by the user. A finer grid will result in more trajectories being examined, but will also require more computation.
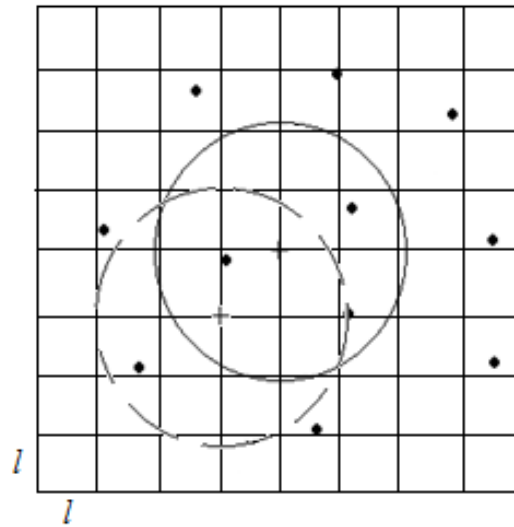
Figure 4. 3 Setting grids as potential center of optimal circular trajectory

A brief outline of Algorithm-C2 is given below:

(1) Set grid size to create P intersection points.

(2) Select each grid intersection point as the center $c(x_i, y_i)$ of a potential circular trajectory.

(3) Call Algorithm-C1 to find radius r_i, which results in minimum energy dissipation (E^i_{max}) for a trajectory centred at (x_i, y_i) .

(4) Output the circular trajectory, $(c\ (x_k, y_k), r_k)$, such that $E^k_{max} = \text{Min}\{E^i_{max}|\ i = 1, 2, \dots P\}$.

4.3 Conclusions

In this Chapter, we have presented two algorithms for calculating simple trajectories for a MDC. The goal in both cases is to minimize the maximum energy dissipation of any relay node, and consequently to extend the network lifetime as much as possible. The first algorithm computes a linear trajectory, where the MDC travels back and forth along a straight line. The second algorithm is an extension of the first one, that determines an appropriate circular trajectory for the MDC. The execution time is quite short (fraction of a second) for the networks we tested, and does not depend on the number of sensor nodes.

CHAPTER V

EXPERIMENTAL RESULTS

5.1 Simulation of ILP Formulation

In this section, we present the simulation results of our formulation for selecting the relay nodes in the middle tier of the network. We have conducted different sets of experiments, by setting different values for the parameters in our formulation.

In the first set of experiments, our objective is to jointly optimize the number of relay nodes required to form the middle tier relay node network, and the maximum buffer requirement by the relay nodes. The relative importance of each term is determined by the value of the constant W_1 and W_2, used in equation (1). Since our primary goal is to minimize the number of relay nodes, while the secondary objective is to reduce the buffer requirement of each node, we set $W_1 = 8000$ and $W_2 = 0.1$ for our simulations. We have used an experimental setup, where the sensor nodes are randomly distributed over a 200×280 m^2 area. We have assumed that the maximum transmission range of a sensor node, $r_{max} = 40$m. The results are obtained by CPLEX 9.1 solver.
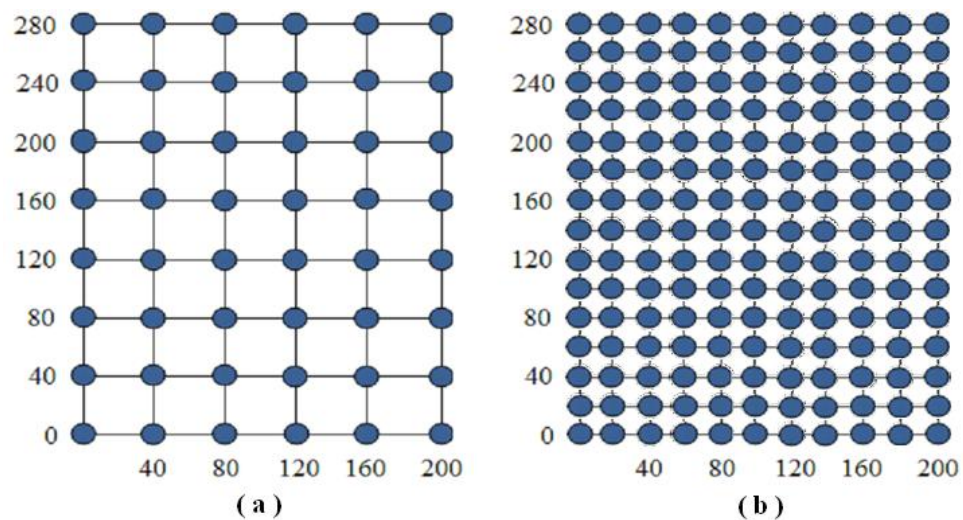
**Figure 5. 1 Grid Sensor Network Model. (a) 48-Grid (b) 165-Grid**

We have simulated our scheme with different number of sensor nodes, ranging from 100 – 600 nodes. For each size of the sensor node network, we randomly generate five 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 section reflect the averages of all the different runs for each network size. As in [50], we have used a grid based approach to compute the initial *potential* positions of the relay nodes. The number of potential relay node locations were set to 48 (for coarse grid) and to 165 (for fine grid), as shown in Figure 5.1. These two configurations are referred to as 48-Grid and 165-Grid respectively in the following discussions of our results. We have also assumed that each sensor node generates data at a rate of 100 bits/unit-time, i.e., $b_i = 100$, $\forall i,\ 1 \leq i \leq n$.
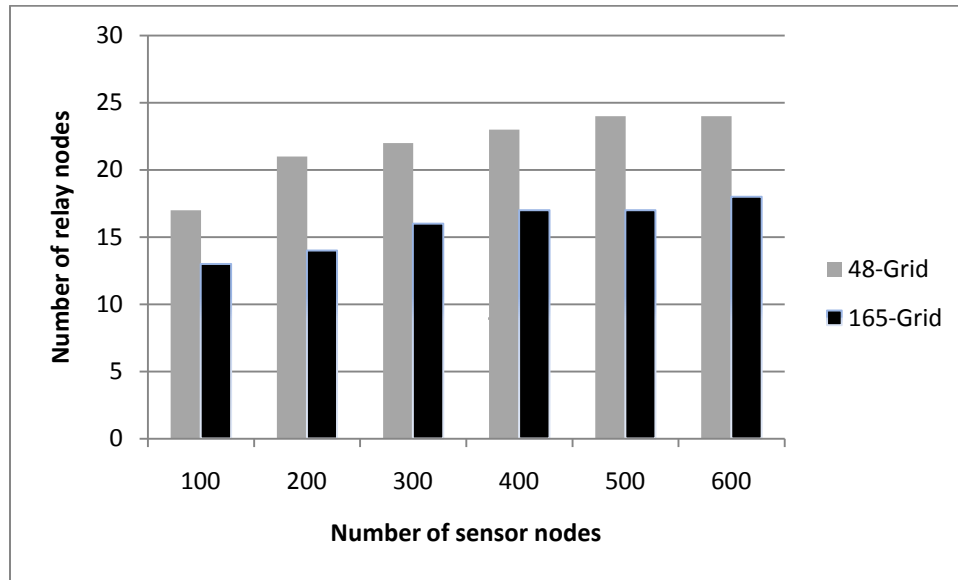
Figure 5. 2 The number of relay nodes required to form the middle-tier network for different number of sensor nodes

Figure 5.2 shows the number of relay nodes needed in the middle tier for different number of sensor nodes distributions. We note that for the same distribution, using 165-

grid (fine grid) consistently leads to better solutions compared to 48-grid. This is because the 165-grid configuration results in a much larger search space. This significantly increases the computational complexity, but also leads to better solutions. It is also interesting to note that, although the number of relay nodes required in the middle tier increases with the number of sensor nodes, the rate of increase is not very high. For example using the 165-grid only a few additional relay nodes are required to cover 600 sensor nodes, as compared to 100 sensor nodes.
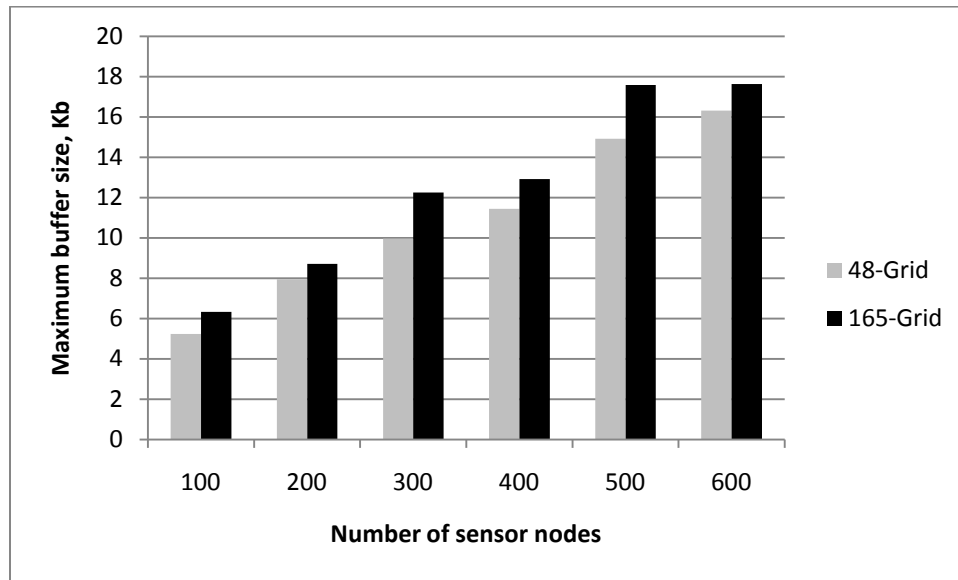
Figure 5. 3 The maximum buffer capacity per node required for different number of sensor nodes

Next we consider the buffer requirements of the relay nodes selected for the middle tier. Figure 5.3 shows the value of the maximum buffer size (B_{max}) calculated by our ILP using 48-grid and 165-grid configurations. At first glance, the figure seems to indicate that 48-grid produces better results (i.e. lower buffer size) compared to 165-grid. However, we must remember that the 48-grid configuration requires a higher number of relay nodes. This means that the same amount of data is distributed over more relay

nodes, resulting in a lower buffer requirement per node. But, when we compare the total

buffer requirements (as shown in Fig. 5.4), we see that the 165-grid generates better

results, both in terms of the number of relay nodes and the total buffer size.
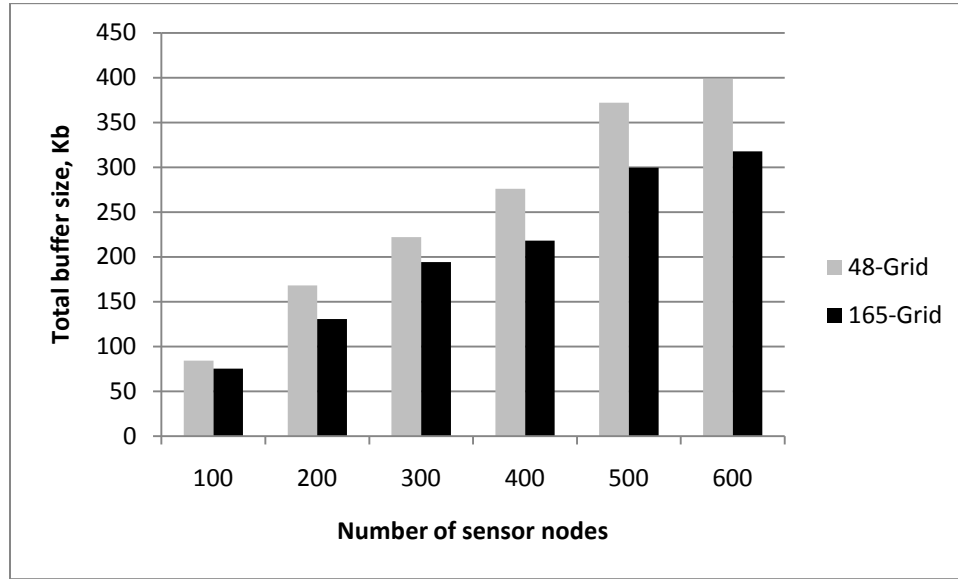
Figure 5. 4 The maximum buffer capacity per node required for different number of sensor nodes

5.2 Simulation of Trajectory Computation Algorithm

The goal of our trajectory computation algorithm is to calculate the trajectory of

the MDC (either along a straight line, or in a circular path), such that the maximum

energy dissipation (E_{max}) of any relay node is minimized. Figure 5.5 shows the average

value of E_{max}, for different size of sensor node networks, corresponding to a linear

trajectory that minimizes the value of E_{max}, for each configuration. As before, we note

that although the value of E_{max} appears to be lower for 48-grid, this is because it requires

more relay nodes resulting in lower energy dissipation per node. As expected, the value

of E_{max} increases steadily with the number of sensor nodes for 165-grid case. However,

for the 48-grid case, we notice an anomalous case, where the value of E_{max} for 300 sensor

nodes is actually higher than that for both 400 and 500 sensor node distributions. This is because, the performance of coarse grid configurations is not always reliable and may sometimes fail to find a good solution (e.g. for the 48-grid and 300 sensor node case). On the other hand, when we use finer grids (e.g. 165-grid), the computational complexity increases, but we get more consistent and reliable solutions.
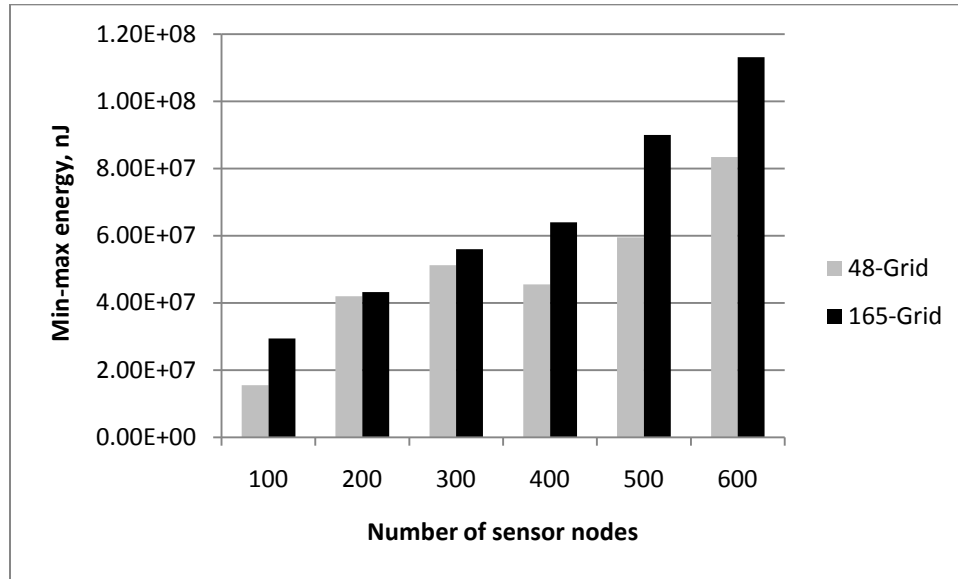
Figure 5. 5 The minimum of the maximum energy dissipation by the relay nodes in the networks with different number of sensor nodes, for a linear trajectory

Figure 5.6 shows how the value of E_{max} varies with the angle of the straight line trajectory for the MDC. In general, the angle at which the value of E_{max} is minimized will depend on the distribution of the sensor nodes and the shape of sensing area. In our experiments the sensing area was a rectangular shape (200m along x-axis and 280m along y-axis), and the sensor nodes were randomly distributed in the sensing field. Therefore, we can expect that the best trajectory will be a (nearly) vertical line. This is exactly what we find in Fig 5.6, where the minimum value of E_{max} is obtained at an angle of about 90°

for each sensor node distribution. We also note that the value of E_{max} varies widely with

the angle for higher values of n, but as n decreases, these variations are greatly reduced.
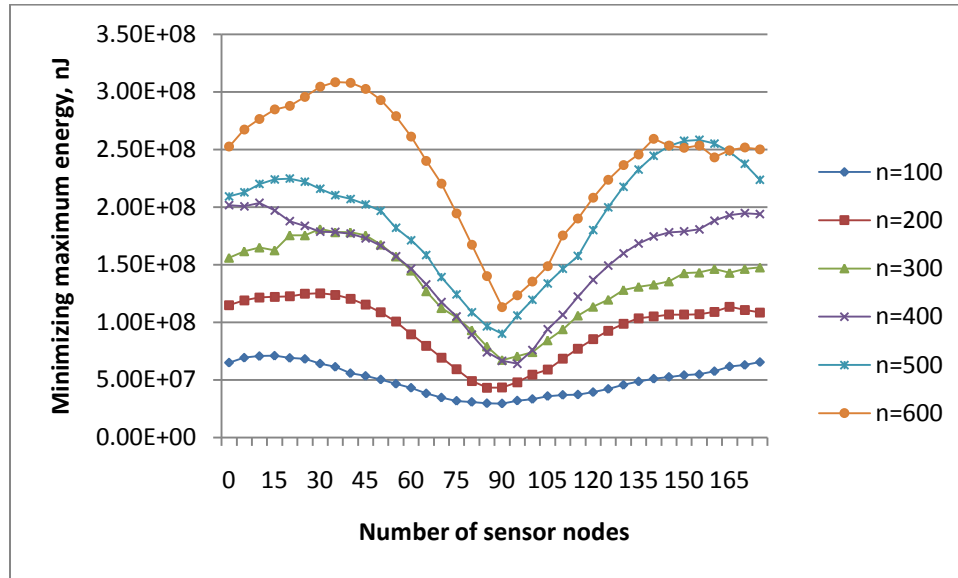
Figure 5. 6 Variation of the E_{max} with the rotation of the axis, in the networks with

different number of sensor nodes with grid setting 165-Grid

Figure 5.7 shows the average energy dissipations for 100~600 sensor nodes

networks, using 165-grid configurations, using linear and circular trajectories. In general,

the energy dissipation of relay nodes increases as with the number of sensor nodes, and

the circular trajectories always result in lower energy dissipations. This is because,

although the sensing area was a rectangular shape (200m along *x*-axis and 280m along *y*-

axis), the area was not narrow enough to be appropriate for a linear trajectory. A circular

path allowed the MDC to get closer to more relay nodes, and performed better overall.

This seems to indicate that it would be beneficial to select the type of trajectory, based on

the shape area of sensing area. We also note that the rate at which the maximum energy

dissipation of relay nodes (E_{max}) increases with the number of sensor nodes, is lower for

circular trajectories compared to linear trajectories, for the rectangular area.
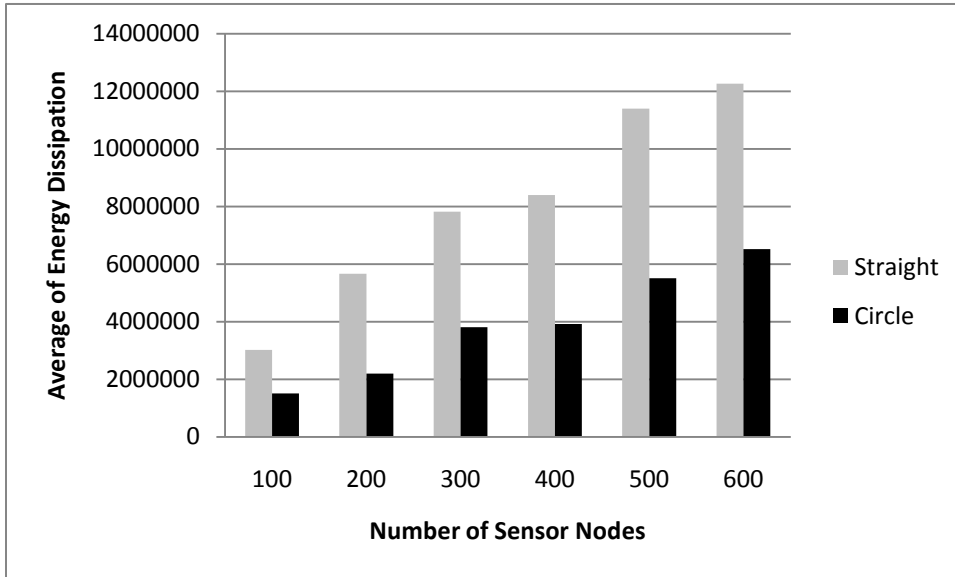
Figure 5. 7 Comparison of the maximum energy dissipation of the relay node between straight and circular trajectories followed by MDC

Finally, Figures 5.8 and 5.9 show the execution times for Algorithm I-II and Algorithm C1-C2 respectively. We can see that the execution time is not dependent on the number of sensor nodes, but does depend on the number of relay nodes. Since the 48-grid configuration results in a higher number of relay nodes, the solution time also increases compared to the 165-grid solutions.
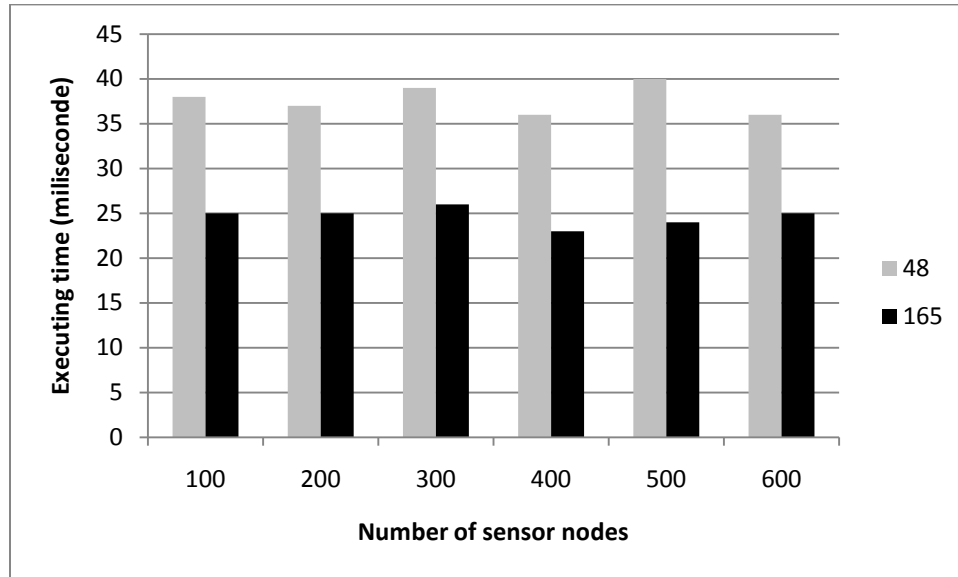
Figure 5. 8 Executing time by Algorithm I-II
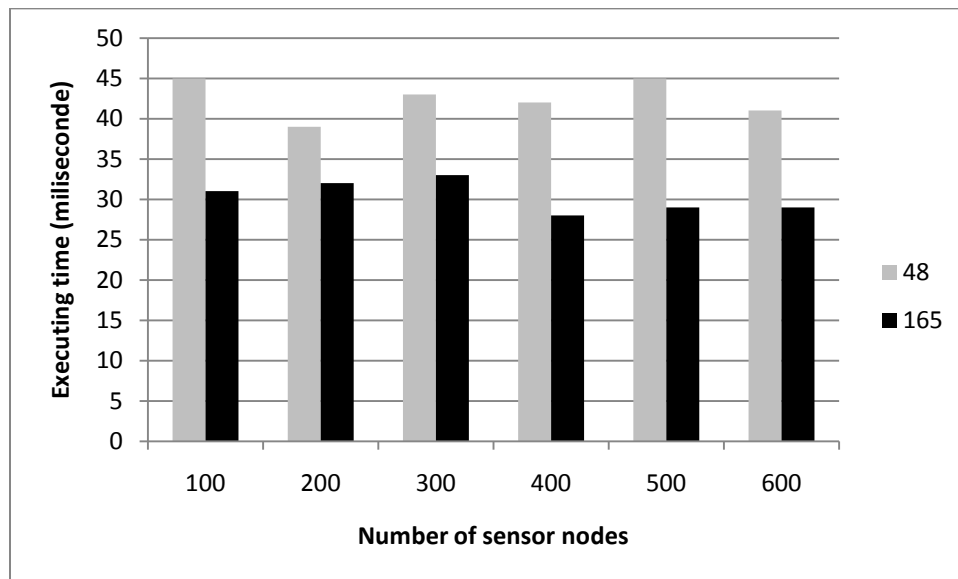
Figure 5. 9 Executing time by Algorithm C1-C2

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

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

i)   each sensor node is covered by at least one relay node;

ii)   no relay node suffers from the buffer overflow;

iii)   maximum buffer requirement of the relay nodes are minimized.

Our ILP is able to generate optimal solutions for networks with hundreds of sensor nodes.

We have also proposed two heuristic algorithms for calculating the trajectory for the MDC that minimizes the maximum energy dissipation of the relay nodes. The first algorithm assumes that the MDC travels back and forth along a straight line, and is suitable for narrow, elongated sensing areas. The second algorithm extends this for circular trajectories.

6.2 Future Work

The work presented in this thesis can be extended in a number of ways. These include:

- Developing alternative types of paths, such as rectangular or elliptical trajectories to be followed by the MDC to prolong the lifetime of wireless sensor network,

- Considering latency and fault tolerance, when designing the middle tier of the network, and

- Extending the work to include multiple mobile elements, e.g. multiple MDCs travelling along parallels straight lines.

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