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Energy Aware Design Strategies for Heterogeneous Sensor Networks

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Energy Aware Design Strategies for Heterogeneous Sensor Networks

by

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Energy Aware Design Strategies for Heterogeneous Sensor Networks

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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 incorporates the results of a joint research undertaken in collaboration with Ms. Ritu Chaturvedi. That research was done under the supervision of my thesis supervisors, Professors Subir Bandyopadhyay and Arunita Jaekel. The results of that research are given in Chapter 6 of this thesis. In that investigation, the key ideas, the primary contributions, the experimental designs, the data analysis and the interpretations were performed by myself working under my supervisors. The contribution of Ms. Ritu Chaturvedi was in developing the programming part.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-author(s) to include the above material(s) in my thesis.

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This thesis includes some materials from 4 original papers that have been previously published in peer reviewed journals/conferences, as follows:

Thesis Chapter	Publication title/full citation	Publication Status
Chapter 3	Optimal Placement of Relay Nodes in Two-Tiered, Fault Tolerant Sensor Networks; Bari, A.; Jaekel, A.; Bandyopadhyay, S.; Computers and Communications, 2007. ISCC 2007. 12th IEEE Symposium on; 1-4 July 2007 Page(s):159–164 Digital Object Identifier 10.1109/ISCC.2007.4381590 ©IEEE 2007. Reprinted with permission of IEEE.	Published
Chapter 4	Clustering strategies for improving the lifetime of two-tiered sensor networks Bari, A.; Jaekel, A.; Bandyopadhyay, S.; Journal: Computer Communications. Volume 31, Issue 14, 5 September 2008, Pages 3451–3459. doi:10.1016/j.comcom.2008.05.038 ©Elsevier 2008. Reprinted with permission of Elsevier.	Published
Chapter 5	Energy-efficient design techniques for large-scale, two-tiered sensor networks; Bari, A.; Jaekel, A.; Bandyopadhyay, S.; Journal: Ad Hoc and Sensor Wireless Networks (AHSWN). To appear. Reprinted with permission of Old City Publishing.	In press
Chapter 6	Energy Aware Distributed Clustering in Two-Tiered Sensor Networks; Bari, A.; Chaturvedi, R.; Jaekel, A.; Bandyopadhyay, S.; Computer Communications and Networks, 2009. ICCCN 2009. Proceedings of 18th IEEE International Conference on 3-6 Aug. 2009 Page(s):1–8 Digital Object Identifier 10.1109/ICCCN.2009.5235368 ©IEEE 2009. Reprinted with permission of IEEE.	Published

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Abstract

A sensor network is an interconnection of sensor nodes, each equipped with sensor(s), a micro-processor, some memory, and a wireless transceiver. Data from sensor nodes are usually collected at a central entity known as the *base station* or *sink*. Sensor nodes are powered by lightweight batteries, and it is often not feasible to replace or recharge these batteries. Therefore, the *lifetime* of a sensor network is considered to be over as soon as the batteries of *critical* nodes are depleted. For scalability and efficient data gathering, a hierarchical two-tier architecture has been proposed in the literature, where the sensor nodes constitute the lower-tier. The network is organized as a number of clusters, and, in each cluster, one node is assigned the role of the cluster head. The cluster heads constitute the upper-tier of the network. Each cluster head receives data from the sensor nodes in the corresponding cluster and communicates the data to the base station. The cluster heads may communicate with the base station either directly, using *single-hop* communication, or by forming a network among themselves using *multi-hop* communication. In recent years, a special node, provisioned with higher initial energy and communication capabilities, called the *relay node*, has been proposed in the literature to act as a cluster head in hierarchical sensor networks. The three major subproblems when designing this type of network are i) to find a suitable placement of the relay nodes within the network, using the minimal number of relay nodes, so that each sensor node can communicate effectively with its cluster head, and the upper-tier network can tolerate fault(s), ii) to assign sensor nodes to clusters in an energy efficient manner, and iii) to compute a routing scheme for the relay nodes, such that the network lifetime is maximized. In this dissertation, we present two strategies for the placement of relay nodes, and five energy-aware strategies for the clustering and routing in a hierarchical, heterogeneous, two-tiered sensor network using relay nodes as cluster heads.

Dedication

To my parents, (Late) Dr M. A. Salam, (Late) Mrs Salma Salam, my sister, Lovely, my wife Limi and my children Chhoaa, Chhuti and Prashna.

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I take this opportunity to thank my thesis supervisors, Dr. Subir Bandyopadhyay and Dr. Arunita Jaekel, for their guidance and cooperation throughout my graduate studies. This work could not have been achieved without their help and support. I also thank Dr. Yash P. Aneja, Dr. Richard Frost and Dr. Jessica Chen for their valuable time, cooperation and thoughtful suggestions.

I wish to express my sincerest gratitude to my wife and my children for their understanding and cooperation all the way.

Contents

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Acronym & Notation Used

Acronym

ADC - analog-to-digital converter.

ADC-M - Algorithm for Distributed Clustering in Multi-hop Networks.

ADC-S - Algorithm for Distributed Clustering in Single-hop Networks.

AN - Application/Aggregation node.

BER - bit error rate.

EECS - Energy-efficient clustering approach.

HEED - Hybrid Energy-Efficient Distributed clustering.

GC - Greedy-Clustering.

GPS - Global positioning system.

ILP - Integer Linear program.

ILP-FP - ILP Formulation for Fault Tolerance.

ILP-FS - ILP for Flow-Splitting Model.

ILP-M - ILP Formulation for Multi-hop Hop Routing.

ILP-NFS - ILP Formulation for Non Flow-Splitting Model.

ILP-S - ILP Formulation for Single Hop Routing.

ILP-SC - ILP Formulation for Single Coverage.

LDC - Least-Distance-Clustering.

LEACH - Low-Energy Adaptive Clustering Hierarchy.

LP - Linear program.

MCVC - Minimal-Cardinality-Variance-Clustering.

MDC - Mobile data collector.

MH - minimum hop.

MHDTM - multi-hop data transmission model.

MILP - Mixed Integer Linear program.

MTE - minimum-transmission-energy.

NFS-H - Non Flow Splitting-Heuristic.

NLP - Non Linear Programm.

QoS - Quality of Service.

SHDTM - single-hop data transmission model.

WSN - wireless sensor network.

Notation Used

- α_1: Energy coefficient for receiving data.
- α_2: Energy coefficient for transmitting data.
- β: Energy coefficient for amplifier.
- γ_j: Color assigned to relay node j.
- ℓ: Number of predecessor relay nodes.
- λ_k: k-th predecessor of a relay node j.
- μ: Maximum number of other relay nodes to be taken into the consideration by relay node j while transforming flow-splitting routing to non-flow-splitting routing.
- ξ_j: Energy required to send the data corresponding to a single sensor node from j to the next relay node in the multi-hop path from j to the base station.
- $\mathcal{A}^j$: Set of next hop relay nodes for the relay node j under flow-splitting routing.
- B_j: Total number of bits generated by the sensor nodes belonging to cluster j in one round.
- $\mathcal{B}_{i,j}$: Bit error rate of link between node i and node j.
- b_i: Number of bits generated by sensor node i per round.

- C: A large constant, greater than the total number of bits received by the base station in a round.

- $\mathcal{C}^j$: Set of sensor nodes currently belonging to the j-th cluster, with the relay node having label j as the cluster head, $j \in \mathcal{R}$.

- C_j: Continuous variable indicating the number of other relay node(s) that may be used by relay node r_j, at location j, to forward data towards the base station.

- $c_{k,j}$: Input indicating whether relay node k, in a multi-hop network, sends it's data to the relay node j. Different routing schemes can be implemented by setting the values of $c_{k,j}$ appropriately.

$$c_{i,j} = \begin{cases} 1, & \text{if relay node } i \text{ uses the link } i \rightarrow j \text{ to communicate data to another} \\ & \text{relay node (or to the base station) } j, \\ & \quad \forall i, j : n+1 \leq i, j \leq n+m+1,\ i \neq n+m+1, \\ 0, & \text{otherwise.} \end{cases}$$

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

- d_{max}: Transmission range of a relay node.

- $E_{R_x}(b)$: Energy spent by the transceiver to receive b bits.

- $E_{T_x}(b, d)$ Energy spent by the transceiver to transmit b bits at a distance d.

- E_j: Total energy currently required by relay node j.

- $E_{initial}$: Initial energy of each relay node.

- F_{max}: The total energy spent per round by the relay node which is being depleted at the fastest rate.

- $f_{j,k}$: Number of bits sent by relay node j to relay node k in one round.

- $g_1, g_2, \ldots, g_\ell$: Predecessor relay nodes of j.

- j: Label of a relay node.

- k: Label of a relay node.

- k_s: Desired number of relay nodes covering each sensor node.

- k_r: Desired number of other relay node that a relay node is able to use to forward data towards the base station in a multi-hop data communication model.

- $\mathcal{L}$: Maximum possible number of relay nodes in the path of any relay node to the base station,

- M_j: Maximum energy required by all relay nodes in the network, as known by the relay node j in the distributed algorithm.

- $\mathcal{M}$: Maximum possible number of relay nodes which can be predecessors of any relay node.

- m: Total number of relay nodes, with each relay node having a unique label from $n + 1$ to $n + m$.

- m_p: The total number of possible positions of relay nodes, with each position having a label from $n + 1$ to $n + m_p$.

- $\mathcal{N}_{lifetime}$: Lifetime of the network in rounds.
- n: Total number of sensor nodes, with each sensor node having a unique label from 1 to n.
- n_j^0: Number of sensor nodes which are in cluster $\mathcal{C}^j$.
- n_j^i: Number of sensor nodes whose data is routed from the i-th predecessor of $j, 1 \leq i \leq \mathcal{M}$,
- n_j: Total number of sensor nodes processed using relay node j.
- $\mathcal{P}$: Set of colors, to be used for coloring G.
- Q_j: Maximum of $(E_j + \xi_j, E_{j_1} + \xi_{j_1}, E_{j_2} + \xi_{j_2}, \ldots, E_{j_h} + \xi_{j_h})$.
- q: Path loss exponent.
- $q_{j,k}$: Path loss exponent between link $j \rightarrow k$.
- R_j: Number of bits received by relay node j from other relay nodes and from its own cluster in one round.
- $\mathbb{R}_j$: Number of bits received by relay node j from other relay nodes in one round.
- $\mathcal{R}$: Set of relay nodes in the network.
- $\mathcal{R}^p$: Set of potential locations for the relay nodes in a network.
- r_{max}: Transmission range of a sensor node.
- $\mathcal{S}$ be the set of sensor nodes in the network.

- s: Label of a sensor node.

- T_j: Number of bits transmitted by relay node j in one round.

- $\mathcal{T}^j$: Number of sensor nodes belonging to relay node $\mathcal{C}^j, j \in \mathcal{R}$.

- $\mathcal{U}^j$: Set of sensor nodes that are covered by relay node j but have not been allocated to any cluster yet.

- w: The maximum number of sensor nodes that a relay node can allocate to the clusters.

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

$$X_{i,j} = \begin{cases} 1, & \text{if sensor node } i \text{ belongs to the cluster of relay node } j, \\ & \quad \forall i,j : 1 \le i \le n, n+1 \le j \le n+m, \\ 0, & \text{otherwise.} \end{cases}$$

- $Y_{j,k}$: Binary variable defined as follows:

$$Y_{j,k} = \begin{cases} 1 & \text{if relay node } j \text{ transmits to relay node } k, \\ 0 & \text{otherwise.} \end{cases}$$

- $\mathcal{Y}_j$: Binary variable defined as follows:

$$\mathcal{Y}_j = \begin{cases} 1 & \text{if the relay node at location } j \text{ is selected to be} \\ & \quad \text{includes in the upper-tier network,} \\ 0 & \text{otherwise.} \end{cases}$$

- z: Label of a relay node.

Chapter 1

INTRODUCTION

1.1 Sensor Networks

A wireless sensor network (WSN) is a network of battery-powered, multi-functional devices, known as *sensor* nodes. Each node typically consists of a micro-controller, a limited amount of memory, sensing device(s), and wireless transceiver(s) [1]. Nodes in a sensor network normally communicate via radio links [1], [40], [46]. A sensor network usually tracks/monitors some physical or environmental attributes or parameters in the area where the network is deployed. For example, a sensor network can be deployed for measuring the humidity or the temperature of a certain region, for tracking some objects, as well as for monitoring habitats, battlefields, human health conditions or nuclear radiation levels [1].

A sensor node is typically small in size (e.g., MICA2-DOT [73] is 25 mm in diameter and 6 mm in height) and the capabilities of a sensor node, in terms of processing, memory, communications and energy provisioning are limited. However a sensor network performs bigger tasks through the collaborative efforts of a large number (hundreds or even thousands) of sensor nodes that are densely, and possibly redundantly, deployed within the sensing field [1], [2], [27]. Data from each node in a sensor network are gathered at a central entity, often called the *base station* [1], [46]. The base station is not constrained with respect to power or other capabilities and its location is usually fixed[1]. The data gathered by the base station can be accessed, even from a remote location, for further analysis and processing. Fig. 1.1 shows a general layout of a sensor network.

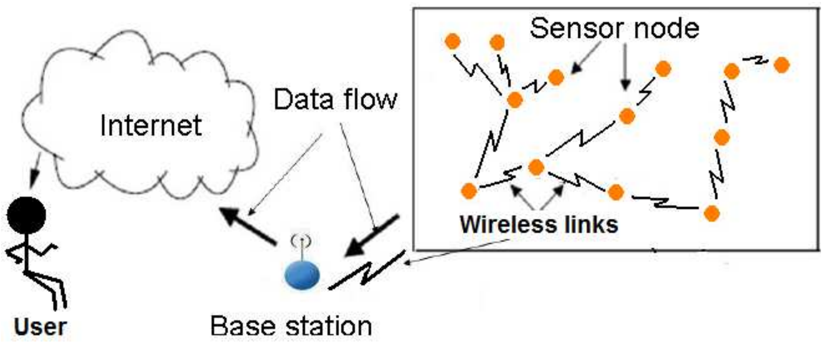

Figure 1.1: A general layout of sensor network

In many applications, sensor networks are deployed in a remote and/or hostile territory and are expected to function in an unattended manner. Sensor nodes are powered by batteries, and recharging or replacing the batteries is often not feasible due to economic reasons and/or environmental constraints [1]. A major source of power dissipation in a sensor network is due to the energy needed for wireless communication, which increases rapidly with the increase of the distance between the source and the destination of the communication [46]. Therefore it is extremely important to design

[1]Some researchers have also investigated sensor networks with multiple and/or mobile base station(s) [75], [78].

communication protocols and algorithms that are energy efficient, so that the duration of useful operation of a network, often referred to as the *lifetime* [78] of the network, can be extended as much as possible [2], [27], [33], [46].

Based on the data communication scheme used, sensor network architectures can be broadly classified into two major categories, [3], as follows:

i) The *flat architecture* [45], [53], [47], and

ii) The *hierarchical architecture* [46], [71], [72].

In a network based on the flat architecture, all nodes are treated equally, so that each sensor node is responsible for

a) sensing the environment, and

b) forwarding its own data as well as data from any other nodes, which are using this node as an intermediate node in a multi-hop path towards the base station.

Fig. 1.2 shows an example of a sensor network, based on the flat architecture.

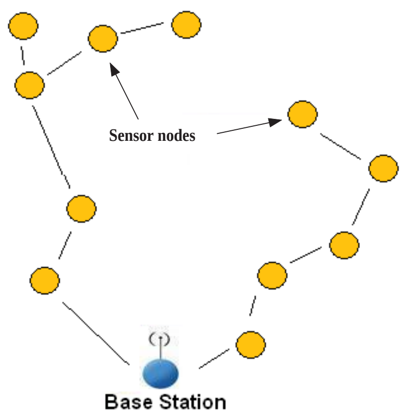

Figure 1.2: An example of flat architecture of sensor network

For scalability and for efficient handling of networks with a large number of sensor nodes, a hierarchical architecture has been proposed in the literature [10], [18], [40], [41], [46], [87]. In a hierarchical *two-tier* architecture, the network is organized as a number of clusters, where

i) each sensor node

   a) belongs to only one cluster, and

   b) lies in the *lower-tier* of the network.

ii) one node in each cluster is designated to be the *cluster head* of that cluster.

iii) the cluster heads constitute the *upper-tier* of the network and bear additional responsibilities (e.g., data gathering, data aggregation, routing), compared to the remaining sensor nodes.

1.2 Relay Nodes in Sensor Network

Recently, in addition to the sensor nodes, some special nodes, called *relay* nodes have been proposed for sensor networks [9], [10], [24], [40], [41], [42], [48], [49], [87]. These relay nodes help achieve a number of different objectives (e.g., energy-efficient data gathering, better load-balancing, improved connectivity, and fault tolerance [40], [41], [48]). The use of relay nodes has also been proposed as cluster heads in two-tiered sensor networks [10], [11], [13], [40], [87]. In such a network model, each relay node is responsible for collecting data from the sensor nodes belonging to its own cluster and for forwarding the collected data to the base station. The model for transmission of data from a relay node to the base station may be categorized either as the *single-hop data transmission model (SHDTM)* or the *multi-hop data transmission model (MHDTM)*. In SHDTM, each relay node transmits its data directly to the base station, assuming that the distance from each relay node to the base station is less than the transmission range of the relay node [46]. On the other hand, in MHDTM, the relay nodes, in general, use some intermediate relay node(s) to forward the data to the base station [48], [49], [54], [87]. The MHDTM is particularly suitable for larger networks, where the relay nodes form a network among themselves, and forward, towards the base station

i) data gathered from the sensor nodes in their respective clusters, and

ii) data received from some other relay nodes.

Fig. 1.3 shows an example of a two-tiered sensor network with relay nodes acting as cluster heads, and using MHDTM[2]. Since all data are collected at the base station, in MHDTM, there is at least one path from each relay node to the base station.

Two data communication models have been investigated for sensor networks [48]. In the *flow-splitting* model for data communication, sensor/relay nodes can arbitrarily split the traffic into a number of components and transmit each component to several different nodes, in their respective paths to the base station. In the *non-flow-splitting* model, a node is *not* allowed to split the traffic, and forwards all its

[2] In this dissertation all links in the upper-tier are symmetric, i.e., if a relay node j can transmit to a relay node k, then k can also transmit to j.

data to a single node, and there is always a *single* path from each node to the base station. Such a topology forms a tree, rooted at the base station, and is referred to as a *routing tree* [5], [65].

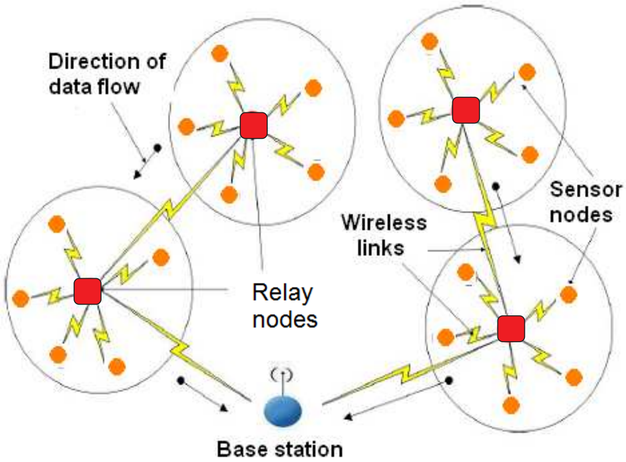

Figure 1.3: An example of a hierarchical two-tiered sensor network where the relay nodes, acting as cluster heads, are using MHDTM to communicate data to the base station.

Relay nodes, acting as cluster heads, usually need to communicate large amounts of data over longer distances, and, hence, dissipate more energy than the ordinary sensor nodes. To enable relay nodes to communicate large amounts of data over longer distances, researchers have proposed provisioning each relay node with a higher initial energy and ensuring that each has a larger transmission range, as compared to the sensor nodes [10], [13], [87]. In this dissertation, we have considered this particular architecture of two-tiered, heterogeneous sensor network, where each relay node is provisioned with higher power, and is used as a cluster head[3].

Some researchers have investigated clustering schemes where the role of cluster heads are rotated among different sensor nodes [46]. In such schemes the location of

[3]In describing our work in this dissertation, we have used the terms "relay node" and "cluster head" interchangeably, as, in our model, each relay node corresponds to a cluster head and vice-versa.

each cluster head changes with time. In contrast, the role of the sensor nodes and the relay nodes are not interchangeable in our model and the locations of the relay nodes, by definition, denote the locations of the cluster heads. For each sensor node to be able to communicate its data successfully, it is important to place the relay nodes in the network in such a way that each sensor node can find at least one relay node within its transmission range, so that each sensor is a candidate to be part of at least one cluster.

Although provisioned with higher power, the relay nodes are also battery operated and hence, are power constrained [49], [87], just like the sensor nodes. In networks using relay nodes as cluster heads, the overall lifetime of the network is primarily determined by the duration for which the relay nodes are operational [10], [13]. Therefore, to prolong the network lifetime, it is very important to

1) allocate the sensor nodes to the relay nodes appropriately, and

2) find an efficient communication scheme that minimizes the energy dissipation of the relay nodes.

The allocation of the sensor nodes to clusters in a network is decided by the clustering scheme used, and a proper clustering scheme can play an important role in effectively balancing the load on different relay nodes [42], and hence, significantly improving the lifetime of the network. The effectiveness of a clustering scheme depends on a number of factors, such as the physical distribution of the sensor nodes within the networking area, the number and the locations of the relay nodes and the specific routing strategy used.

A number of routing schemes for two-tiered networks have been proposed in the literature [2], [10], [13], [40], [41], [48], [49], [54] that use different approaches (e.g., non linear programm (NLP), integer linear program (ILP), linear program (LP), heuristic approach, and genetic algorithm).

1.3 Problems Addressed in this Dissertation

Given the locations of sensor nodes in an area, the objective of this dissertation is to present new algorithms to design two-tiered sensor networks, where relay nodes are used as cluster heads. The design of such a network involves solving the following three subproblems:

Subproblem 1) Relay node placement problem.

Subproblem 2) Clustering problem.

Subproblem 3) Routing problem.

These three subproblems are inter-related and, ideally, should be solved simultaneously. However, each of these three subproblems, taken in isolation, has been shown to be NP-hard [4], [37], [37], [55], [66], [67], [87], [95]. Therefore, to make the design problem tractable, researchers have solved the three subproblems independently [43], [49], [62], [78], [87], [40], [42], [46], [47], [46], [71], [96].

1.3.1 Relay Node Placement Problem

The relay nodes are, in general, nodes with higher capability compared to the sensor nodes, and hence, are more expensive. The placement strategy attempts to find a set of relay nodes, along with the location of each relay node within the network, such that

i) each sensor node can communicate with at least one relay node, and

ii) the number of relay nodes is minimum.

This problem is defined as relay node *placement* problem. It has been shown in [37], [87] that the problem of finding an optimal placement of relay nodes is NP-hard.

If the relay nodes have limited transmission range, and they need to use MHDTM to send their data to the base station, then the placement strategy also needs to ensure that each relay node can find another relay node (or the base station) within its transmission range, so that data from the relay node can be communicated to the base station.

Like other networks, components of sensor networks may fail. In order to handle failures of the relay nodes, it is important to have a placement strategy with some redundancy, so that

i) each sensor node can send its data to more than one relay nodes, and

ii) (for MHDTM networks) there are several distinct paths from each relay node to the base station.

The desired level of redundancy depends on the intended application, and a generalized formulation should be capable of handling this.

1.3.2 Clustering and Routing Problem

The relay nodes are power constrained, and total depletion of the power of a relay node can seriously impact the functionality of the entire network. Therefore, maximizing the lifetime[4] of a sensor network, using our model, is directly related to maximizing the lifetime of the network of relay nodes [50]. The lifetime of a network based on the MHDTM can vary considerably with

i) the clustering of the network, i.e., the assignment of sensor nodes to relay nodes [40], and

ii) the actual routing scheme used [48], [49], [54], [78].

The objective of the clustering algorithm is to achieve a balanced distribution of "load" among the relay nodes, so that the maximum load on each relay node is minimized. The general case of such load-balanced clustering is known to be NP-hard [66], [67]. The clustering heuristics, proposed in the literature (e.g., [40]), typically measure the load on a relay node (defined by the number of sensor nodes assigned to the corresponding cluster). These heuristics try to balance the amount of data that each relay node is required to forward towards the base station. However, the specific routing strategy used by the network is also likely to be important when determining the clusters. For example, in the single-hop model, where each relay node transmits

[4]various measures for the *lifetime* proposed in the literature has been discussed in Section 2.4.

directly to the base station, it may be more effective to assign fewer sensor nodes to clusters which are further away from the base station, rather than distribute the load uniformly. The approaches based on a heuristic typically cannot guarantee optimality in terms of extending the lifetime of the network, which is the primary objective of load balanced clustering.

The goal of an energy-efficient routing strategy is to find a suitable data gathering schedule, such that the lifetime of the network is maximized. This problem is also known to be NP-hard [95]. Many routing schemes have been proposed in the literature [3], [40], [42], [55], [68], [71], [88]. Optimal routing schemes for two-tier networks, using relay nodes, are also proposed in [10], [13]. The clustering and the routing problems have traditionally been considered independently and solved separately, resulting in sub-optimal solutions, and an integrated approach that jointly optimizes these two problems can result in substantial improvements in terms of the lifetime of the network.

1.4 Solution Outline and Contributions

In our investigations, we have considered a sensor network architecture where

1) higher powered relay nodes are used as cluster heads, and
2) individual sensor nodes belong to only one cluster and communicate directly with the corresponding relay node.

We have assumed that both sensor nodes and relay nodes communicate through an ideal shared medium, and communication between nodes is handled by appropriate

MAC protocols (as in [40], [41]).

We have considered the following problems:

i) The placement problem of the relay nodes.

ii) The clustering problem.

iii) The joint problem of clustering and routing.

First, we have presented two integer linear program (ILP) formulations (called ILP-SC and ILP-FT, described in Chapter 3) for the optimal placement of the relay nodes in a specified sensing area. ILP-SC minimizes the number of relay nodes in a given network, with the constraint that each sensor node must be able to communicate with at least one relay node. Given a set of possible locations for the relay nodes, this formulation is able to optimally select locations of the relay nodes for the network, where each relay node sends its data directly to the base station using SHDTM. ILP-FT extends ILP-SC to incorporate fault tolerance, using MHDTM, such that each sensor node can communicate with at least $k_s,\ k_s = 1, 2...$ relay node(s) and each relay node that has to use another relay node to route its data towards the base station should be able to communicate to at least $k_r,\ k_r = 1, 2, ...$ other relay node(s).

After determining the positions of the relay nodes, we have presented two ILP formulations for optimal load balanced clustering (called ILP-S and ILP-M, described in Chapter 4). ILP-S focuses on direct transmission, using the SHDTM, and ILP-M focuses on the MHDTM. The ILP formulation, ILP-S (ILP-M), assigns each sensor node to a cluster in such a way that maximizes the lifetime of the relay node network.

In view of the limitations[5] of the flow-splitting model, we have mainly used the non-flow-splitting model for data communication in this dissertation.

As mentioned in Section 1.3, clustering and routing are normally considered as two separate problems and are solved independently. We have presented a new ILP formulation (called ILP-NFS, described in Section 5.2.1) that jointly optimizes both clustering and routing, with the objective of maximizing the lifetime of the upper-tier relay node networks. The simulation results demonstrate that the integrated approach significantly outperforms existing approaches that solve these two problems separately.

ILP-NFS can quickly become computationally intractable, as the network size increases. To handle larger networks, we have proposed a heuristic approach (called NFS-H, described in Section 5.3.3) that works in two steps. In the first step, we allow the flow from each relay node to split, using a formulation based on an LP-relaxation (called ILP-FS, described in Section 5.3.1). We note that ILP-FS can be used to find optimal clustering and routing solution for the flow-splitting routing model. In the second step of our heuristic, we use the solution obtained by ILP-FS, to reduce the search space of each relay node, and to obtain the solution for the joint problem under non-flow-splitting routing model.

We have used a centralized approach in this dissertation when proposing the ILP formulations. Such an approach is appropriate when the exact positions of the nodes can be predetermined. This kind of approach has been adopted in a number of recent papers [47], [48], [49], [59], [74], [82], [90], and can be used in different

[5]Limitations of the flow-splitting model [48], [50] have been discussed in Section 2.7.

application areas, such as monitoring a habitat, the environment, or a building, where there may be some initial movement during the deployment phase of the network. However, the nodes remain stationary during the normal operation of the network [28], [35], [40]. The schemes presented in this dissertation are applicable for such a model and are not intended for dynamic topologies.

In the context of sensor networks, adopting a centralized approach may not always be feasible, and finding a solution using a distributed approach is more appropriate. We have proposed a distributed algorithm (called ADC-M, described in Chapter 6) to solve the clustering problem that assigns sensor nodes into clusters based on limited local information only. We have adopted a bottom-up approach for clustering, where each relay node only accesses local information about its "neighborhood" and periodically broadcasts requisite information to its neighbors. Relevant information percolates throughout the relay node network by the means of these periodic broadcasts. The relay nodes gradually add sensor nodes to their respective clusters iteratively, in a way that increases the "worst-case" energy dissipation of the relay nodes as little as possible. We have shown that this approach extends the network lifetime significantly.

1.5 Thesis Organization

We briefly review relevant background material in Chapter 2. We describe, in Chapter 3, our placement strategy, with simulation results, for both fault-free and fault-tolerant sensor networks. In Chapter 4, we present two ILP formulations for determining the clustering strategy and corresponding simulation results. In Chapter 5, we present our ILP formulation, and a heuristic based on an LP-relaxation that jointly optimizes the problems for clustering and routing in a network, along with the simulation results. In Chapter 6, we discuss our distributed approach, and corresponding simulation results, for clustering of sensor nodes. Finally, we conclude, in Chapter 7, with suggestions for some future research directions.

Chapter 2

REVIEW OF LITERATURE

2.1 Sensor Nodes and Sensor Networks

A sensor node, in its simplest form, is powered by lightweight batteries and consists of a micro-processor, a limited amount of memory and a wireless transceiver. Sensing devices or *sensors* are usually mounted on each sensor node, which are capable of measuring some physical or environmental phenomenon in the vicinity of the sensor node. A variety of sensors are currently available that includes sensors that are able to record/detect temperature, humidity, illumination, pressure, movement, noise, mechanical stress, radiation level, lightning and biomedical information. A sensor node is also equipped with an analog-to-digital converter (ADC) to convert the sensor signal to a digital form. The wireless transceiver is used to communicate data via radio links. Additionally, sensor nodes can be equipped with a location-finding system (e.g., a Global Positioning System, often called a GPS) and mobilizers. The components of a typical sensor node are shown in Fig. 2.1. Usually, the detection range of a sensor is small, as compared to its transmission range. To carry out the sensing task effectively, the nodes in a sensor network are deployed inside or very close to the phenomenon being observed. The placement of sensor nodes in a network can be

i) pre-determined (e.g., the deployment of a sensor network in a factory, in the body of a human, in an animal or inside a robot), or

ii) random (e.g., the deployment of nodes by dropping them from a helicopter or an airplane or by delivering them in an artillery shell or in a missile) [1].

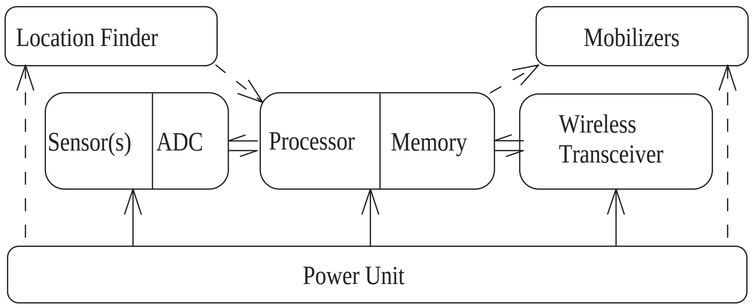

Figure 2.1: The components of a sensor node (redrawn from [1], p. 399).

2.2 Energy Model Used

As mentioned earlier, a sensor node typically consists of a sensing circuit, a digital signal processor, and a radio transceiver [40], [46]. The dominant factor in power consumption in sensor networks is the power needed for wireless communication [46]. The computation of actual cost due to radio communication is fairly complex and is difficult to model. However, in this dissertation, we have computed the communication cost based on a simplified model, called the *first-order radio model* in [46].

In this model, energy is dissipated at a rate of α_1 nJ/bit (α_2 nJ/bit) for receiving (transmitting) the data. This energy is required to run the circuitry of the receiver and the transmitter. In addition to that, the transmit-amplifier also dissipates β amount of energy to transmit one bit of data over unit distance. The energy loss/bit due to channel transmission at distance d, is βd^q, where q is the *path loss exponent*, $2 \leq q \leq 4$, for free space using short to medium-range radio communication [78]. Therefore, the energy dissipated to receive b bits is computed by the following expression:

$$E_{R_x}(b) = \alpha_1 b \tag{2.1}$$

and the energy dissipated to transmit b bits over a distance d is computed by the following expression:

$$E_{T_x}(b, d) = \alpha_2 b + \beta b d^q \tag{2.2}$$

2.3 Relay Nodes in Sensor Networks

In a sensor network, relay nodes, if used, have special functions, where the main task is to relay data that they receive from other nodes in the network. The deployment of a small number of relay nodes in a sensor network can improve the network performance in a number of ways [24], [25], [29], [31], [35], [40], [49], [78], [79], [86]. Researchers have shown that the use of relay nodes lead to better performance of the network, in terms of the

1) lifetime,

2) data gathering,

3) connectivity, and

4) fault tolerance.

Relay nodes have been proposed for the flat architecture as well as for the hierarchical architecture. Fig. 2.2 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. An example of the use of relay nodes in hierarchical networks is shown in Fig. 1.3, in Section 1.2.

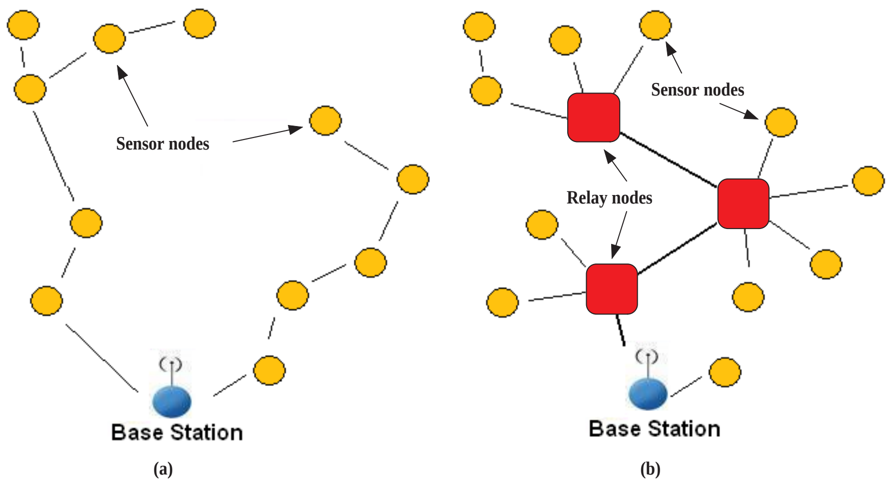

Figure 2.2: Use of relay nodes in a flat sensor networks architecture. (a) A flat sensor network architecture where the sensor nodes located close to the base station are overloaded due to the data they receive from other sensor nodes. (b) The deployment of three relay nodes in the same network reduces the burden of the overloaded nodes.

The placement problem of relay nodes in flat architectures is considered in [24], [29], [34] and [79]. In [29], 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 [24], 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 predetermined, and modeled the problem based on the well known *Steiner minimum tree with minimum number of Steiner points and bounded edge length* [61] problem. They propose two approximation algorithms. In [34], 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. In [79], 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,

c) maximizing the lifetime, and

d) maximizing the utilization of the resources in sensor networks.

The general problem of finding an optimal placement of relay nodes is NP-hard - even finding approximate solutions is NP-hard in some cases [86].

In a hierarchical sensor network, relay nodes were first considered in [40] and [78]. In [40], 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 (referred to as *gateway nodes*), which were provisioned with higher power and acted as cluster heads. In [78], the authors consider a two-tiered sensor network model, where the sensor nodes lie in the lower-tier and the relay nodes (referred to as *application nodes (AN)*) as well as the base stations lie in the upper-tier. The focus of the work is to maximize the network lifetime by arranging the base station(s), and by optimal inter-aggregation node relaying. In this approach, the sensor nodes form clusters and send their readings directly to the respective AN. The approach is based on Computational Geometry that finds the optimal locations of the base station(s) under different definitions of network lifetime. The theoretical upper and lower bounds on the maximal lifetime of a sensor network also appears in [78].

The use of relay nodes in hierarchical sensor network architectures has also been proposed in a number of recent papers [13], [30], [39], [49], [60]. In [49], 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 [13], the authors propose a routing scheme, for networks with relay nodes, which uses a genetic algorithm to maximize the lifetime of such networks. A genetic algorithm is used in [60] to jointly solve a multi-objective problem - *balanced energy consumption* and *minimized total energy consumption*. Energy-efficient storage architecture in multi-tier sensor networks is investigated in [30]. A *Tenet* architecture for tiered sensor networks is proposed in [39] that can be used to simplify application development and to reuse *mote-tier* software.

2.4 Lifetime of Sensor Networks using Relay Nodes

The *lifetime* of a sensor network is usually defined as the time interval from the inception of the operation of the network, to the time when a number of *critical* nodes "die" (i.e., the power supplies of the critical nodes are depleted to such an extent that the network no longer remains useful) [46], [78]. A number of different metrics have been used in the literature to measure the lifetime of a sensor network [19], [22], [32], [69], [78]. In [19], the lifetime of a sensor network is defined as the minimum of

i) the time when the percentage of nodes that are *alive* (i. e., nodes whose batteries are not depleted) drops below a specified threshold,

ii) the time when the size of the largest connected component of the network drops below a specified threshold, and

iii) the time when the coverage drops below a specified threshold.

In [22], the authors focus on coverage and considered the network lifetime as the period during which the entire region can be covered. In [32], the authors provide a comprehensive survey on the definitions of network lifetime used in the literature and present a general and concise definition of the network lifetime. In [69], the authors define the lifetime of the network as the lifetime of the sensor node that dies first.

In hierarchical sensor networks using higher powered relay nodes as cluster heads, the time period the relay nodes are operative is critical in determining the lifetime of the network. The failure of a sensor node results in the loss of information from this single sensor node. This is likely to have only a limited impact on the results, due to the inherent data redundancy in sensor networks. When the battery of a relay node is totally depleted,

1) the sensor nodes which are transmitting to that relay node will no longer be able to send their data to the base station, so that all the sensor nodes in that cluster become inaccessible from other parts of the network. As a result, an entire region within the network becomes effectively inoperative.

2) any other relay node that is using the depleted node for forwarding its data to the base station would no longer be able to do so. This may either make the network disconnected, or require those nodes to find an alternate path, which may be costly in terms of energy dissipation, resulting in early depletion of power of those nodes.

In [78], the authors use a number of metrics to define the lifetime of heterogeneous networks, e.g., *N-of-N* lifetime (i.e., the intended *mission* for the deployment of the network fails if any relay/gateway node dies), *K-of-N* lifetime (i.e., the mission survives if a minimum of K relay/gateway nodes are alive) and *m-in-K-of-N* lifetime (i.e., the mission survives if all m supporting nodes and overall a minimum of K

relay/gateway nodes are alive) [78].

In this dissertation, we have assumed the *periodic* [75] model for data reporting/gathering. In the periodic data gathering model, data are collected and forwarded to the base station periodically, following a predefined schedule. Each period of data gathering is referred to as a *round* [10], [54]. In each round of data gathering, each relay node gathers the data it receives from its own cluster and transmits that data, either directly to the base station (i.e., using SHDTM), or forwards the data towards the base station using a multi-hop path (i.e., using MHDTM). In the case of multi-hop routing, in addition to the data gathered from its own cluster, each relay node also relays any data it receives from neighboring relay nodes.

We have measured the *lifetime* of a network, following the *N-of-N* metric[1] [78], by the number of rounds the network operates from the start, until the first relay node depletes its energy completely and ceases to function. In a hierarchical sensor network, if the *N-of-N* metric is used, assuming equal initial energy provisioning in each relay node, the lifetime of the network is defined by the ratio of the initial energy to the maximum energy dissipated by any relay node in a round, i.e.:

$$\mathcal{N}_{lifetime} = \lfloor E_{initial}/F_{max} \rfloor \tag{2.3}$$

where $\mathcal{N}_{lifetime}$ denotes the lifetime of the network in terms of rounds, $E_{initial}$ denotes the initial energy of each relay node and F_{max} is the maximum energy dissipated by any relay node in a round. In such a model, it is easy to see that maximizing

[1] However, other metrics can be used as well, with a little modification of the proposed ILP formulations given in this dissertation.

the lifetime is equivalent to minimizing the maximum energy dissipated by any relay node in a round.

In the periodic data gathering model, nodes may enter a low-power mode, often referred to as *sleep mode*, during the idle time, to save energy. Energy efficient sleep/wake synchronization and scheduling problems in sensor networks are extensively addressed in the literature [85], [93], [92], [97], [98]. These issues are handled in the MAC layer. In [98], Ye et. al propose sensor-MAC (S-MAC) that reduces the energy consumption, while providing scalability and collision avoidance. Control overhead is reduced by forming virtual clusters based on common sleep schedule. The effect of synchronization on sleep/wake scheduling in low duty-cycle sensor networks using single-hop intra-cluster communication has been studied and the results are described in [91], [93]. This approach has been extended to multi-hop communication model in [92].

2.5 The Placement of Relay Nodes in Sensor Networks

In two-tiered sensor networks using relay nodes as cluster heads, the location of a cluster head is, by definition, 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.

Definition. *A sensor node s is* covered *by a relay node j, only if j lies within the transmission range of s.*

The above definition ensures that s can transmit its data directly to j only if

s is covered by j. The relay nodes should be placed in the network such that each sensor node must be covered by at least one relay node. This ensures that, in the case of fault-free networks, the data from the each sensor node can be communicated to the base station.

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 omnidirectional 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 in the network 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 [37], [87].

Fig. 2.3 (redrawn from [7]) shows the significance of the placement strategy of relay nodes in a network. Fig. 2.3(a) shows that placing four relay nodes at locations A, B, C and D, in an area bounded by the square $ABCD$, does not guarantee that all sensor nodes within the area can be covered, as some sensor node can lie within the shaded region. The circle drawn around the relay nodes are with a radius equal to the transmission range of the sensor nodes and hence, indicate the area that can be covered by these relay nodes. On the other hand, Fig. 2.3(b) shows how four relay

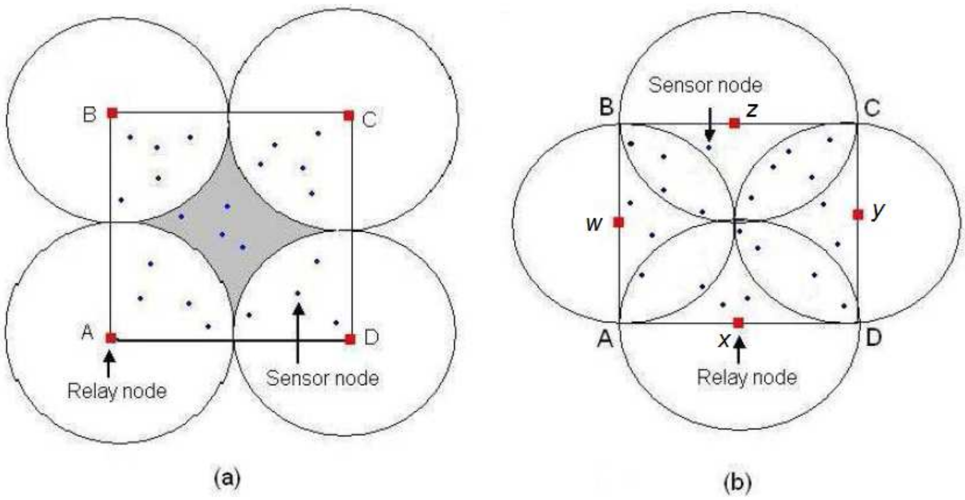

Figure 2.3: An example of the relay node placement problem. (a) The placement that leaves some sensor nodes uncovered . (b) The placement that covers all sensor nodes in the area.

nodes can be placed at locations *w, x, y* and *z* so that entire region can be guaranteed to be covered.

In a fault-free environment, it is sufficient that each sensor node is able to send data to at least one relay node. However, due to the nature of the wireless media, and based on the territory of the deployment (e.g., chemical environment), nodes in a sensor network can be prone to faults. Therefore, a sensor network should ideally be resilient with respect to faults. Fault tolerance is especially important when the relay nodes form a network among themselves, and use MHDTM for communication, as the failure of a single relay node may have a significant effect on the overall lifetime of the network. To provide fault tolerance, we need a placement strategy that allows some redundancy of the relay nodes, so that, in the event of any failure(s) in relay node(s),

i) each sensor node belonging to the cluster of a failed relay node should be able to send its data to another fault-free relay node, and

ii) data from all fault-free relay nodes will still be able to reach the base station successfully.

The problem of relay node placement in hierarchical sensor network architecture has been addressed in [43], [49], [62], [78], and [87]. In [78], the authors propose strategies that maximize the topological lifetime of a sensor network by arranging the relay nodes, and finding the optimal location of the base station(s). In [43], the authors propose an approximation algorithm to achieve single-connectivity and double-connectivity of the sensor and relay nodes in a network. In [62], authors propose a two-step approximation algorithm to obtain a 1-connected (in the first step) and a 2-connected (in the second step, by adding extra back-up nodes to the result of the first step) sensor and relay node network. The general case of k-connectivity for fault tolerance is not addressed in [43] and [62]. In [49], 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. Fault tolerance is not discussed in this work. In [87], a hierarchical network architecture is considered, 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 $2r_{max}.l$, 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 $\mathbf{x}$ and $\mathbf{y}$ are defined as the point(s) of intersection (if any) of two circles of radius r_{max} with centers at $\mathbf{x}$ and $\mathbf{y}$ in the same cell. An optimal placement of relay nodes for each cell is computed from the set, $\wp$, of P-positions for all pairs of sensor nodes within the cell, by checking *all* subsets of $\wp$ of size four or less. Their method requires that the transmission range of the relay nodes, d_{max} must be at least $4r_{max}$ and do not consider the general case of k-connectivity.

2.6 Clustering in 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 its own cluster and routing the collected data towards the base station. Therefore, it is convenient to use higher-capacity nodes as cluster heads. However, even if nodes with the same capacity are used as cluster heads, the role of cluster heads can be rotated among the sensor nodes and the benefit of hierarchical architecture can be exploited [46]. Efficient clustering in sensor networks contributes to the improvement of overall system performance, including scalability, network lifetime, and efficient energy utilization [3]. Hierarchical routing can lower the energy consumption for intra-cluster communication and lower the energy consumption for inter-cluster communication by data aggregation and fusion [3], [40], [42], [46], [47], [71], [77].

In a two-tiered sensor network using higher powered relay nodes as cluster heads, the number of clusters and the locations of the cluster heads are determined by the locations of the relay nodes. Therefore, the clustering strategy in such a network is to assign sensor nodes to the relay nodes in a way that maximizes the overall lifetime of the network of relay nodes. Clustering of nodes in a wireless network is a well-researched field [40], [46], [41], [71], [72], [77]. However, most clustering protocols do not consider higher energy relay nodes as cluster heads, but use factors, such as the cluster ID or the degree of connectivity to form clusters. The clustering problem for relay nodes is illustrated in Fig. 2.4, where the sensor nodes in the shaded region can be assigned to any one of clusters A, B or C. Depending on the routing scheme and the energy dissipations 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.

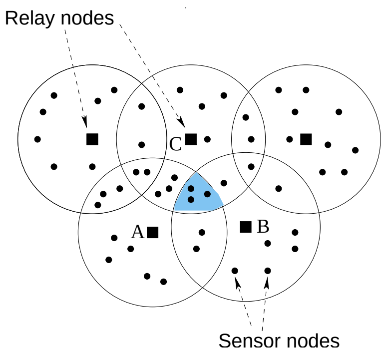

Figure 2.4: Sensor nodes in overlapping coverage area.

In [40], the authors investigate the problem of forming clusters around a few high-energy *gateway* nodes. The authors define "cardinality" of a cluster as the number of sensor nodes associated with the cluster and provide a heuristic that attempts to minimize the variance of the cardinality of each cluster in the system. The idea is to distribute the sensor nodes as evenly as possible, over all the clusters. The authors show, in [42], that suitable clustering techniques can be used to increase the system lifetime. In [41], the authors focus on fault-tolerant clustering, and propose a two-phase fault-tolerant approach, namely, *detect* phase and *recover* phase. The types of failures considered in [41] include complete failure, link failure and range failure. The idea is to perform periodic checks on the status of the gateway nodes so that the system can learn about the failure of any gateway node. The clustering scheme includes the creation of backup information during the clustering phase, which can be used to re-assign sensor nodes managed by the any failed gateway node, thereby eliminating the necessity of a full-scale re-clustering involving the entire network.

A number of papers have addressed distributed clustering in sensor networks. A self-organizing, adaptive clustering protocol, called *Low-Energy Adaptive Clustering Hierarchy* (LEACH) protocol is proposed in [46] that distributes the burden of transmitting the data to the base station among all the nodes at different time points. In this scheme, the sensor nodes organize themselves into local clusters and one node takes the role of a cluster head. The basic idea of the LEACH protocol is to randomly rotate the cluster heads, to ensure that the energy consumptions are evenly distributed among all the nodes in the network. The protocol also uses data aggregation in the cluster head, so that the amount of data transmitted to the base station is reduced. In [77], the authors consider a quasi-stationary, location-unaware cluster-based sensor network model, where all the nodes in the network have equal significance and the sensor nodes can have multiple power levels. They focus on the clustering, and selecting the cluster heads in such networks, in order to prolong the network lifetime, and propose a distributed clustering approach, called *Hybrid Energy-Efficient Distributed clustering* (HEED). In HEED, the cluster heads are selected periodically, probabilistically and the selection is primarily based on the availability of the residual energy of each node. In [99], a single-hop wireless sensor network is considered, and an *energy-efficient clustering approach* (EECS) is proposed. The idea is the dynamic sizing of clusters, based on the cluster distance from the base station. The cluster head is elected by localized competitions, based on the residual energy. A randomized multi-hop clustering algorithm is proposed in [103] that organizes the sensors into overlapping clusters. The clustering process also ensures that each node is either a cluster head or at most k hops away from at least one cluster head, where k is a preset cluster radius [103]. In [63], a distributed clustering algorithm is proposed for mobile sensor networks. In [6], a distributed clustering scheme that minimizes the *total* energy spent in the system due to the communication of data is studied. In [101], a hybrid approach for clustering is proposed where cluster heads are selected, taking into consideration the residual energy, and then sensor nodes are assigned to clusters, such that the communication cost is minimized. A survey on clustering algorithm can be found in [102].

2.7 Routing in Sensor Networks

In a sensor network, usually all data are gathered at the base station. Routing in sensor networks deals with finding a communication scheme among various nodes in the network that are using multi-hop paths for forwarding their data. The objectives of routing schemes may vary from one scheme to another. Typical objectives include minimizing the total energy dissipation, minimizing the maximum energy dissipation by any node, and minimizing the transmission delay. Finding an efficient routing scheme in sensor networks can be complex [3] due to the following reasons:

- The capabilities of a sensor node, with respect to the energy provisioning, processing, storage and communication, is limited. The sensor nodes are usually powered by lightweight batteries, and the lifetime of the network is considered to be over as soon as the battery power of the critical nodes are completely depleted.
- The design of a sensor network depends on the requirements of the application. The communication scheme may need to be customized, based on the specific application.
- The nodes in a sensor network use wireless media for the communication, the quality of which may vary widely, based on the networking environment.
- Location awareness of nodes is usually required, as the data collected from a sensor node is often required to be associated with the current position of the node.
- Sensor networks are densely deployed with a large number of sensor nodes, data generated by a group of sensor nodes may be highly cor-

related and redundant. Appropriate techniques are required to handle such redundancy for the efficient use of the bandwidth and unnecessary energy dissipation due to the communication of redundant data.

- Sensor nodes are prone to failures (e.g., if deployed in a hostile territory). Any failure of a node and/or a communication link may change the network topology. The routing scheme must be able to handle such changes.

As energy conservation is *the* most important issue in a sensor network, most of the routing approaches proposed in the literature focus on minimizing the energy consumption of the nodes to extend the lifetime of the network. Routing protocols proposed in the literature can be classified in a number of ways. For example, based on the network structure, most of the routing protocols can be classified into three major categories, *flat* routing (e.g. [45], [53]), *hierarchical* routing (e.g. [46], [71], [96]) and *location-based* routing (e.g. [3], [23]). In flat routing, all nodes are treated equally and are typically assigned equal functionality and role. Hierarchical routing protocols group sensor nodes into distinct clusters around some specific nodes, known as *cluster-head* nodes. These cluster-head nodes are responsible for collecting data from the respective cluster and forwarding them to the base station. In a location based routing protocol, information regarding the locations of the nodes, (e.g., obtained through the use of GPS), are used to take appropriate data routing decisions [83], [84], [88]. A location based geographic routing is proposed in [84]. In [83], the authors employ a localized algorithm[2], using the locations of the nodes, and is based on a depth-first search. The approach in [83] guarantees that data from a source node can reach the destination node, even when the location information of the destination node is inaccurate (e.g., due to node mobility). A set of localized algorithms, using depth-first search, is proposed in [88]. The algorithms use location information and integrate power metrics to find the solution of the routing problem that minimizes the total power.

In [2], Akkaya and Younis classify the routing protocols in sensor networks as *data-centric, hierarchical, location-based*, *network flow*, or *QoS-aware* routing protocols. In the data-centric protocols, routing is query-based. These protocols use attribute-based naming to specify the properties of data. The network flow protocols model and solve the routing as a network flow problem. The QoS-aware protocols take into consideration the requirement for the end-to-end delay while setting up a route [2]. In addition, routing protocols can also be classified as *proactive, reactive,* and *hybrid*, based on how a source finds a route to the destination. Proactive protocols compute all routes beforehand, i.e., before routes are actually needed. Reactive protocols compute routes on demand while hybrid protocols use a combination of both proactive and reactive protocols. An overview of the proposed routing protocols, can be found in survey papers [2], [3].

Due to the well known advantages related to scalability and efficiency in communication [3], the hierarchical architecture has been exploited for sensor networks

[2]In a localized algorithm, each node takes a decision based on local information only. A localized algorithm is usually considered as a special case of distributed algorithm [89].

to perform energy-efficient routing. In a hierarchical two-tiered sensor network, each sensor node in the network belongs to one distinct cluster and sends data to only its own cluster head. Cluster heads, on the other hand, are responsible for collecting data from all the sensor nodes belonging in its own cluster, processing the data and sending the data towards the base station. The cluster heads may either use a single-hop to send data directly to the base station, or may use a multi-hop path to forward the data towards the base station. For the latter case, each cluster head needs to act as a router for any data forwarded to it by some neighboring cluster head nodes, as shown in Fig. 1.3, Section 1.2.

One of the advantages of the hierarchical architecture is that it can utilize relay nodes, which are provisioned with higher-energy, as cluster heads, to account for the additional tasks performed by these nodes as compared to a regular sensor node. Sensor nodes, in such models, can be low-cost, low-energy nodes, as each node performs only the sensing task and transmits its data to the immediate cluster head, which usually lies at a short distance. Typically, in such a model, the sensor nodes do not participate in the routing. Conventional routing schemes used by the relay nodes in two-tiered sensor networks include

i) the *single-hop* (or *direct-transmission-energy*) model (SHDTM) [46], where each relay node sends its data directly to the base station.

ii) the *multi-hop* model (MHDTM) [44], [42], where the relay nodes form a network among themselves, and use multi-hop paths for routing data towards the base station. Conventional multi-hop routing includes

a) the *minimum-transmission-energy* (MTE) model [46], [44], where each relay node transmits to its nearest neighbor towards the base station, and

b) the *minimum hop* (MH) model [42], where the multi-hop route used is the one that minimizes the number of hops from each relay node to the base station. If the transmission ranges of the relay nodes are sufficiently high, this may reduce to the single-hop model.

The problem of routing in wireless sensor networks, under the “flow-splitting” model, is extensively covered in the literature. In [49], Hou et al. propose to maximize the lifetime of a sensor network by provisioning relay nodes and sensor nodes with additional energy. They formulate the problem as a mixed-integer *non-linear* program and propose a heuristic algorithm. In [54], the authors formulate the lifetime optimization problem in terms of an integer linear program, and propose a polynomial-time algorithm as well. In [35], Falck et al. address the issue of balanced data gathering in sensor networks and propose an LP formulation that enforces some balancing constraints in the data gathering schedule. In [40], Gupta and Younis focus on load balanced clustering and propose a heuristic solution for the optimization problem. Allowing flow-splitting simplifies the problem formulation for routing by allowing linear relaxation of the routing variables [20] and typically results in longer network lifetimes compared to *non-flow-splitting* routing. However, as mentioned in [48], [50] the flow-splitting model has a number of limitations as follows:

i) Costly packet level power control may be required if relay nodes, equipped with a single transceiver, are used.

ii) A number of transceivers may be used. However, the use of multiple transceivers for each relay node is not scalable, and therefore is not suitable for large scale sensor networks,

iii) The relay nodes have to perform complex routing functions.

The non-flow-splitting approach can be conveniently used in conjunction with a directional antenna [50], which has been shown to improve the performance of wireless sensor and ad hoc networks [26], [56], [104].

Routing under the non-flow-splitting model has been studied in [10], [13], [20], [50] and [95]. In [10], ILP formulations that maximize the lifetime of the network of relay nodes are proposed, and in [13], a genetic algorithm is applied to find an efficient routing scheme for the relay node network. In [50], the authors present a transformation algorithm to convert a multiple outgoing flow routing model to a single outgoing flow routing model. In [95], the authors investigate the problem of maximizing network lifetime by appropriately placing nodes which are not energy constrained (e.g., connected to a wall outlet). In [20], the authors propose a formulation for constructing minimum-energy data-aggregation trees, for a flat network architecture.

Chapter 3

PLACEMENT OF RELAY NODES IN HIERARCHICAL SENSOR NETWORKS

3.1 Introduction

The *relay node placement* problem in a two-tier sensor network, using relay nodes as cluster heads, is to find locations of the relay nodes such that

i) each sensor node can communicate with at least one relay node, and

ii) the number of relay nodes is minimum.

This relay node placement problem is very similar to the *Minimum Geometric Disk Cover* problem which is known to be NP-hard [37], [87] as discussed in Section 2.5. In this chapter, we present two integer linear program (ILP) formulations for the optimal placement of the relay nodes in a specified sensing area, assuming that a set of possible locations is given as an input to the formulation.

We first propose an initial formulation that minimizes the number of relay nodes in a given network, with the constraint that each sensor node must be able to communicate with at least one relay node. This formulation solves the relay node placement problem, and is suitable for finding a solution for the network model, where each relay node sends its data directly to the base station using the single-hop Data Transmission model (SHDTM). This is also suitable for use in a network model where a mobile data collector travels within the network, and collects data from each relay node [16], [17].

As the energy dissipated by a transmitting relay node increases rapidly with the distance between the source and the destination nodes, it may not be cost effective to use the SHDTM in all networks. The SHDTM is also not feasible for large networks, where the base station may not lie within the transmission range of all relay nodes. A better alternative is to allow the relay nodes to form an upper-tier network and use multi-hop paths to forward the received data to the base station, using the Multi Hop Data Transmission model (MHDTM). To define this upper-tier network, the relay node network topology should be such that each relay node is

a) either able to send its data to another relay node, which is in the path from the node to the base station, or

b) be able to send its data directly to the base station.

The topology of the relay node network is a tree, the *routing tree* [5], [65], that is rooted at the base station, and is a spanning tree for all the relay nodes in the network. There can be multiple possible routing trees in a network, as some relay nodes may be able to send their data to more than one relay node. However, for the MHDTM to work, each relay node must be able to send its data to at least one other relay node, or to the base station. A relay node network is 1-connected [87], if each relay node in the network has at least *one* such destination node (either another relay node or the base station).

Under fault-free conditions, it is sufficient for the relay node network to be 1-connected. But in this scenario, the failure of a single relay node results in data loss from all sensor nodes belonging to the cluster for which the failed relay node is the cluster head. Such a failure of a relay node may also prevent information flow of other relay nodes, which are using the failed node to forward their data towards the base station. Therefore, to handle the failure of one or more relay node(s), both tiers of a fault-tolerant network must have the following capabilities:

a) Each sensor node must be able to send its data to more than one relay node, so that when one or more relay node(s) fail, the sensor node can still send its data to a fault-free relay node.

b) Each relay node, unable to send its data directly to the base station, must be able to send its data to more than one relay node, so that when one or more relay node(s) fail, it is guaranteed that there is a fault-free path from each fault-free relay node to the base station.

The desired level of redundancy will depend on the intended application, and a generalized formulation should be capable of handling any desired redundancy level.

Our second formulation extends the initial formulation to incorporate the multi-hop communication by the relay node networks, as well as fault tolerance, such that each sensor node can communicate with at least $k_s, k_s = 1, 2, \ldots$ relay node(s), and each relay node that needs another relay node to send its data to the base station, should be able to find at least k_r, $k_r = 1, 2, \ldots$ such other relay node(s). The parameters k_s and k_r are determined by the application, and are specified as inputs to the ILP. Mission-critical applications will typically use higher values of k_s and k_r. The objective is to achieve the desired level of fault tolerance, with as few relay nodes as possible. As in [87], our placement strategy assumes that the positions of the sensor nodes, within the area of interest, are known. Recently, some strategies have been proposed in the literature for the special cases where $k_s = 1$ ($k_s = 2$), termed *single* (*double*) *coverage* of sensor nodes and $k_r = 1$ ($k_r = 2$), termed *single* (*double*) *connectivity* of the relay node network. [24], [87], [43], [62]. However, these heuristic approaches cannot handle arbitrary values of k_s, k_r. The formulations presented in this chapter guarantee that the relay node network has k_s-coverage and is k_r-connected[1], for arbitrary values of k_s and k_r.

[1] In this chapter, we have used the term "k_s-coverage" to indicate that each sensor node is able to send its data to at least k_s relay nodes, and the term "k_r-connected" to indicate that each relay node, which cannot send its data directly to the base station, is able to communicate with least k_r other relay nodes, which are closer to the base station than itself.

3.2 The Network Model

We consider a two-tiered wireless sensor network, where the lower-tier consists of a set $\mathcal{S}$ of n sensor nodes, randomly distributed in the sensing area. We assign a label $i, 1 \leq i \leq n$ to each sensor node in $\mathcal{S}$. Our objective is to determine the minimum number and the positions of the relay nodes to form the upper-tier network, with a pre-specified degree of redundancy. Our proposed formulation designs the upper-tier relay node network, such that each sensor node is *covered* by at least k_s relay node(s), where $k_s = 1, 2, ..$, and each relay node can forward its data to $k_r, k_r = 1, 2, ..$ other relay node(s) (or directly to the base station). This means that each sensor node can still transmit its data to at least one fault-free relay node, even if up to $k_s - 1$ relay nodes fail. Similarly, our formulation guarantees that each relay node, which is not sending its data directly to the base station, has a viable path to the base station, even if up to $k_r - 1$ relay nodes fail. For proper functioning of the network, it is required that, at a minimum, $k_s = 1$, i.e., each sensor node is capable of communicating with at least one relay node and $k_r = 1$, i.e., the upper-tier relay node network is 1-connected.

We assume that the positions of the sensor nodes are known beforehand, or can be determined (e.g., using a GPS or any other localization algorithm [51], [58]), and that the relay nodes can be placed at the locations determined by our placement strategy. We are also given a set of *potential* locations for the relay nodes. To define these potential locations, we consider an imaginary set of equally spaced grid lines, parallel to the x-axis and parallel to the y-axis, covering the entire network area, including the base station. The intersection point of a grid line parallel to the x-axis and a grid line parallel to the y-axis defines one potential location for a relay node. The spacing between successive grid lines can be varied, i.e., the grid can be "coarse", or "fine". However, to ensure that there exists a sufficient number of potential locations for the ILP's to achieve k_s, k_r fault tolerance, we have defined the grid lines so that the spacing between the grid lines is no greater than $\min\{\frac{r_{max}}{k_s}, \frac{d_{max}}{k_r}\}$, where r_{max} (d_{max}) is the transmission range of the sensor (relay) nodes. The grid may be made as fine as desired. A finer grid increases the number of potential locations and typically results in better solutions. However, this increases the amount of the computation, and hence the time required to obtain a solution. Once the set of potential locations of the relay nodes is determined, our ILP can be used to generate the upper-tier network, with desired values of k_s and k_r.

Let $\mathcal{R}^p$ be the set of m_p *potential* locations for the relay nodes. We start by assigning each location a label $j, n+1 \leq j \leq n+m_p$, and we assign a label $n+m_p+1$ to the base station. In the description below, we will use the term "relay node j" meaning a relay node placed at the location corresponding to label j.

3.3 ILP Formulation for Single Coverage (*ILP-SC*)

In this section, we propose a formulation that solves the relay node placement problem by guaranteeing that each sensor node is covered by at least one relay node. The objective is to minimize the number of relay nodes.

Given the network model as described in Section 3.2, a formulation[2] for this

[2]the symbols used in all algorithms and ILP formulations, including this one, have been described under *Acronym & Notation Used.*

problem is given below.

$$\textbf{Minimize} \sum_{j=n+1}^{n+m_p} \mathcal{Y}_j \tag{3.1}$$

Subject to:

a) Sensor node i can transmit to relay node j, only if the distance between i and j is less than the range r_{max} of the sensor node.

$$X_{i,j} \cdot d_{i,j} \leq r_{max} \qquad \forall i, 1 \leq i \leq n, \tag{3.2}$$
$$\forall j, n+1 \leq j \leq n+m_p$$

b) Relay node j is included in the upper-tier network, if it is selected as the cluster head by at least one sensor node i.

$$\mathcal{Y}_j \geq X_{i,j} \qquad \forall i, 1 \leq i \leq n, \tag{3.3}$$
$$\forall j, n+1 \leq j \leq n+m_p$$

c) A sensor node must be allocated to exactly one cluster.

$$\sum_{j=n+1}^{n+m_p} X_{i,j} = 1 \qquad \forall i, 1 \leq i \leq n \tag{3.4}$$

Equation (3.1) is the objective function for the formulation that minimizes the total number of relay nodes required to cover all the individual sensor nodes in the area of interest. Constraint (3.2) enforces the restriction that a sensor node can only transmit to a relay node, if the relay node is within the transmission range of the sensor node. Constraint (3.3) ensures that, if 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 upper-tier network. Conversely, if relay node j is not chosen as a cluster head for any sensor node, it should not be included in the upper-tier network. The latter requirement is not specifically enforced by any constraint, but is taken care of by the objective function, which will set $\mathcal{Y}_j = 0$, if this does not violate any of the other constraints. Constraint (3.4) ensures that a sensor node i selects one relay node j as its cluster head. Sensor node i will always transmit its data directly to j.

The formulation presented above solves the placement problem. It guarantees that each sensor node is covered by at least one relay node but does not consider fault tolerance. If the base station is within the transmission range of all relay nodes, then the entire data collected by each relay node can be communicated to the base station using a single-hop transmission by the relay node. ILP-SC is useful whenever each relay node sends its data directly to the base station, using the SHDTM. In the following section, we will describe how this formulation can be extended to include multi-hop routing and to guarantee the desired fault tolerance for both the sensor nodes and the upper-tier relay node network.

3.4 ILP Formulation for Fault Tolerance (*ILP-FT*)

As described in Section 3.1, the MHDTM gives important advantages in terms of maintaining the robustness of the network, as well as extending the lifetime of the network, particularly when the sensing area is large. For this model, it is necessary that the selected relay nodes must form a routing tree, rooted at the base station. Formulation ILP-SC assumes that each relay node has sufficient transmission range to reach the base station directly, and does not take into account the actual transmission range of the relay nodes. Therefore, if some relay nodes have limited transmission ranges and cannot reach the base station directly, the solution obtained using ILP-SC may leave such relay nodes without any feasible route to the base station.

Formulation ILP-FT, given below, is intended to account for this problem by enforcing the requirements of the MHDTM. ILP-FT is a generic formulation that can be used to design either a 1-connected network, which is simply a relay node network using MHDTM, or can be used to design a fault tolerant network. The level of fault tolerance in the network can be specified in both the tiers of the network by appropriately selecting the values of the parameters k_r and k_s. The formulation ILP-FT is given below.

$$\textbf{Minimize} \sum_{j=n+1}^{n+m_p} \mathcal{Y}_j \tag{3.5}$$

Subject to:

a - b) Constraints (3.2) and (3.3).

c) A sensor node must be connected to k_s relay nodes.

$$\sum_{j=n+1}^{n+m_p} X_{i,j} = k_s \qquad \forall i, 1 \leq i \leq n \tag{3.6}$$

d) The number, C_j, of relay nodes that relay node j can use to route data towards the base station must equal the number of relay nodes which are within the transmission range of j and are closer to the base station.

$$C_j = \sum_{z:(d_{j,z} \leq d_{max})\ AND\ (d_{z,n+m_p+1} < d_{j,n+m_p+1})} \mathcal{Y}_z \qquad (3.7)$$

Constraint (3.7) has to be repeated for all j and for all z, $n+1 \leq j, z \leq n+m_p$, $j \neq z$.

e) If the base station lies outside of the transmission range of relay node j, there must be k_r other relay nodes to which j can forward its data.

$$C_j \geq k_r, \qquad \forall j \ni d_{j,n+m_p+1} \geq d_{max} \qquad (3.8)$$

Equation (3.5) is the objective function that minimizes the total number of relay nodes, and is identical to Equation (3.1). Constraints (3.2) and (3.3) are used, as in ILP-SC, to ensure that a sensor node chooses a cluster head within its transmission range and any relay node selected as a cluster head is included in the topology. Constraint (3.6) is similar to (3.4), but requires that each sensor node be covered by k_s relay nodes, instead of a single relay node. The actual value of k_s, can be chosen, based on the intended application[3]. Under fault-free conditions, each sensor node will select one relay node (from the k_s relay nodes it is associated with) to send its data. If that node fails, it can select another cluster head from the remaining $k_s - 1$ nodes. Constraints (3.7) and (3.8) ensure that relay node network is robust.

[3]For most applications $k_s = 2$ or 3 suffices.

Theorem 1. *Constraints (3.7) and (3.8) guarantee that the relay node network can survive* $k_r - 1$ *faults.*

Proof. For each relay node j in the upper-tier network, constraint (3.7) computes the number of relay nodes that are:

a) within the transmission range of j, *and*

b) closer to the base station than j.

These are the nodes that may be used by j to forward its data to the base station, if the base station is not within its transmission range. Constraint (3.8) ensures that there are at least k_r such nodes, for any relay node which cannot transmit to the base station directly. This means that, even if up to $k_r - 1$ relay nodes fail, there will still be at least one surviving node within the transmission range of j, which is closer to the base station than j. Since this is true for *all* relay nodes, constraint (3.8) ensures that there will be a viable path from each relay node to the base station. This guarantees that the relay node network is robust, even in the presence of $k_r - 1$ relay node failures. □

We note that, unlike ILP-SC, ILP-FT formulation may select relay nodes, which are not acting as cluster heads for *any* sensor nodes. Such nodes are used to maintain the required level of fault tolerance, and are included in the topology only if necessary.

3.5 Analysis of ILP-SC and ILP-FT

It is well-known that an ILP formulation is characterized by the number of binary variables, the number of integer variables and the number of constraints [76]. Table 3.1 gives the number of integer variables, and the number of constraints in the formulations ILP-S and ILP-M.

Table 3.1: Number of binary variables, integer variables, and constraints used in ILP-SC and ILP-FT

	Number of binary variables	**Number of integer variables**	**Number of constraints**
ILP-SC	$m_p + nm_p$		$nm_p + 2n$
ILP-FT	$m_p + nm_p$	m_p	$nm_p + 2n + 2m_p$

3.6 Simulation Results

In this section, we present the simulation results for our placement strategy to minimize the number of relay nodes forming the upper-tier relay node network, for specified values of k_r and k_s. We have used an experimental setup similar to [87], where the sensor nodes are randomly distributed over a $480 \times 480m^2$ area. The communication range of sensor nodes is assumed to be $r_{max} = 40m$, and the range of a relay node is set to $d_{max} = 200m$. We experimented with different network configurations, with the number of sensor nodes varying from 600 to 1200. We also varied the grid size, and hence, the number of potential locations of the relay nodes in the network. We started with a coarse grid having 169 potential positions, and refined the grid in subsequent runs. The finest grid we used in our simulation had 1681 potential locations.

Fig. 3.1 and Fig. 3.2 show how the number of relay nodes in the upper-tier network changes with different sensor distributions, for $k_s = k_r = 1$ and $k_s = k_r = 2$ respectively. We see that the quality of the solution improves with the initial number of potential positions that are considered. Initially there is a noticeable improvement, as the number of potential locations is increased (e.g. from 169 to 289 to 625). However, as the number of potential locations increases beyond a certain point, it does not lead to any significant additional improvements in the solution. This is reflected in both Fig. 3.1 and Fig. 3.2, where the curves level out, after the initial steep decline in the number of nodes required for the cover. For a given number of potential locations, the number of relay nodes required to cover the network increases with the number of sensor nodes (NS) in the distribution.

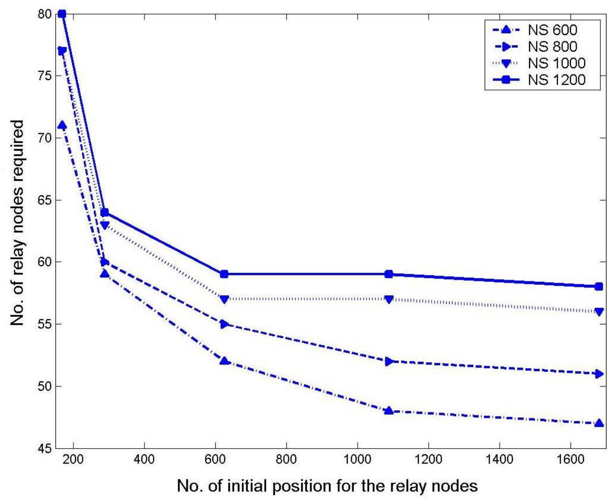

Figure 3.1: Variation of the number of relay nodes with the number of potential locations, for $k_s = k_r = 1$.

Although we used the same value for both k_r and k_s in the two examples

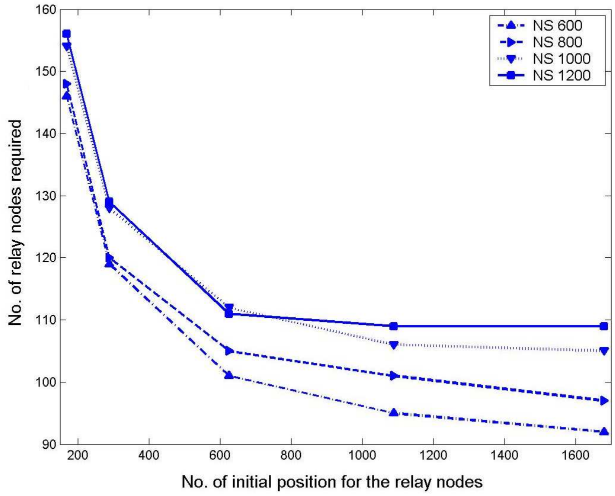

Figure 3.2: Variation of the number of relay nodes with the number of potential locations, for $k_s = k_r = 2$.

discussed above, this is not required by our formulation. The two values can be adjusted independently. For example, it is quite possible to have $k_r = 1, k_s = 2$ or $k_r = 3, k_s = 1$ depending on user requirements. The results for different values of k_r and k_s are similar to those given in Fig. 3.1 and Fig. 3.2, except that the actual number of relay nodes in the cover increases as k_r and k_s increases. Fig. 3.3 illustrates how the number of relay nodes varies with the sensor node distribution and the desired values for k_s and k_r, when the grid spacing was such that the number of potential locations of the relay nodes was 1089. We see that, for a network with $k_r = 2$, where each sensor node is covered by at least two relay nodes (i.e., $k_s = 2$), the number of relay nodes required is almost double of that for a network with $k_r = 1$, and $k_s = 1$. However, we also note that, for a given k_s and k_r, only a few extra relay nodes were needed when the number of sensor nodes was increased from 600 to 1200.

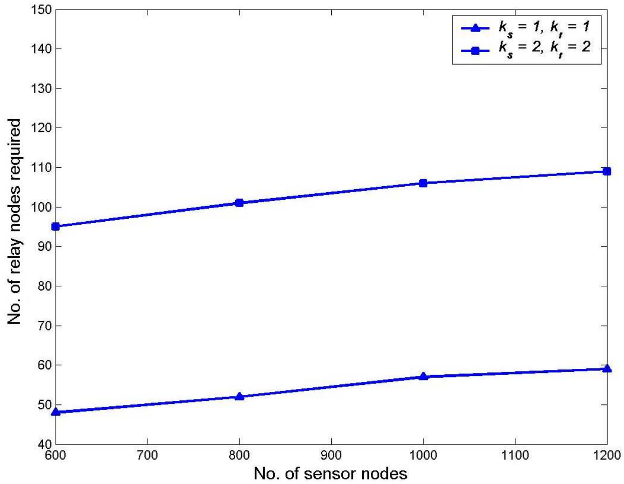

Figure 3.3: Variation of the number of relay nodes with the number of sensor nodes.

3.7 Discussion

In this chapter, we have investigated the problem of appropriately placing relay nodes in a sensing area, in order to design a network with desired levels of fault tolerance. We have first presented ILP-SC, an ILP formulation that selects the positions of the relay nodes to ensure that each sensor node is covered by at least one relay node, and that the number of relay nodes is minimized. We have then extended ILP-SC to define ILP-FT, which incorporates fault-tolerance, by requiring that each sensor nodes is covered by k_s relay nodes, and the relay node network is k_r-connected. ILP-FT is a generalized formulation that guarantees fault tolerance, for arbitrary values of k_s and k_r. The experimental results demonstrate that this approach is feasible for practical networks, with over one thousand sensor nodes.

Chapter 4

CENTRALIZED CLUSTERING IN HIERARCHICAL SENSOR NETWORKS

4.1 Introduction

A great deal of research has focused on energy conservation in sensor networks to maximize the lifetime of the network. In a two-tiered sensor network architecture using higher powered relay nodes as cluster heads, total depletion of the power of a relay node can impact the functionality of the network more severely than the depletion of the battery of a single sensor node. In this section, we maximize the lifetime of the *relay node network*, rather than the lifetime of individual sensor nodes.

The primary factors contributing to the energy dissipation of a relay node are the communication scheme (also called routing) used, and the load on the individual relay node (determined by the total amount of data communicated by the relay node). For routing in a two-tiered sensor network, relay nodes may use either the single-hop, or the multi-hop communication scheme, as discussed in Section 2.7.

In cases when a routing scheme is already computed separately (e.g., using techniques discussed in Section 2.7, such as the MTE or the MH, or by using approaches using the Depth First Search (DFS) and the position-based routing algorithms [83], [84], [88]), an important factor that decides the lifetime of the relay node network is the way clustering is performed, i.e., how the sensor nodes are assigned to the clusters. An appropriate clustering scheme can effectively balance the load on different relay nodes [42], and hence substantially extend the network lifetime.

The clustering model closest to our approach is the one presented in [40]. As in [40], we consider a situation where the clusters are formed around higher energy *relay nodes*, which act as cluster heads. However, our approach takes a more comprehensive view. We consider not only the *cardinality* of each cluster (defined as the number of sensor nodes associated with the cluster) but other factors, such as the routing scheme and the energy dissipation for transmitting and receiving data. We also directly maximize the network lifetime, rather than optimize a secondary objective such as the variance in the cardinalities. This makes our approach much more effective, compared to existing load balanced clustering techniques.

We present two ILP formulations for optimal load balanced clustering. Formulation ILP-S is for direct transmission, using the single-hop model, and ILP-M is for the multi-hop model. Our ILP formulations take into account

1) the amount of data to be forwarded by each relay node,
2) the distances to the base station and the neighboring nodes from each relay node, and
3) the specific routing strategy to be used.

The ILP formulations then assign each sensor node to a cluster in such a way that maximizes the lifetime of the relay node network.

We assume that the routing strategy by which the relay nodes communicate with the base station is already determined, using any existing approach [2], [10], [13]. The goal is to find a clustering that maximizes the network lifetime for a given routing scheme. Our algorithm is not affected by the actual choice of the routing strategy, and can be used to maximize the lifetime for any valid routing. However, to evaluate the performance of our proposed clustering schemes, we have considered the following routing schemes:

i) The *single hop* (or *direct-transmission-energy*) model (SHDTM) [46].
ii) The *minimum-transmission-energy (MTE)* model [46], [44], where each relay node transmits to its nearest neighbor which is closer to the base station.
iii) The *minimum-hop (MH)* model [42], where a multi-hop route from each relay node to the base station that minimizes the number of hops

is used. If the transmission ranges of the relay nodes are high enough, this may reduce to the single-hop model.

iv) The *random-routing* model, where each relay node j that cannot send its data directly to the base station, randomly selects a relay node k as its next hop such that k is within the transmission range of j and k is closer to the base station than j.

4.2 ILP Formulations for Optimal Clustering

In this section we present our ILP formulations for load balanced clustering. The first formulation (ILP-S) is for single-hop communication and the second (ILP-M) is for multi-hop communication.

4.2.1 The Network Model

For our model, we consider a two-tiered wireless sensor network with a set $\mathcal{S}$, containing n sensor nodes, and a set $\mathcal{R}$, containing m relay nodes, and one base station. For convenience, we assign each node a unique label as follows:

i) for each sensor node in $\mathcal{S}$, a label $i, 1 \leq i \leq n$,

ii) for each relay node in $\mathcal{R}$, a label $j, n+1 \leq j \leq m+n$ and

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

Each sensor node belongs to only one cluster and each relay node acts as the cluster head of exactly one cluster. In other words, let $\mathcal{C}^j, n+1 \leq j \leq m+n$, be the set of sensor nodes belonging to the j-th cluster. Then, $\mathcal{S} = \mathcal{C}^{n+1} \cup \mathcal{C}^{n+2} \cup \ldots \cup \mathcal{C}^{m+n}$ and $\mathcal{C}^j \cap \mathcal{C}^k = \emptyset$, $\forall j, k, j \neq k, n+1 \leq j, k \leq m+n$. The set $\mathcal{C}^j$ will constitute the cluster, with the relay node having label j as the cluster head.

We assume that all nodes are stationary after deployment and the positions of both the sensor nodes and the relay nodes are known beforehand. There are two possible scenarios for determining the positions of the relay nodes and the sensor nodes as follows:

Case i) It is possible to determine, before the deployment of the network, a) the desired positions of the sensor nodes, and b) the relay nodes and place each node at its desired location. In this scenario, we can

1) use our formulations to determine the optimal clustering and the routing,
2) pre-configure the sensor nodes and the relay nodes with the clustering and routing information, and
3) start operating the network as soon as all the nodes are in place.

Case ii) The locations of the nodes are not known before being deployed but it is possible to find these locations using some mechanism, once the nodes are in place. For instance, a GPS system in each node was proposed in [40], [41], [42], [83], [84], [88] for this purpose, which has to be active only once, right after the node is in place. Each sensor or relay node has to broadcast its location to the base station. After the base station solves the clustering and routing problem using our formulations, the base station sends, to each sensor or relay node, the clustering/routing information relevant to that node. It was pointed out in [40], [41], [42] that the energy dissipated for these communications is insignificant, compared to the energy for the subsequent transmissions, and will not have any substantial impact on the lifetime of the network[1].

We also assume that the average amount of data generated by each sensor node is known, and may vary from one sensor node to another. We further assume that the placement strategy applied, during the deployment phase of the network, ensures proper "coverage" of each sensor node (i.e., each sensor node is able to send its data to at least one relay node) and the connectivity of the relay node network. As mentioned in Section 2.4, maximizing the lifetime is equivalent to minimizing F_{max}, the maximum energy dissipation of any relay node in a round. The objective of ILP-S (ILP-M) is, therefore, to minimize F_{max}.

4.2.2 The ILP Formulation for Single-Hop Routing (ILP-S)

Given a collection of sensor nodes, relay nodes and a base station, along with their locations, the objective of the formulation is to form a cluster, for each relay node $j, n+1 \leq j \leq n+m$, consisting a set of sensor nodes $\mathcal{C}^j$, such that the lifetime of the network is maximized. In this section, we consider the single-hop model for transmitting data from relay nodes directly to the base station. Therefore, relay node j receives data from the sensor nodes belonging to its own cluster $\mathcal{C}^j$, and sends the

[1]We note that a scheme involving GPS is not an essential requirement for our approach to work, as any other localization scheme (e.g., [51], [58]) can also be used as well.

data directly to the base station. Since our interest is in extending the lifetime of the network by increasing the number of rounds until one relay node ceases to function, it is much more important to minimize the energy dissipation of the relay node that is being depleted most rapidly, than to decrease the average energy dissipation of relay nodes. This is exactly what we have done in our formulation. Using the labels for the sensor nodes, relay nodes and the base station, as discussed in Section 4.2.1, we define the formulation as follows:

$$\textbf{Minimize } F_{max} \tag{4.1}$$

Subject to:

a) A sensor node must belong to exactly one cluster.

$$\sum_{j=n+1}^{n+m} X_{i,j} = 1 \qquad \forall i, 1 \leq i \leq n \tag{4.2}$$

b) A sensor node i can transmit to a cluster-head j, only if the distance between i and j is less than the range r_{max} of the sensor node.

$$X_{i,j} \cdot d_{i,j} \leq r_{max} \qquad \forall i, 1 \leq i \leq n, \ \ \forall j, n+1 \leq j \leq n+m \tag{4.3}$$

c) The total number of bits generated by the sensor nodes belonging to cluster j in one round, B_j, must be equal to the total number of bits received at relay node j from its own cluster in one round of data gathering.

$$\sum_{i=1}^{n} b_i \cdot X_{i,j} = B_j \qquad \forall j, n+1 \leq j \leq n+m \tag{4.4}$$

d) The total energy dissipated by any relay node in one round of data gathering cannot exceed the energy spent per round by the relay node, which is being depleted at the fastest rate.

$$\alpha_1 B_j + \alpha_2 B_j + \beta B_j \cdot (d_{j,n+m+1})^q \leq F_{max} \tag{4.5}$$

Constraint 4.5 has to be repeated $\forall j, n+1 \leq j \leq n+m$.

Equation (4.1) is the objective function that minimizes the maximum energy F_{max} dissipated by a relay node in one round of data gathering. Constraints (4.2) - (4.4) are straight-forward, as explained in the formulation. The left hand side of constraint (4.5) gives the total energy dissipated by the j-th relay node. The right hand side of constraint (4.5) is F_{max}, the objective function for the formulation. Since constraint (4.5) is repeated for all relay nodes, j, F_{max} must be greater than or equal to the largest value of the total energy dissipated by any relay node. The objective function to be minimized is F_{max}. Therefore F_{max} must be equal to the largest value of the total energy dissipated by any relay node.

4.2.3 The ILP Formulation Multi-hop Routing (ILP-M)

Given the same network as in Section 4.2.2, the objective of this formulation is to maximize the lifetime of the network using a multi-hop routing scheme. An important point here is that this formulation may be used for many of the popular multi-hop strategies (e.g., minimum distance, minimum hops, random routing) [42].

In this model, in addition to receiving data from the sensor nodes belonging to its own cluster, each relay node can also receive data from any number of other relay nodes. However, since we use the non-flow-splitting model, each relay node can transmit either to the base station or to only one other relay node. The only difference between ILP-M, given below, and ILP-S is the way the objective function F_{max} is computed.

$$\textbf{Minimize } F_{max} \tag{4.6}$$

Subject to:

a - c) Equations 4.2 - 4.4.

d) The number of bits received by relay node j, R_j, must be equal to the total number of bits received per round at relay node j from its own cluster and from other relay nodes.

$$\sum_{k=n+1;k\neq j}^{n+m} R_k \cdot c_{k,j} + B_j = R_j \qquad \forall j, n+1 \leq j \leq n+m \tag{4.7}$$

e) The total energy dissipated by any relay node in one round of data gathering cannot exceed the energy spent per round by the relay node, which is being depleted at the fastest rate in the multi-hop model, F_{max}.

$$\alpha_1 R_j + \alpha_2 R_j + \beta R_j \cdot (d_{j,k})^q \leq F_{max} \tag{4.8}$$

Constraint 4.8 has to be repeated $\forall j, n+1 \leq j \leq n+m$, and $\forall k, n+1 \leq k \leq n+m+1$ such that $c_{j,k} = 1$.

Here the pre-computed constants $c_{k,j}$ determine which routing strategy we use. If $c_{k,j} = 1$, then relay node k sends all its data (i.e., the data collected from the cluster having relay node k as its cluster head and the data k received from other relay nodes) to relay node j. Since the positions of the relay nodes are known, the value of $c_{k,j}$, for all pairs of relay nodes (k, j), can be pre-computed, based on the strategy to be used. For instance, if the "minimum hop" model is to be used, $c_{k,j} = 1$ if relay node j is the node lying in the path involving the minimum number of hops from relay node k to the base station.

Equation (4.6) is the objective function and is very similar to equation (4.1). The total number of bits received at relay node j from its own cluster, in a round, is B_j. The total number of bits relay node k generates is R_k. This is added to the number of bits received by relay node j from its own cluster only if $c_{k,j} = 1$. The left hand side of constraint (4.7) therefore gives the total number of bits received by relay node j in a round. Finally, the left hand side of constraint (4.8) is based on the energy models described by equations (2.1) and (2.2) to compute the total energy dissipated by the relay node with label j. Using arguments similar to that used to

Table 4.1: Number of constraints and integer variables in ILP-S and ILP-M

	Number of integer variables	**Number of constraints**	**Number of continuous variables**
ILP-S	mn	$2m + n + mn$	$m + 1$
ILP-M	mn	$3m + n + mn$	$2m + 1$

explain constraint (4.5) in Section 4.2.2, constraint (4.8), for all j, gives the maximum energy dissipated by any relay node.

4.2.4 Analysis of ILP-S and ILP-M

An integer linear program is characterized by the number of integer variables and the number of constraints [76]. Table 4.1 gives the number of integer variables, continuous variables and constraints in the formulations ILP-S and ILP-M.

4.3 Clustering Heuristics

In this section we have presented some straight-forward heuristics for clustering. The input to each of the heuristics is the set of relay nodes $\mathcal{R}$ and a set of sensor nodes, $\mathcal{S}$. Each heuristic determines mutually disjoint sets of sensor nodes $\mathcal{C}^j$, for all $j \in \mathcal{R}$ such that relay node j can be a cluster head for all sensor nodes in $\mathcal{C}^j$ and $\bigcup_{j \in \mathcal{R}} \mathcal{C}^j = \mathcal{S}$.

Heuristic 1 : ***Greedy-Clustering*** **(GC)**

begin
  $\mathcal{C}^j \longleftarrow \emptyset, \forall j \in \mathcal{R}$
  for *Each* $j \in \mathcal{R}$ **do**
    for *Each* $i \in \mathcal{S}$ **do**
      if i *can communicate with* j **then**
        $\mathcal{C}^j \longleftarrow \mathcal{C}^j \cup \{i\}$.
        $\mathcal{S} \longleftarrow \mathcal{S} \backslash \{i\}$.
      end
    end
  end
end
return $\mathcal{C}^j, \ \forall j \in \mathcal{R}$**.**

Heuristic 2 : ***Least-Distance-Clustering*** **(LDC)**

begin
  $\mathcal{C}^j \longleftarrow \emptyset, \forall j \in \mathcal{R}$
  Let $d_{i,j} \longleftarrow$ distance between sensor node i and relay node j.
  for *Each* $i \in \mathcal{S}$ **do**
    Find a $j \in \mathcal{R}$ such that $d_{i,j} \leq d_{i,k}, \forall k \in \mathcal{R} \backslash \{j\}$
    $\mathcal{C}^j \longleftarrow \mathcal{C}^j \cup \{i\}$.
    $\mathcal{S} \longleftarrow \mathcal{S} \backslash \{i\}$.
  end
end
return $\mathcal{C}^j, \ \forall j \in \mathcal{R}$**.**

Heuristic 1 considers each relay node and greedily picks all sensor nodes which may communicate with the relay node under consideration. Heuristic 2 assigns each sensor node to the relay node closest to it. In our model, where sensor nodes transmit data directly to their cluster heads, this approach minimizes the energy dissipation of the sensor nodes. Heuristic 3 forms, in a greedy way, clusters in such a way that the variation of cluster sizes is as small as possible. In heuristic 3, $\mathcal{T}^j$ will denote the number of sensor nodes belonging to relay node $j \in \mathcal{R}$. The idea of heuristic 3 is similar to that used in [40].

Heuristic 3 : ***Minimal-Cardinality-Variance-Clustering*** **(MCVC)**

begin
  $\mathcal{T}^j \longleftarrow 0, \mathcal{C}^j \longleftarrow \emptyset, \forall j \in \mathcal{R}$
  for *each* $i \in \mathcal{S}$ **do**
    if *sensor node* i *can communicate only with relay node* j **then**
      $\mathcal{C}^j \longleftarrow \mathcal{C}^j \cup \{i\}$.
      $\mathcal{S} \longleftarrow \mathcal{S} \backslash \{i\}$.
      $\mathcal{T}^j \leftarrow \mathcal{C}^j + 1$.
    end
  end
  for *each* $i \in \mathcal{S}$ **do**
    Find the relay node $j \in \mathcal{R}$ such that
    a) i can communicate with j, and
    b) $\mathcal{T}^j \leq \mathcal{C}^k, \forall k \in \mathcal{R}$ such that $j \neq k$ and i can communicate with k.
    $\mathcal{S} \longleftarrow \mathcal{S} \backslash \{i\}$.
    $\mathcal{T}^j \leftarrow \mathcal{T}^j + 1$.
    $\mathcal{C}^j \longleftarrow \mathcal{C}^j \cup \{i\}$.
  end
end
return $\mathcal{C}^j, \ \forall j \in \mathcal{R}$**.**

4.4 Simulation Results

We have carried out a number of simulations to test the effectiveness of our formulations, with different sensor and relay node distributions. We have considered networks with areas up to 240m $\times$ 240m. The sensor nodes were randomly distributed over the region. We varied the number of sensor nodes from 75 to 750 nodes. For each relay node setup, and for each size of sensor nodes, a separate placement scheme is used, which ensures that each sensor node is able to communicate with at least one relay node. We have measured the achieved lifetime of the network by the number of rounds until the first relay node runs out of battery power. The ILP formulations were solved using ILOG CPLEX version 9.1 [52], on a 900MHz SUN platform. We have assumed that

i) the communication energy dissipation is based on the first order radio model, described in Section 2.2.

ii) the values for the constants are the same as in [46], so that:

  a) $\alpha_1 = \alpha_2 = 50nJ/bit$,

  b) $\beta = 100pJ/bit/m^2$ and

  c) the path-loss exponent, $q = 2$.

iv) the transmission range of each sensor node is 40 meters, as in [87].

v) the initial energy of each relay node, $E_{initial}$ is $5J$, as in [87].

We varied the transmission range of the relay nodes from 100 meters to 350 meters. For each relay/sensor node distribution, we compared the performance of our formulation to the clustering heuristics GC, LDC and MCVC outlined in Section 4.3. We have simulated our approach with two different settings, one with 12 relay nodes and the other with 24 relay nodes. In the configuration with 12 relay nodes, all nodes were distributed over an area of $160m \times 160m$; with 24 relay nodes, nodes were distributed over an area of $240m \times 240m$. All lifetimes are computed using equation (2.3) given in Section 2.4. In the following sections, we have presented the results of the simulation.

4.4.1 Performance Evaluation for ILP-S

In this section, we present the simulation results for our formulation ILP-S when the relay nodes send data directly to the base station. Our objective is to form, for each relay node, a cluster of sensor nodes such that the maximum energy dissipation of a relay node is minimized. Table 4.2 and Table 4.3 show the achieved lifetimes of the networks with 12 and 24 relay nodes, respectively, when we applied different clustering heuristics to the same network of relay nodes and sensor nodes. The first three rows show the lifetimes achieved using *Greedy Clustering* (GC), *Least Distance Clustering* (LDC) and *Minimum Cardinality Variance* (MCVC) heuristics respectively. The last row indicates the lifetime achieved using our formulation (ILP-S). The corresponding values for 12 relay nodes (24 relay nodes) are plotted in Fig. 4.1 (Fig. 4.2). For both networks, our formulation was able to extend the network lifetime significantly, as shown in Fig. 4.1 and Fig. 4.2. The percentage improvements obtained using ILP-S over the other clustering schemes, for the 24 relay node network, are shown in Fig. 4.3. For this network, our formulation was able to nearly double the lifetime of the network, compared to the GC and LDC approaches. ILP-S also resulted in significant improvements (30%-40%) over the heuristic, MCVC, having the best performance for single-hop routing, which is based on the approach proposed in [40].

	Number of sensor nodes		
Clustering method	$n = 75$	$n = 100$	$n = 150$
GC	1220	871	938
LDC	2090	1520	1460
MCVC	2030	1610	1350
ILP-S	2530	2290	1740

Table 4.2: Network lifetimes with different clustering methods for a 12 relay node network under the single-hop routing scheme.

	Number of sensor nodes				
Clustering method	$n = 200$	$n = 300$	$n = 400$	$n = 500$	$n = 750$
GC	375	235	282	137	106
LDC	395	341	338	215	133
MCVC	626	390	340	254	169
ILP-S	751	563	442	338	228

Table 4.3: Network lifetimes with different clustering methods for a 24 relay node network under the single-hop routing scheme.

4.4.2 Performance Evaluation for ILP-M

We consider the following three multi-hop routing schemes, as discussed in Section 4.1.

1) The minimum-transmission-energy (MTE) model.

2) The minimum hop (MH) model.

3) The random routing (RR) model.

The results of the simulation with the MTE model is shown in Table 4.4 for the 12 relay nodes network and in Table 4.5 for the 24 relay nodes network. As shown in Table 4.5, for the MTE model, the performance of all the heuristics are very similar and are quite close to optimal. ILP-M provides only a modest 3% - 13% improvement over the heuristics. The results indicate that, for the MTE model, the clustering strategy does not have a significant effect on the network lifetime. This is expected, since the relay nodes closest to the base will always have the heaviest load and hence will determine the network lifetime, no matter what clustering scheme is used.

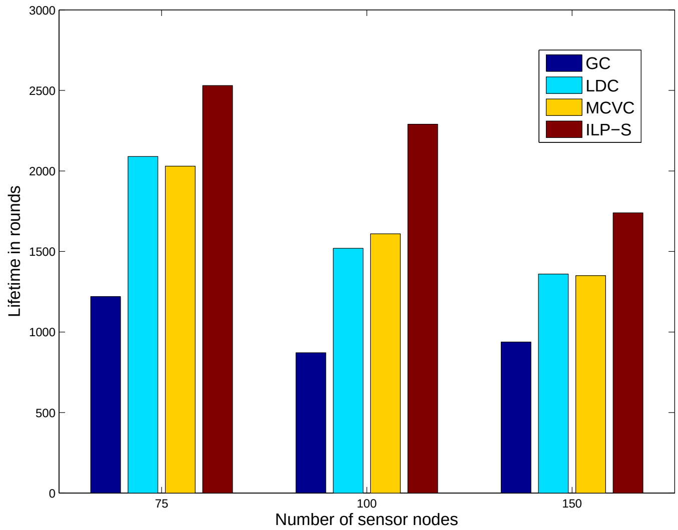

Figure 4.1: Comparison of network lifetimes with different clustering methods for a 12 relay node network under the single-hop routing scheme.

For the MH model, our ILP formulation provided improvements of 15% - 30% over the heuristics for different distributions, as shown in Table 4.6. For the RR model, ILP-M was able to extend the lifetime by at least 25%, and, in several cases, was able to more than double the lifetime achieved by the best performing heuristic. The results for the RR model are shown in Table 4.7.

The percentage improvements obtained using ILP-M over the other clustering schemes, for the 24 relay node network, with the MTE, the MH and the RR models, are shown in Fig. 4.4, 4.5 and 4.6, respectively.

It is clear from these figures that, for multi-hop routing, the relative performance of the three heuristics vary considerably with the routing strategy. Even for a specific routing scheme (e.g., the MH model, or the MTE model), the relative performance varied with the sensor node distributions. For example, when using the MH

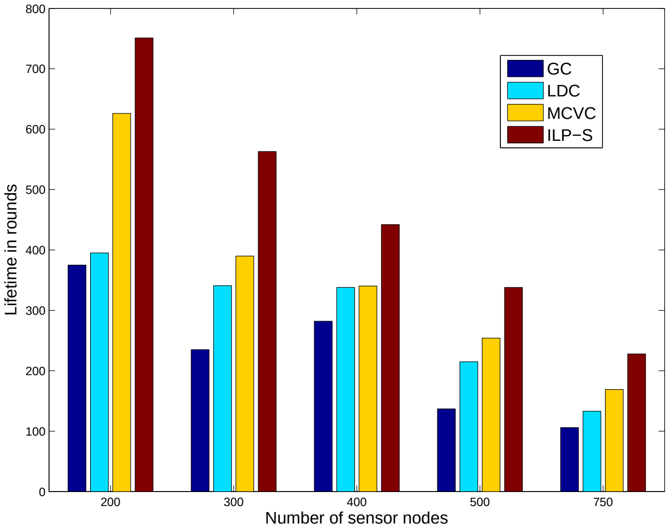

Figure 4.2: Comparison of network lifetimes with different clustering methods for a 24 relay node network under the single-hop routing scheme.

model, the GC performed better with 200 sensor nodes, but the MCVC performed better with 750 sensor nodes. This means that, although an individual heuristic may perform well for a specific situation, there is no guarantee of consistency. This is a significant advantage when using an ILP, which always guarantees an optimal solution.

4.5 Discussion

In this chapter, we have presented two ILP formulations for optimal load balanced clustering in two-tiered sensor networks, and compared them with a number of heuristic techniques available in the literature. Our ILP for multi-hop routing is a *generalized* formulation that can be used in conjunction with any specified routing strategy. To the best of our knowledge, these are the first mathematical programming formu-

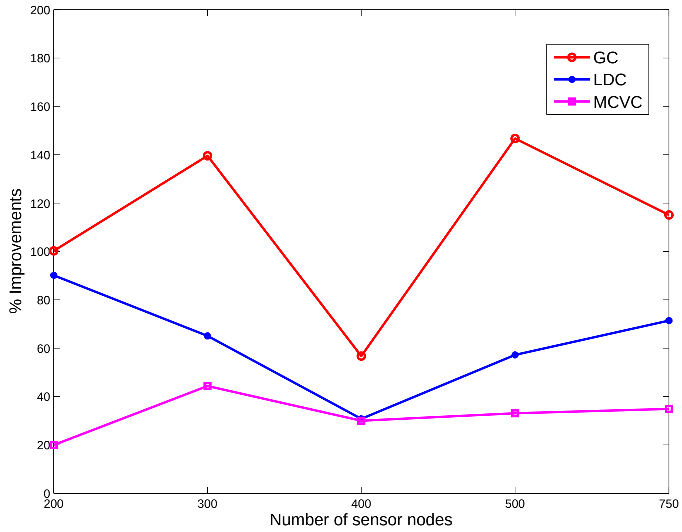

Figure 4.3: Percentage improvement of the network lifetimes using *ILP-S*, over GC, LDC and MCVC, on a 24 relay node network.

lations for optimally allocating sensor nodes to clusters in a two-tier network, where higher powered relay nodes are used as cluster heads. Our formulations directly maximize the network lifetime. We have also implemented three simple heuristics, based on existing clustering techniques. For single-hop routing, our approach consistently improves the network lifetime by 30% or more, even when compared to the heuristic that performs the best. For multi-hop routing, the amount of improvement depends on the routing strategy, but our ILP always outperforms the existing heuristics and guarantees an optimal solution. As expected, for a given set of relay nodes, the network lifetime decreases with the number of sensor nodes. This is because the average load on each relay node increases as the number of sensor nodes is increased.

An important feature of our ILP formulations is that they are quite fast and can quickly generate solutions for networks with hundreds of sensor nodes. This

	Number of sensor nodes		
Clustering method	$n = 75$	$n = 100$	$n = 150$
GC	3310	2650	1510
LDC	3310	2480	1800
MCVC	3720	2430	1920
ILP-M	3720	2900	1950

Table 4.4: Network lifetimes with different clustering methods for a 12 relay node network under the multi hop routing scheme when MTE model is used.

	Number of sensor nodes				
Clustering method	$n = 200$	$n = 300$	$n = 400$	$n = 500$	$n = 750$
GC	1250	815	589	474	328
LDC	1180	815	611	496	340
MCVC	1140	778	629	511	338
ILP-M	1290	856	640	518	350

Table 4.5: Network lifetimes with different clustering methods for a 24 relay node network under the multi hop routing scheme when MTE model is used.

means that it is possible to obtain *optimal* solutions for practical networks. Therefore, we propose that in sensor networks using relay nodes as cluster heads, our ILP formulations be used for clustering due to the following advantages:

a) The ILP formulations guarantee an optimal solution,

b) the solutions obtained using our ILP formulations can be significantly better than the solutions obtained using existing heuristics,

c) the time needed to run the ILP formulations is reasonably low, and

d) it is feasible to use the proposed ILP formulations, since they can generate fast solutions for practical-sized networks.

	Number of sensor nodes				
Clustering method	$n = 200$	$n = 300$	$n = 400$	$n = 500$	$n = 750$
GC	632	437	332	252	157
LDC	578	437	334	273	176
MCVC	597	451	326	280	187
ILP-M	731	514	388	308	211

Table 4.6: Network lifetimes with different clustering methods for a 24 relay node network under the multi hop routing scheme when MH model is used.

	Number of sensor nodes				
Clustering method	$n = 200$	$n = 300$	$n = 400$	$n = 500$	$n = 750$
GC	559	337	375	202	165
LDC	588	458	377	260	218
MCVC	790	533	402	290	254
ILP-M	985	764	522	447	336

Table 4.7: Network lifetimes with different clustering methods for a 24 relay node network under the multi hop routing scheme when RR model is used.

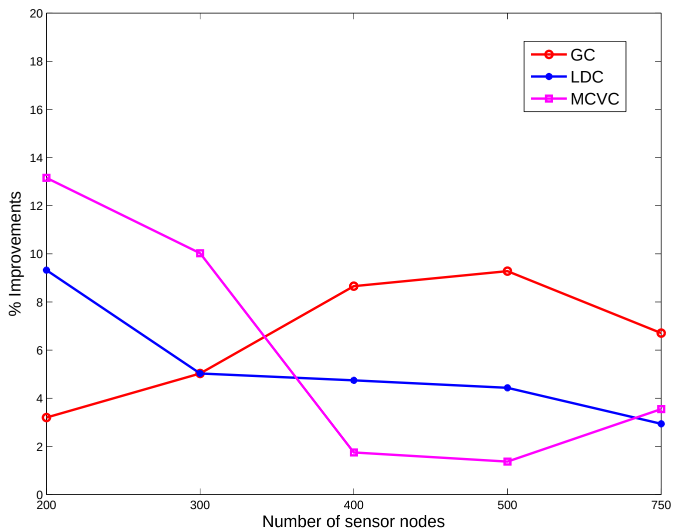

Figure 4.4: Percentage improvement of the network lifetimes using *ILP-M*, over GC, LDC and MCVC, on a 24 relay node network, when the MTE model is used.

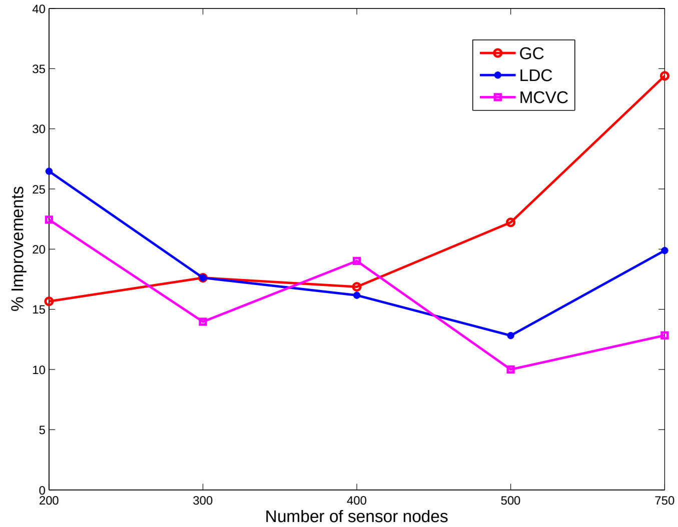

Figure 4.5: Percentage improvement of the network lifetimes using *ILP-M*, over GC, LDC and MCVC, on a 24 relay node network, when the MH model is used.

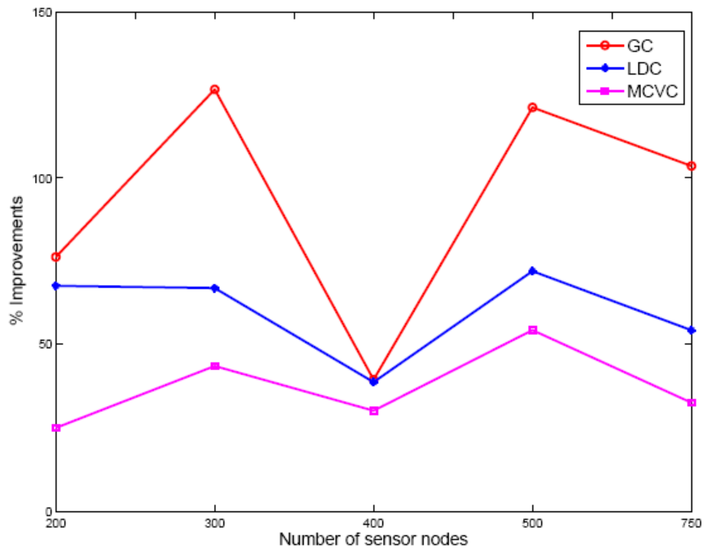

Figure 4.6: Percentage improvement of the network lifetimes using *ILP-M*, over GC, LDC and MCVC, on a 24 relay node network, when the RR model is used.

Chapter 5

INTEGRATED CLUSTERING AND ROUTING IN HIERARCHICAL SENSOR NETWORKS

5.1 Introduction

For a given placement of the sensor nodes and the relay nodes in a two-tier sensor network, the important factors that affect the lifetime of the network are

a) the clustering scheme used to assign sensor nodes to the appropriate clusters, and

b) the routing scheme used for the data communication.

Proper clustering and routing schemes can play an important role in effectively balancing the load on different relay nodes, and have been shown to improve the lifetime of the network [13], [11], [42], particularly for non-flow-splitting routing. Previous approaches to clustering and routing have considered these two problems independently. Typically, the assignment of sensor nodes to clusters is done first, and then a routing scheme is calculated to maximize the network lifetime.

In this chapter, we present an integer linear program (ILP) formulation that jointly optimizes both clustering and routing to maximize the lifetime of the upper-tier relay node network. In our network model:

i) The roles of the sensor nodes and the relay nodes are not interchangeable.

ii) The relay nodes

   a) do not perform sensing tasks,

   b) are provisioned with higher energy, and

   c) transmit over much larger distances, compared to regular sensor nodes.

iii) The transmission range of each relay node, though longer than that of a sensor node, is still limited. This means that all relay nodes will not be able to reach the base station in a single-hop.

iv) Each sensor node is located close enough to some relay node, so that the sensor node can transmit directly to at least one relay node. Sensor nodes only communicate to their respective cluster heads and do not take part in routing the data to the base station.

Our proposed approach

i) assigns sensor nodes to clusters, and

ii) calculates a multi-hop path from each relay node to the base station, using the non-flow-splitting model, in such a way that the overall lifetime of the network is maximized.

We show that our integrated approach can lead to significant improvements over techniques that consider clustering and routing separately. We have

a) presented ILP-NFS (ILP-FS) - a formulation for optimal clustering and routing using non-flow-splitting (flow-splitting) model, to maximize the lifetime of the network,

b) demonstrated that combining clustering and routing leads to a significant increase in the lifetime of the network when non-flow-splitting routing is used, compared to the situation where the two problems are solved separately,

c) proposed NFS-H - a heuristic, based on the ILP-FS to achieve "near-optimal" lifetimes for larger networks, using the non-flow-splitting model, and

d) provided a comparative analysis of network lifetimes, under the non-flow-splitting and flow-splitting models.

5.2 ILP Formulation for Optimal Clustering and Routing

Given the network as described in Section 4.2.1, our objective for formulation ILP-NFS is to maximize the lifetime of the network, by finding an optimal clustering and routing scheme. In this section we have also discussed how we can handle the situation where the link quality may be different on different links.

5.2.1 ILP Formulation for Non-Flow-Splitting Model (ILP-NFS)

In ILP-NFS, each relay node, in addition to receiving data from the sensor nodes belonging to its own cluster, can also receive data from any number of other relay nodes. The implication of the non-flow-splitting model used in ILP-NFS is that each relay node can transmit either to the base station or to only one other relay node. The formulation is given below.

$$\textbf{Minimize } F_{max} \tag{5.1}$$

Subject to:

a) A sensor node i can transmit to a relay node j, only if the distance between i and j is less than the range r_{max} of the sensor node.

$$X_{i,j} \cdot d_{i,j} \leq r_{max} \qquad \forall i, 1 \leq i \leq n, \tag{5.2}$$
$$\forall j, n+1 \leq j \leq n+m$$

b) Relay node j can transmit to relay node k (or to the base station), if k

(or the base station) is within the transmission range of j.

$$Y_{j,k} \cdot d_{j,k} \leq d_{max}, \quad \forall j,k, \quad n+1 \leq j \leq n+m, \tag{5.3}$$
$$n+1 \leq k \leq n+m+1; j \neq k$$

c) A sensor node must belong to exactly one cluster.

$$\sum_{j=n+1}^{n+m} X_{i,j} = 1 \qquad \forall i, 1 \leq i \leq n \tag{5.4}$$

d) The total number of bits generated by the sensor nodes belonging to cluster j in one round, B_j, must be equal to the total number of bits received at relay node j from its own cluster in one round of data gathering.

$$\sum_{i=1}^{n} b_i \cdot X_{i,j} = B_j \qquad \forall j, n+1 \leq j \leq n+m \tag{5.5}$$

e) Relay node j can only transmit to one relay node or to the base station (non-flow-splitting constraint).

$$\sum_{k=n+1;k\neq j}^{n+m+1} Y_{j,k} = 1, \qquad \forall j, n+1 \leq j \leq n+m \tag{5.6}$$

f) The total number of bits transmitted by relay node j in one round of data gathering, T_j, must be equal to the total number of bits received at relay node j (either from other relay nodes or from its own cluster).

$$T_j = \sum_{k=n+1;k\neq j}^{n+m+1} f_{j,k}, \qquad \forall j, n+1 \leq j \leq n+m \tag{5.7}$$

g) The incoming flow, $\mathbb{R}_j$, to relay node j from other relay nodes must be equal to the total number of bits received per round at relay node j from other relay nodes.

$$\mathbb{R}_j = \sum_{k=n+1;k\neq j}^{n+m} f_{k,j}, \qquad \forall j, n+1 \leq j \leq n+m+1 \tag{5.8}$$

h) Relay node j can transmit to k, only if either k is the next relay node in the multi-hop path from j to the base station, or k is the base station.

$$f_{j,k} \leq C \cdot Y_{j,k}, \qquad \forall j,k,\ n+1 \leq j \leq n+m, \quad n+1 \leq k \leq n+m+1; j \neq k \tag{5.9}$$

i) The incoming flow $\mathbb{R}_j$ to relay node j from other relay nodes, together with the incoming flow B_j from sensor nodes in the cluster for j, must balance the outgoing flow T_j.

$$T_j - \mathbb{R}_j = B_j, \qquad \forall j, n+1 \leq j \leq n+m \tag{5.10}$$

j) The total energy dissipated by any relay node in one round of data gathering cannot exceed F_{max}.

$$\alpha_1(\mathbb{R}_j + B_j) + \alpha_2 T_j + \beta \sum_{k=n+1;k\neq j}^{n+m+1} f_{j,k} \cdot (d_{j,k})^q \leq F_{max}, \quad \forall j, n+1 \leq j \leq n+m \tag{5.11}$$

Equation (5.1) is the objective function that minimizes the maximum energy F_{max} dissipated by a relay node in one round of data gathering. Constraints (5.2) - (5.8) are straight-forward, as explained above. Constraint 5.9 states that, if $Y_{j,k} = 0$, relay node j cannot transmit any bit to relay node k, so that $f_{j,k}$ must be 0. Otherwise, the value of $f_{j,k}$ cannot exceed C, the total number of bits received by the base station. In summary, constraint (5.9) (together with constraint (5.6)) enforces the non-flow-splitting constraint. The total number of bits received at relay node j from its own cluster, in a round, is B_j. The total number of bits received (transmitted) by relay node j is $\mathbb{R}_j$ (T_j), so that constraint (5.10) ensures flow conservation. Finally, the left hand side of constraint (5.11) is based on the energy models described by constraints (2.1) and (2.2), to compute the total energy dissipated by the relay node with label j. The right hand side F_{max}, of constraint (5.11), must be greater than or equal to the maximum of the energies dissipated by the relay nodes. Since the objective function is to minimize F_{max}, constraint (5.11) forces F_{max} to be the maximum energy dissipated by any relay node.

5.2.2 Consideration of Link Quality and Reconfiguration of the Communication Scheme

The *ILP-NFS* formulation, presented in Section 5.2.1 assumes that the value of q, the path loss exponent is the same for all links. It also does not consider link quality parameters such as the bit error rate (BER) [38] of the selected links. For practical networks, the value of q may be different on different links, based on the networking conditions. Also, it may not be practical to use a link with high BER. The *ILP-NFS* can be easily extended to account for different values for the path loss exponent between various links as well as to set the upper bound for BER in the selected links. To ensure that all links selected are within an allowable BER limit, the following two constraints can be added to the *ILP-NFS* formulation:

$$X_{i,j} \cdot \mathcal{B}_{i,j} \leq \mathcal{B}_{max} \qquad \forall i, 1 \leq i \leq n, \quad \forall j, n+1 \leq j \leq n+m \tag{5.12}$$

$$Y_{j,k} \cdot \mathcal{B}_{j,k} \leq \mathcal{B}_{max} \qquad n+1 \leq j \leq n+m, \quad n+1 \leq k \leq n+m+1; j \neq k \tag{5.13}$$

Here, $\mathcal{B}_{i,j}$ ($\mathcal{B}_{j,k}$) is the bit error rate of link between sensor node i and relay node j (relay nodes j and k), and $\mathcal{B}_{max}$ is the maximum allowable bit error rate of a link that is used for data communication. Constraint 5.12 (5.13) simply discards all links between a sensor node and a relay node (two relay nodes), whose bit error rates exceed the allowable limit.

To accommodate different values for the path loss exponent, constraint 5.11 can be replaced by constraint 5.14, given below:

$$\alpha_1(\mathbb{R}_j + B_j) + \alpha_2 T_j + \beta \sum_{k=n+1;k\neq j}^{n+m+1} f_{j,k} \cdot (d_{j,k})^{q_{j,k}} \leq F_{max}, \quad \forall j, n+1 \leq j \leq n+m \tag{5.14}$$

Where $q_{j,k}$ is the path loss exponent for the link $j \rightarrow k$.

The link condition and the BER in links may vary with time and it might be useful to recompute the communication scheme periodically, to accommodate changes in the network parameters.

There may be certain applications that allow the routing scheme to be changed during normal operations. For such applications, the rescheduling strategy we have proposed in our earlier work [7], [10] may be used, where the routes are recomputed at periodic intervals[1], taking into consideration the available residual energy of each relay node. This rescheduling is simply a repeated application of ILP-NFS, which is run at specified intervals, instead of only once at the beginning. We have shown in [7], [10] that it is possible to increase the lifetime of the network by this technique.

5.3 The Heuristic for clustering and Routing

ILP-NFS guarantees an optimal solution that maximizes the lifetime of the upper-tier relay node network. However, this formulation becomes computationally intractable for larger networks. Our previous work on routing [7], [10] indicates that the time

[1] Clustering was not considered in that paper.

required to solve the formulation is determined by the number of integer *routing* variables, i.e., the variables $Y_{j,k}$, even though the number of integer *clustering* variables $X_{i,j}$ is higher. This is because most $X_{i,j}$ values are set to 0, by equation (5.2). In this section, we present a heuristic based on a LP-relaxation of the routing variables $Y_{j,k}$, which we will call ILP-FS in our discussions below. In this approach, we first solve ILP-FS for the combined clustering and routing problem under the flow-splitting model. This means that we allow the traffic to be split among different nodes, and no longer require the integer variables $Y_{j,k}$. The result obtained for the flow-splitting model is then used to guide the search for a solution where the data communication will use the non-flow-splitting model . We note that ILP-FS still contains the integer variables $X_{i,j}$, but our experiments indicate that this does not significantly affect the time needed to solve the formulation. Finally, it is interesting to note that although ILP-FS allows the traffic to be split arbitrarily among different nodes, our simulation results indicate that each node typically transmits to only one or two neighboring nodes. Only in isolated cases, a node transmits to three or four other nodes, but it is extremely rare that a node transmits to more than four other nodes. We have used this observation to restrict the search space for ILP-NFS. The idea is that, based on the results from ILP-FS, we will define a small set $\mathcal{A}^j$ of "promising" relay nodes for the next hop, for all $j, n+1 \leq j \leq n+m$. $\mathcal{A}^j$ only includes those node(s) that j selected as the next node(s) in its path(s) to the base station. The search space for ILP-NFS is restricted in the sense that, when looking for the next node, in the path from j to the base station, the heuristic forces ILP-NFS to select a node from $\mathcal{A}^j$.

In this section, we will first give a brief outline of ILP-FS and then present our heuristic NFS-H for combined routing and clustering under the non-flow-splitting model.

5.3.1 ILP for Flow-Splitting Model (ILP-FS)

The formulation for ILP-FS is similar to ILP-NFS presented in the previous section, with the following modifications:

1. The variables $Y_{j,k}$ are eliminated. Since we allow the traffic to split arbitrarily, the integer routing variables $Y_{j,k}$ are no longer needed and traffic flows can be determined by the continuous flow variables $f_{j,k}$.
2. Since a relay node can transmit to any number of other nodes, constraint (5.6) is no longer needed, and is removed.
3. Since there can be non-zero flow to more than one node, constraint (5.9) is not needed, and is removed.
4. Constraint (5.3) is modified as follows:

$$f_{j,k} = 0, \qquad \forall j, k, \ni d_{j,k} > d_{max}; j \neq k \tag{5.15}$$

All other variables and constraints, as well as the objective function are identical to ILP-NFS.

5.3.2 Analysis of the ILP

It is well-known that the complexity of an ILP is exponential in the number of integer variables [76]. In addition, the number of constraints and the number of continuous variables in an ILP can also play a significant role in determining the time needed to solve an ILP. Therefore, in this section, we will analyze our formulations in terms of following three parameters:

i. The number of integer variables.

ii. The number of continuous variables.

iii. The number of constraints.

Table 5.1 shows the number of integer variables, the number of continuous variables and the number of constraints in the formulations ILP-NFS and ILP-FS. Of these three parameters, the primary factor affecting the performance of the ILP is the number of integer variables. For ILP-NFS, there are m^2 binary routing variables and mn binary clustering variables. Of these, it is the m^2 routing variables primarily affect the time required to solve the formulation. This is because most of the binary clustering variables are automatically set to 0, due to the limited transmission range of the sensor nodes, as discussed in Section 5.3. Therefore, the actual number of clustering variables that may possibly have a non-zero value is considerably less than mn. In ILP-FS, the binary routing variables are completely removed, resulting in a substantial reduction in the number of integer variables. As a result of this, in our experiments we find that, in practice, ILP-FS converges significantly faster than

Table 5.1: Number of variables and constraints in ILP-NFS and ILP-FS

	Number of integer variables	**Number of continuous variables**	**Number of constraints**
ILP-NFS	$m^2 + mn$	$m^2 + 3m + 1$	$2m^2 + 6m+$ $mn + n$
ILP-FS	mn	$m^2 + 3m + 1$	$m^2 + 5m+$ $mn + n$

ILP-NFS.

5.3.3 Heuristic for Non-Flow-Splitting Model (NFS-H)

NFS-H uses both ILP-FS and ILP-NFS to obtain a solution for the combined problem of clustering and routing, under the non-flow-splitting data communication model. The main steps of our heuristic are outlined below.

Heuristic 4 : *Non-Flow-Splitting Heuristic* (NFS-H)

```
begin
    A^j ⟵ ∅, ∀j ∈ R
    Solve ILP-FS to generate a solution for the flow-splitting model.
    for each j ∈ R do
        for each k ∈ R do
            if f_{j,k} > 0 in ILP-FS then
                A^j ⟵ A^j ∪ {k}.
            end
        end
    end
    for each j ∈ R do
        for each k ∈ A do
            if k ∉ A^j then
                Y_{j,k} ⟵ 0.
            end
        end
    end
    Run ILP-NFS to generate a solution for combined clustering and routing, under non-flow-
    splitting model.
end
```

The first step in the heuristic is to run ILP-FS to identify the set, $\mathcal{A}^j$, of promising relay nodes for the relay node j. By setting $Y_{j,k} = 0$, for all relay nodes not in $\mathcal{A}^j$, ILP-NFS is forced to select one of the nodes in $\mathcal{A}^j$ as the next node in the path from node j to the base station. Our experimental results indicate that the size of $\mathcal{A}^j$, for all j, typically ranges from 1 to 4. In other words, $|\mathcal{A}^j| << m$. When searching for the next relay node in the path from j to the base station, the heuristic only considers the small number of relay nodes in $\mathcal{A}^j$. This considerably reduces the number of routing variables required for ILP-NFS and allows ILP-NFS to quickly converge to a solution. We note that we cannot rule out the possibility of a higher value of $|\mathcal{A}^j|$ in isolated pathological cases. To handle such cases, it is reasonable to set an upper limit for $|\mathcal{A}^j| = \mu$, where μ is a small, pre-determined constant, $\mu << m$. A simple extension to our proposed heuristic that only considers the top μ relay nodes with the highest flows from relay node j, can then be used to handle these few special cases.

5.4 Simulation Results

We have carried out a number of simulations to test the effectiveness of our formulations, with different sensor and relay node distributions. We have measured the achieved lifetime of a network by the number of rounds from the start until the first relay node of the network runs out of battery power, as discussed in Section 2.4. We used CPLEX version 9.1 [52] to solve the ILP formulations. To evaluate the performance of our approach, we compared the achieved lifetime with standard multi-hop routing schemes such as the *minimum hop* (MH) routing and the *minimum transmission energy* (MTE) routing, as discussed in Section 4.1. We also considered ILP-R - an optimal non-flow-splitting routing scheme [7], [10], which maximizes the network lifetime for a specified clustering strategy. For each routing scheme, we experimented with the following clustering techniques discussed in Section 4.3:

i. Greedy-Clustering (GC).

ii. Least-Distance-Clustering (LDC).

iii. Minimal-Cardinality-Variance-Clustering (MCVC).

We used the first set of experiments (Section 5.4.1) to calibrate the performance of the heuristic with respect to the optimal solution. In the second set of experiments (Section 5.4.3), we considered larger networks, with up to 44 relay nodes and 5000 sensor nodes. For such networks, we could not obtain an optimal solution using ILP-NFS. So, we compared our heuristic only with the MTE and the MH routing. We have assumed that

a. the communication energy dissipation is based on the first order radio model, discussed in Section 2.2.

b. the values for the constants are the same as in [46], so that:

i) $\alpha_1 = \alpha_2 = 50nJ/bit$,

ii) $\beta = 100pJ/bit/m^2$ and

iii) the path-loss exponent, $q = 2$.

c. the range of each sensor (relay) node is $40m$ ($200m$), as in [87].

d. the initial energy of each relay node was $5J$, as in [87].

5.4.1 Performance Evaluation for Moderate Sized Networks

For these sets of experiments, we have tested our ILP formulation on a network deployed over an area 160m × 160m, with 12 relay nodes, and a network deployed over an area 160m × 200m, with 15 relay nodes. In this section, we present the results for the network with 12 relay nodes. Results for the network with 15 relay nodes are similar. We varied the number of sensor nodes from 100 to 500, with the locations of the sensor nodes generated randomly for each run. Using a separate placement algorithm for sensor nodes, we ensured that each sensor node can send its data to at least one relay node. The values given in the following figures represent the average values over a five experimental runs with different distributions, for a specified number of sensor nodes, while keeping the layout of the relay nodes the same. Figures 5.1, 5.2, and 5.3, show the average network lifetimes, obtained by using our integrated approach, versus the MH, the MTE, and the ILP-R routing strategies combined with the GC, the LDC, and the MCVC clustering schemes respectively, for the non-flow-splitting model. The error bars shown in these figures are the standard deviations for the corresponding size of the network, measured in five repeated simulations. For each data set, we represented the lifetimes achieved by the different strategies in the following order: the minimum-hop routing (MH), the minimum transmission energy routing (MTE), the optimal routing (ILP-R), the heuristic for combined clustering and routing (NFS-H), and the optimal solution for combined clustering and routing (ILP-NFS).

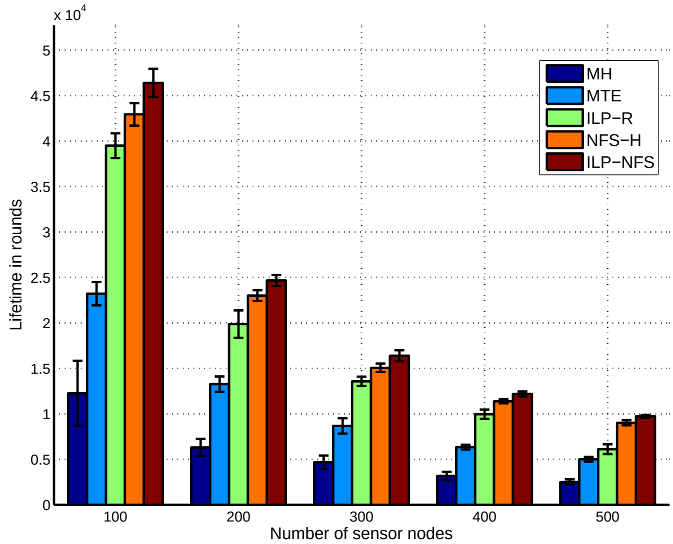

Figure 5.1: Comparison of achieved lifetimes with GC scheme.

The results clearly indicate that an integrated approach performs significantly better than traditional routing schemes, irrespective of the type of clustering heuristic used. The average lifetime using ILP-NFS is 3 (2) times longer, compared to the traditional routing schemes, such as the MH (MTE). Even when compared to the *optimal* routing generated by the ILP-R, the ILP-NFS produced an average improvement of 23%. The results also show that the performance of our heuristic (NFS-H) is quite close to the optimal (within 10% - 15%) in all cases.

Figures 5.1, 5.2 and 5.3 also show that, for a fixed number of relay nodes, if the number of sensor nodes increases, each relay node, in general, handles more traffic and hence the network has reduced lifetime. Although the overall lifetime decreases with the number of sensor nodes (as expected), the ratios of the lifetimes obtained

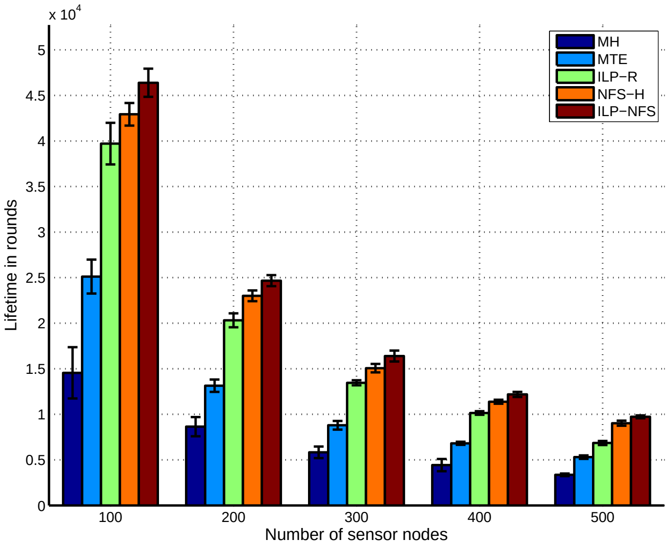

Figure 5.2: Comparison of achieved lifetimes with LDC scheme.

using the different strategies we studied (MH, MTE, ILP-R, NFS-H), compared to the ILP-NFS, did not change significantly as we increased the number of sensor nodes. In Table 5.2 we have shown the changes in the lifetimes, using the different strategies, relative to the ILP-NFS, using the MCVC scheme. Here we have taken the results given in Fig. 5.3, for networks of different sizes. For instance, under the MCVC scheme, as we increased the number of sensor nodes from 100 to 500, routing strategy MH gave a lifetime that varied only slightly (from 29.7% to 32.2%) compared to the lifetime using the ILP-NFS. The results for the other strategies (MTE, ILP-R and NFS-H) under the MCVC scheme also show small variations. Studies with the GC and the LDC schemes gave similar results.

In our simulation experiments for ILP-FS, in addition to the MH and the MTE schemes, we have also considered LPR - a linear program that give the optimal routing under the flow-splitting model, after the clustering decision has been obtained. Figure

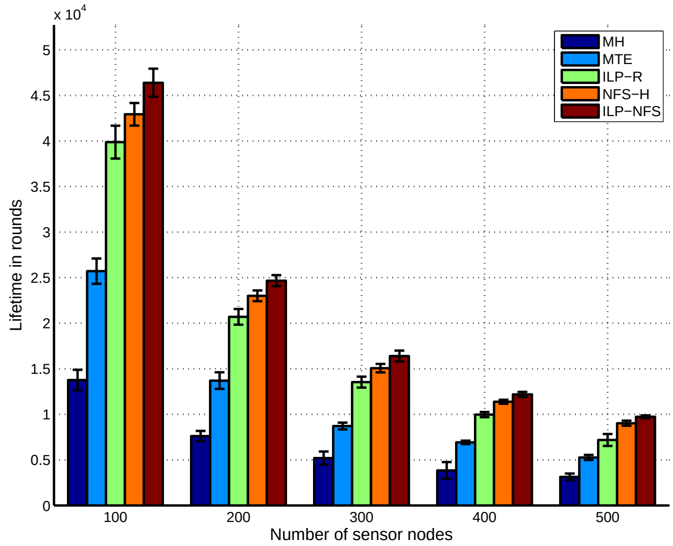

Figure 5.3: Comparison of achieved lifetimes with MCVC scheme.

Table 5.2: Performance of different routing strategies, compared to ILP-NFS

	Number of sensor nodes				
Routing Strategy	100	200	300	400	500
MH	29.7%	30.8%	31.7%	31.5%	32.2%
MTE	55.4%	55.5%	53.1%	56.8%	54.1%
ILP-R	86.0%	83.9%	82.5%	81.8%	73.9%
NFS-H	92.5%	93.3%	91.9%	93.4%	92.8%

5.4 shows the results, using the MCVC clustering scheme, when we varied the number of sensor nodes from 100 - 500 (results for the GC and the LDC were similar). ILP-FS, on an average, achieved improvement over LPR by 4% to 8%. The significance of this result is that ILP-FS gives an upper bound on the achievable network lifetime.

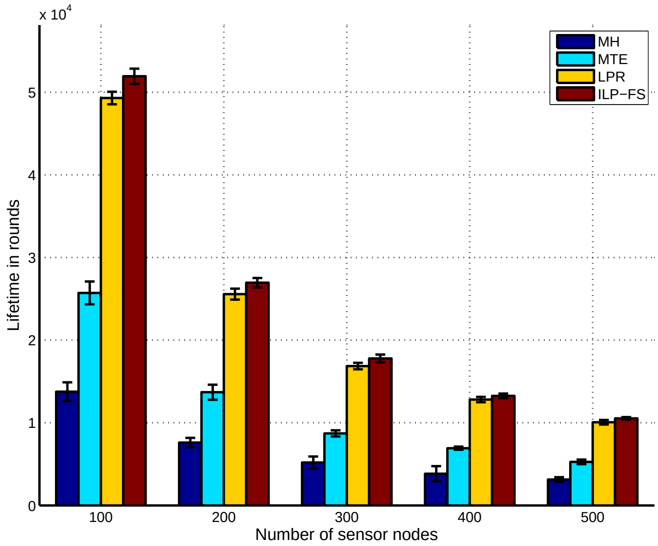

Figure 5.4: Comparison of achieved lifetimes for flow-splitting model.

5.4.2 Comparison of Clustering Heuristics

One of the drawbacks of solving the clustering and routing problems separately is that it is difficult to select the proper clustering scheme. Over a large number of experimental runs, we observed no significant patterns or correlation of the performance of the clustering scheme with the routing scheme, the network area, or the number and the distribution of relay/sensor nodes. This is illustrated in Table 5.3, where we see that, for the MH routing, the LDC (MCVC, GC) generated the best results in 45% (respectively 47%, 8%) of the experimental runs. For the MTE and the ILP-R, the MCVC generated the best solutions for over half of the runs and the rest were almost equally divided between the LDC and the GC. Depending upon the routing strategy used, selecting the wrong clustering scheme may reduce the overall lifetime by over 50%. An integrated approach avoids this problem by combining clustering and routing.

Table 5.3: Effect of clustering scheme on different routing strategies.

	Routing Strategy		
Clustering Scheme	MH	MTE	ILP-R
GC	8%	20%	20%
LDC	45%	24%	28%
MCVC	47%	56%	52%

5.4.3 Performance Evaluation for Large Scale Networks

In the previous sections we compared our heuristic NFS-H, with the optimal solution and have shown that its performance is close to optimal for small networks. For large networks, it was not possible to generate optimal solutions for the non-flow-splitting model, using the ILP-NFS. The optimal routing formulation (ILP-R) in [10] was also unable to generate solutions for larger networks. Therefore, in this section, we will compare the performance of our heuristic with the traditional the MH and the MTE routing schemes and report the lifetime obtained using the ILP-FS[2]. We used the LDC scheme in all the simulation results reported in this section. We have also carried out simulation experiments with the GC and the MCVC schemes, and have obtained similar results.

Figures 5.5, 5.6 and 5.7 show the performance of our heuristic, for large networks with 24, 36 and 44 relay nodes respectively. We varied the number of sensor nodes from 600 (for 24 relay nodes) to almost 2000 (44 relay nodes). We found that the NFS-H *always* outperforms the MH and the MTE schemes. The solutions generated by the NFS-H were also consistently within 15% - 20% of the theoretical upper

[2] As mentioned before, this gives the upper bound of the achievable network lifetime.

bound of the achievable network lifetime, obtained by the ILP-FS. Finally, in order to test whether our heuristic can handle very large networks, we tested our approach on a network with 5000 sensor nodes and 44 relay nodes. Even on such a large network, the heuristic was quite fast and was able to quickly generate the results. This configuration produced an average lifetime improvement of 3.5 times over the MH and 2.7 times over the MTE.

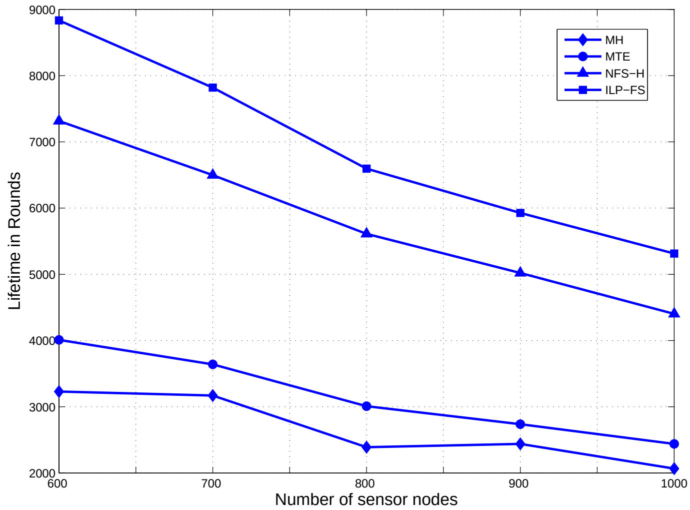

Figure 5.5: Comparison of achieved lifetimes for network with 24 relay nodes.

Figure 5.8 shows how the achieved lifetime varied with the size of the network. For a specific relay node network size, we selected the number of sensor nodes, so that the average cluster size remained approximately the same for all networks. We varied the sensing area 160m × 160m, for a network with 12 relay nodes, to 400m × 280m for a network with 44 relay nodes. Figure 5.8 shows that the combined approach significantly outperforms both the MH and the MTE schemes for large networks. The average improvement of our combined approach was 3 (2) times over the MH (MTE)

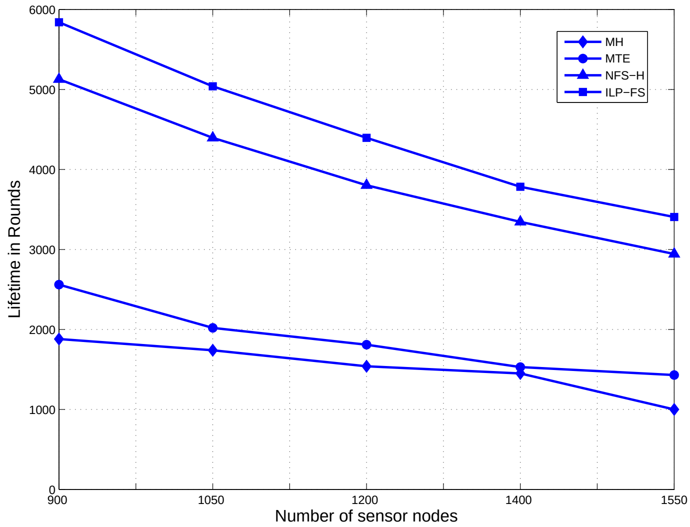

Figure 5.6: Comparison of achieved lifetimes for network with 36 relay nodes.

scheme. As in the case of moderate sized networks, the overall lifetime decreased with increases in the size of the network. This is expected, as the sensing area, as well as the total amount of data to be transmitted, increases with the size of the network. This increase, in turn, affected adversely the maximally loaded node.

5.5 Discussion

In this chapter, we have proposed an integrated approach that jointly optimizes clustering and routing in large scale two-tier sensor networks. We have presented an ILP formulation that maximizes the lifetime of the upper-tier relay node network, as well as a heuristic based on LP-relaxation that can be used for large networks with thousands of nodes. We have calibrated the performance of the heuristic, by comparing with the optimal solutions for smaller networks. We have demonstrated that our combined approach *significantly* increases the network lifetime for non-flow-splitting

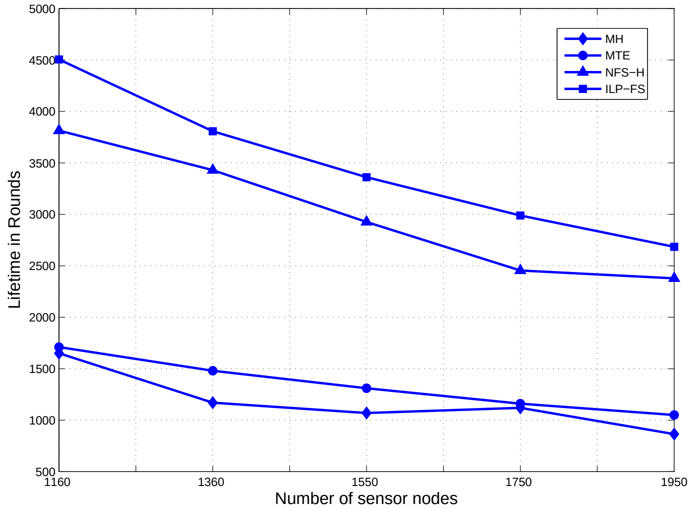

Figure 5.7: Comparison of achieved lifetimes for network with 44 relay nodes.

routing. Our proposed heuristic, based on LP relaxation of the routing variables, clearly outperforms traditional routing schemes such as the minimum-hop routing and the minimum-transmission-energy routing, for large scale networks.

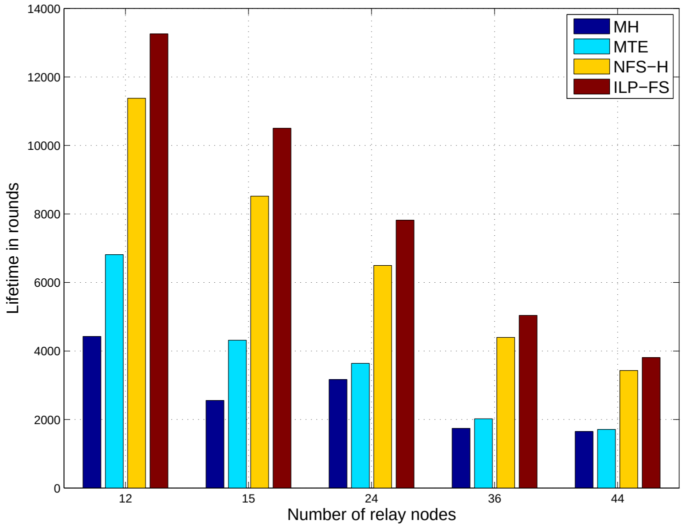

Figure 5.8: Comparison of achieved lifetimes for different networks.

Chapter 6

DISTRIBUTED CLUSTERING IN HIERARCHICAL SENSOR NETWORKS

6.1 Introduction

In Chapter 4, we have presented two centralized approaches using ILP to compute optimal clusterings when the routing scheme is known in advance. In this chapter we have presented a distributed heuristic algorithm, ADC-M, for the same problem. ADC-M uses local information only[1] and is designed to handle the general case of multi-hop communication by the relay node network, and can be easily modified (ADC-S) to accommodate single-hop communication as well, as discussed in Section 6.2.2.

[1]Some authors have characterized this type of algorithms as localized algorithm [88] - a specialized class of distributed algorithms [89].

In the algorithm described below, we have used the same network model and energy model used in Sections 4.2.1 and 2.2. We have computed the lifetime using Equation (2.3), given in Section 2.4. The objective of our algorithm is to form appropriate clusters of sensor nodes, with the relay nodes acting as cluster heads, such that the the network lifetime is maximized, as done in Chapter 4.

6.2 Distributed Algorithm for Clustering

In this section we have presented ADC-M and ADC-S. We have assumed, in the following discussions, that

1) all sensor nodes have a transmission range of r_{max},

2) each relay node has a transmission range of at least $2r_{max}$, and

3) the transmission range of each relay node is sufficient to transmit its data to the next node in the path to the base station.

Our network has n sensor nodes, m relay nodes and one base station. Let $\mathcal{S}$ ($\mathcal{R}$) denote the set of sensor nodes (relay nodes), each of which is identified by a unique label $i, 1 \leq i \leq n$, ($j, n+1 \leq j \leq n+m$), and let the label of the base station be $n+m+1$. We have used $\mathcal{C}^j, j \in \mathcal{R}$, to denote the set of sensor nodes currently belonging to the j-th cluster, with the relay node having label j as the cluster head and $\mathcal{U}^j$ to denote the set of sensor nodes that are covered by relay node j but have not been allocated to any cluster yet. When the algorithm terminates,

i) $\mathcal{S} = \bigcup_{j \in \mathcal{R}} \mathcal{C}^j$ (and hence, $\mathcal{U}^j = \emptyset, \forall j \in \mathcal{R}$), and

ii) $\mathcal{C}^j \cap \mathcal{C}^k = \emptyset$, $\forall j, k \in \mathcal{R}$, $j \neq k$.

We consider relay nodes $j, k \in \mathcal{R}$ to be *neighbors* if the distance between the relay nodes is $2r_{max}$ or less. This ensures that a sensor node can communicate with both relay nodes j and k only if j and k are neighbors.

Henceforth we will call the graph $G = (V, E)$, the *relay node graph*, where V is the set of all relay nodes in the network and there is an edge $(j \to k) \in E$ if relay nodes j and k are neighbors. We will say that a sensor node $s \in \mathcal{S}$ is *essential* to the cluster $\mathcal{C}^j$ of a relay node $j \in \mathcal{R}$, if only j covers s. The clustering decision is taken by each relay node after taking into account only the situations in neighboring relay nodes. Our experiments show that such decisions, based on local information only, still give good results.

The central idea of the algorithm is to start with each cluster $\mathcal{C}^j$ only containing sensor nodes which are essential for relay node j. Each relay node keeps information about its neighborhood and periodically broadcasts needed information (e.g., the maximum energy that each relay is aware of) to its neighbors. Relevant information percolates through the entire network of relay nodes through these periodic broadcasts. The relay nodes gradually add sensor nodes to their respective clusters iteratively, in a way that increases the "worst-case" energy dissipation of the relay nodes (i.e., the value of F_{max}) as little as possible.

The algorithm has three steps — *setup, initialization* and *cluster formation.* For node j, the process of forming cluster $\mathcal{C}^j$ terminates when every sensor node covered by j is allotted to some cluster, so that $\mathcal{U}^j = \emptyset$. During all the three steps, when relay node j is taking decisions about cluster $\mathcal{C}^j$ and broadcasting information about itself, all other relay nodes in the neighborhood of j must be in a quiescent state, passively listening to the message broadcast by j and updating their respective databases. This ensures that two relay nodes never include the same sensor node in their respective clusters. To achieve this, it is necessary to assign a color to each relay node $j \in \mathcal{R}$, using a distributed graph-coloring algorithm [36] on relay node graph G, so that if two relay nodes are neighbors, they are assigned two different colors. Using any distributed graph coloring algorithm [36], let a set $\mathcal{P}$ of colors, be used for coloring G. We have not included the details of the coloring algorithm and assume that each relay node $j \in \mathcal{R}$ is aware of its color $\gamma_j \in \mathcal{P}$ when the algorithm starts.

6.2.1 The Algorithm for Distributed Clustering in Multi-hop Networks (ADC-M)

As in ILP-M (Section 4.2.3), we have assumed that the network uses multi-hop paths for routing data to the base station and that the routing scheme is known. In a multi-hop network, relay node j, in general, communicates using a multi-hop path $j \rightarrow j_1 \rightarrow j_2 \rightarrow \ldots \rightarrow j_h \rightarrow m+n+1$, using some intermediate relay nodes $j_1, j_2, \ldots, j_h$ ($h < m$) to the base station $n+m+1$. Let E_j denote the total energy currently required by relay node j and ξ_j the energy required to send the data corresponding to a single sensor node from j to the next relay node in the multi-hop path from j to the base station. If a sensor node is now added to cluster $\mathcal{C}^j$, the energy of the relay nodes $(j, j_1, j_2, \ldots, j_h)$ in the above multi-hop path become $(E_j + \xi_j, E_{j_1} + \xi_{j_1}, E_{j_2} + \xi_{j_2}, \ldots, E_{j_h} + \xi_{j_h})$ respectively. We will use Q_j to denote the maximum of

$(E_j + \xi_j, E_{j_1} + \xi_{j_1}, E_{j_2} + \xi_{j_2}, \ldots, E_{j_h} + \xi_{j_h})$. In ADC-M (Heuristic 5, given below), if a sensor node s is currently not allocated to any cluster and s is covered by two relay nodes j and k, the algorithm includes s in cluster $\mathcal{C}^j$ only when $Q_j \leq Q_k$.

Relay node j, in general, is also an intermediate node in a number (≥ 0) of paths from other relay nodes to the base station. If ℓ relay nodes, say, $g_1, g_2, \ldots, g_\ell$, use j as the next node in their respective paths to the base station, then we will denote nodes $g_1, g_2, \ldots, g_\ell$ as the *predecessors* of j. Based on the labels of the relay nodes $g_1, g_2, \ldots, g_\ell$, we order the predecessor nodes of each node, so that we associate a predecessor number $\lambda_k, 1 \leq \lambda_k \leq \ell$, for each $g_k, 1 \leq k \leq \ell$. We use:

- $\mathcal{M}$ to denote the maximum possible number of relay nodes which can be predecessors of any relay node.
- n_j^0 to denote the number of sensor nodes which are in cluster $\mathcal{C}^j$.
- n_j^i to denote the number of sensor nodes whose data is routed from the i-th predecessor of $j, 1 \leq i \leq \mathcal{M}$.
- n_j to denote the total number of sensor nodes processed using relay node j.
- $\mathcal{L}$ to denote the maximum possible number of relay nodes in the path of any relay node to the base station.
- M_j to denote the maximum energy required among all relay nodes, as currently known by node j.

We note that we can compute n_j using the formula:

$$n_j \leftarrow \sum_{p=0}^{\mathcal{M}} n_j^p$$

Before the algorithm ADC-M starts, the sensor nodes operate only once, when each sensor node broadcasts a "hello" message notifying its presence. The ADC-M given below describes the operations of relay node j. All other relay nodes carry out the same steps in a synchronized manner. In the setup step (lines 1-8 of Heuristic 5), our intent is to

i) determine which sensor nodes are essential to j,

ii) form the initial cluster $\mathcal{C}^j$, and

iii) determine the values of E_j and n_j^0, based on the essential nodes in $\mathcal{C}^j$.

In lines 2- 8, each relay node exchanges the sensor node coverage information with its neighbors. Each iteration (lines 3-7) give some relay node in the neighborhood of j a chance to be active exactly once. After all the iterations in lines 2- 8 are over, relay node j becomes aware of the allocations of sensor nodes in its neighborhood. In line 9, the set $\mathcal{U}^j$ is the set of sensor nodes which are covered by j but are not essential. We compute the values of M_j, n_j and Q_j, based on current information, namely $M_j = E_j$, $n_j = n_j^0$ and $Q_j = E_j + \xi_j$.

The initialization step (lines 11-17) must be repeated $2 * \mathcal{L}$ times, so that the data broadcast by the relay node furthest from the base station has a chance to propagate all the way to the base station and then back again to that relay node.

Heuristic 5 *Algorithm for Distributed Clustering - Multi-Hop (ADC-M)*

Node j determines the sensor nodes it covers.
for $\forall p \in \mathcal{P}$ **do**
  if $\gamma_j = p$ **then**
    j broadcasts the value of ξ_j and the list of sensors it can cover.
  else
    j receives, from its neighbor k, where $\gamma_k = p$, the list of sensors that k can cover.
  end if
end for
Compute the initial value of M_j, Q_j and n_j.
for $\forall \lambda \in \{1..2 \times \mathcal{L}\}$ **do**
  for $\forall p \in \mathcal{P}$ **do**
    if $\gamma_j = p$ **then**
      j computes and then broadcasts to its neighbors the values of M_j, Q_j, $\mathcal{C}^j$ and n_j.
    else
      j receives and processes, the values of M_k, Q_k, $\mathcal{C}^k$ and n_k from neighbor k, where $\gamma_k = p$.
    end if
  end for
end for
while *all sensor nodes are not allocated to clusters* **do**
  for $\forall \lambda \in \{0..2 \times \mathcal{L}\}$ **do**
    for $\forall p \in \mathcal{P}$ **do**
      if $\gamma_j = p$ **then**
        if $\lambda = 0$ and $\mathcal{U}^j \neq \emptyset$ **then**
          j temporarily assigns, up to w sensor nodes from $\mathcal{U}^j$, to the clusters for itself and all its neighbors.
          j absorbs into cluster $\mathcal{C}^j$ the sensor nodes it has allocated to itself (if any).
          $n_j^0 \leftarrow |\mathcal{C}^j|$.
        end if
        j computes and then broadcasts to its neighbors the values of $\mathcal{C}^j$, M_j, Q_j and n_j.
      else
        j receives and processes, the values of $\mathcal{C}^k$, M_k, Q_k and n_k from neighbor k, where $\gamma_k = p$.
      end if
    end for
  end for
end while

When relay node j becomes active (lines 13), it determines

- the new value of n_j,
- the new value of E_j, the energy to send data from n_j sensor nodes to the next relay node, using the formula $E_j \leftarrow \xi_j \cdot n_j$,
- whether Q_j (M_j) needs to be changed since E_j may have changed.

When relay node j is not active (line 15), it receives data $(\mathcal{C}^k, M_k, Q_k, n_k)$, if relay node k in its neighborhood is active. We use this data to update

- the set $\mathcal{U}^j$,
- the value of M_j, if $M_k > M_j$,
- the value of Q_j, if k is the next node in the multi-hop path from j to the base station and $Q_k > Q_j$,
- the value of n_j^r, if k is the r-th predecessor of j.

The cluster formation step (lines 19 - 34) allots all sensor nodes to clusters. Lines 19 - 34 are repeated until all relay nodes report that they are not aware of any unallocated sensor nodes. Details of the distributed process of determining that there is no unallocated sensor node have been omitted, since it is tedious but straightforward. Inside the while-loop, the lines 21 - 32 are repeated for all values of $\lambda, 0 \leq \lambda \leq 2 \times \mathcal{L}$. Every time $\lambda = 0$ and $\mathcal{U}^j \neq \emptyset$, relay node j allots a number (ranging from 1 to some small, pre-determined number w) of sensor nodes from $\mathcal{U}^j$ to its own cluster $\mathcal{C}^j$ and to clusters of neighboring relay nodes. In line 24, j examines all sensor nodes in $\mathcal{U}^j$ and temporarily allocates, w (or $|\mathcal{U}^j|$ sensors, if $|\mathcal{U}^j| < w$) unassigned sensor nodes in its neighborhood to the clusters for itself and all its neighbors. In this temporary allocation, if $Q_j \leq M_j$, j starts by allocating one sensor node to itself, without looking at the value of Q_k for any neighbor k of j. The remaining allocations (or all the allocations, if $Q_j > M_j$), are based on the values of Q_j, M_j and Q_k, for all neighbors k of node j. A sensor node is temporarily allocated to cluster $\mathcal{C}^k$, where k is a neighbor (or to $\mathcal{C}^j$) in this process if the value of Q_k (or Q_j) is the least of all relay nodes that covers this sensor node. In these temporary allocations, j will increase the value of M_j, if the energy $Q_k > M_j$ (or $Q_j > M_j$). In line 25, relay node j permanently includes, in $\mathcal{C}^j$, the sensor nodes it has allotted to itself. When $\lambda = 1, 2, \ldots 2 \times \mathcal{L}$, the result of including additional sensor nodes to clusters, carried out when $\lambda = 0$, in terms of energy needed for different relay nodes in the multi-hop path from each relay node to the base station is determined. In other words, the changes in the values of M_j, E_j and Q_j for relay node j, for all $j, n+1 \leq j \leq m+n$, corresponding to these changes in the sizes of the clusters are determined iteratively as λ varies from 1 to $2 \times \mathcal{L}$. When all nodes in $\mathcal{U}^j$ have been allotted to clusters, j no longer carries out lines 24 - 26 since $\mathcal{U}^j = \emptyset$.

Theorem 2. *ADC-M converges in at most n iterations of the outermost loop.*

Proof. First, we note that during each iteration of the outermost loop (lines 20-33), there is at least 1 unassigned sensor node that is assigned to a cluster. Let j be one of the nodes such that $\mathcal{U}^j \neq \emptyset$. For a given iteration of the outermost loop, when $\lambda = 0$ and $\gamma_j = p$, in line 24, node j becomes active and ensures that, in its neighborhood, at least 1 and at most w sensor nodes, from $\mathcal{U}^j$, will be assigned to neighboring clusters and the value of M_j is adjusted so that these sensor nodes may be assigned to the neighbors. The new value of M_j will be broadcast in line 28. There are two cases to consider:

Case I: node j itself absorbs at least one of sensor nodes in $\mathcal{U}^j$ during line 25 in the current iteration.

Case II: node j does not allocate any sensor nodes in $\mathcal{U}^j$ to itself in the current iteration.

For case I, at least 1 unassigned sensor node in the network has been allocated to cluster $\mathcal{C}^j$. For case II, in the remaining part of this iteration of the outermost loop and until j becomes active again in the next iteration of the outermost loop, each of the neighbors of j will become active exactly once. Let k be a neighbor of j which was temporarily assigned at least one sensor node by j in the current iteration. Clearly, $\mathcal{U}^k \neq \emptyset$ when j did this temporary assignment. Further, when j assigned a sensor to k, the value of Q_k is the least of all relay nodes that can absorb the sensor node. If $Q_k > M_j$ before the assignment, j will set $M_j = Q_k$ and will broadcast this new value of M_j in line 28. When k becomes active (i.e., $\lambda = 0$ and the value of p in the inner loop from lines 21 to 32 matches γ_k), for the first time following j, the value of M_k is such that it is at least Q_k so that

1) either k will absorb at least one sensor node belonging to $\mathcal{U}^k$,

2) or $\mathcal{U}^k$ has become $\emptyset$ in the period since j was active.

In both cases, the number of sensor nodes in $\mathcal{U}^k$ has been reduced by at least 1. Thus, in all cases, every time there is an iteration of the outermost loop, the number of unassigned sensor nodes in the network will be reduced by at least one. Since the number of sensor nodes in the network is n, the operations in node j must terminate in at most n iterations. □

6.2.2 The Algorithm for Distributed Clustering in Single-hop Networks (ADC-S)

Algorithm ADC-M assumes that the relay nodes form a network of their own and use multi-hop paths to route data to the base station. In a single-hop or direct transmission model, each relay node collects data only from the sensor nodes belonging to its own cluster and sends the data directly to the base station. Our ADC-M algorithm is also able to handle such transmission model by appropriately setting the values of requisite parameters. To accommodate the single-hop transmission model in ADC-M, for each relay node $j \in \mathcal{R}$, we set the number of predecessors of j to zero (and hence $\mathcal{L} = 0$). The value of $\xi_j, j \in \mathcal{R}$, is the energy required by j to send the data gathered from a single sensor node, is computed such that the next hop of each j is the base station. The rest of the algorithm remains the same.

We will use ADC-S to denote this simplified version of ADC-M that incorporates the single-hop data transmission model.

6.3 Simulation Results

We have investigated ADC-M and ADC-S using a custom simulator we have developed. We have considered two different network setups, one with an area of 160m × 160m, having 12 relay nodes, and the other with an area of 240m × 240m area, having 24 relay nodes. For each value of the number of relay nodes in the network, we have placed the relay nodes, such that the entire area of the given network remained covered by the relay nodes, following the scheme proposed in [10]. For both the 12 relay node and the 24 relay node networks, we have randomly generated the locations of sensor nodes in the network. We have varied the number of sensor nodes from 75 to 1000 sensor nodes. We have computed the energy dissipation and the lifetime of the network, following the definitions given in Section 3.2, with the values for the constants[2] $\alpha_1 = \alpha_2 = 50nJ/bit$, $\beta = 100pJ/bit/m^2$, and $q = 2$. We have assumed that the transmission range of each sensor node is $r_{max} = 40m$, and the initial energy of each relay node is $5J$ [87]. For each relay/sensor node distribution, we have compared the performances of ADC-S (discussed in Section 6.2.2) and ADC-M (discussed in Section 6.2.1) with the following clustering approaches described in Chapter 4:

i. Greedy-Clustering (GC),

ii. Least-Distance-Clustering (LDC),

iii. ILP Single-hop (ILP-S),

iv. ILP Multi-hop (ILP-M).

[2]taken from [46].

In order to evaluate the overhead cost associated with ADC-S and ADC-M, we have applied a penalty, equivalent to the energy required to transmit a 2 kb packet over a distance of $2r_{max}$ (i.e., 80 m), to each relay node for each broadcast. For a given network size (in terms of the number of relay nodes) and for a given number of sensor nodes, we have generated 100 different sets of locations of sensor nodes, such that the sensor nodes are randomly distributed within the network. With each distribution, we have computed the lifetime, using the clustering approaches mentioned above and have compared them against the lifetime using the ADC-S or the ADC-M.

6.3.1 Performance Evaluation - Single-hop Networks

Fig. 6.1 (Fig. 6.2) shows the average lifetimes, in terms of rounds, achieved by the above mentioned approaches for the 12 (24) relay node network. For each network size, we have shown the lifetimes, from left to right, in the order GC, LDC, ADC-S and ILP-S. As shown in Fig. 6.1 and Fig. 6.2, ADC-S significantly outperforms GC and LDC, with improvements between 30%-40% and produces results very close to the optimal solution obtained using ILP-S, discussed in Section 4.2.2. We note that, on an average, GC and LDC never achieve more that 70% of the optimal lifetime, while ADC-S typically achieves 95% of the optimal lifetime.

6.3.2 Performance Evaluation - Multi-hop Networks

For clustering in a network with a multi-hop routing scheme, we conducted our experiments using the routing strategies MTE and MH described in Chapter 4.

Fig. 6.3 shows the average lifetimes obtained using existing heuristics (GC

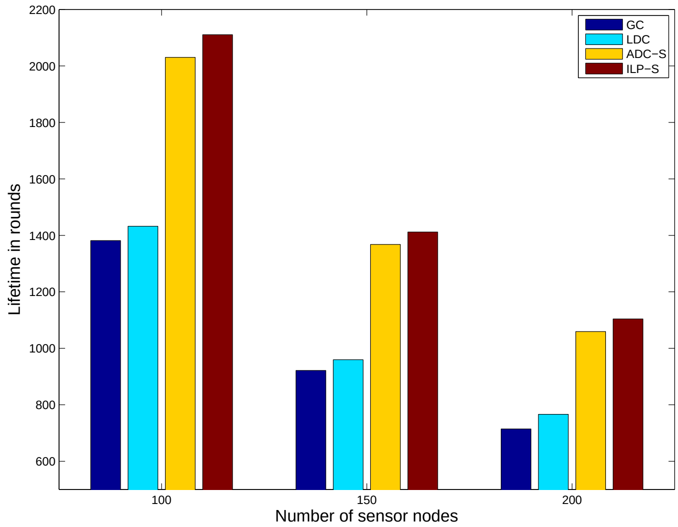

Figure 6.1: Network lifetimes using single-hop routing for a 12 node network.

and LDC), compared to our approach (ADC-M) and the optimal solution (ILP-M), for MTE. In Fig. 6.3, we have shown the lifetimes, from left to right, in the order GC, LDC, ADC-M and ILP-M. Fig. 6.4 shows the same comparison when MH routing is used.

Similar to ADC-S, ADC-M consistently outperforms existing heuristics, although the differences in overall lifetime are not as high. We attribute this to

1. the cost associated with the additional broadcasts required by each relay nodes to update the energy information of the entire path, and

2. the fact that the relay nodes lack global knowledge about the network.

We note, the lifetimes obtained using ADC-M are always within 15% of the optimal lifetime obtained using ILP-M, when MTE and MH routings are used.

The value of w, the number of sensor nodes picked in each iteration of ADC-M,

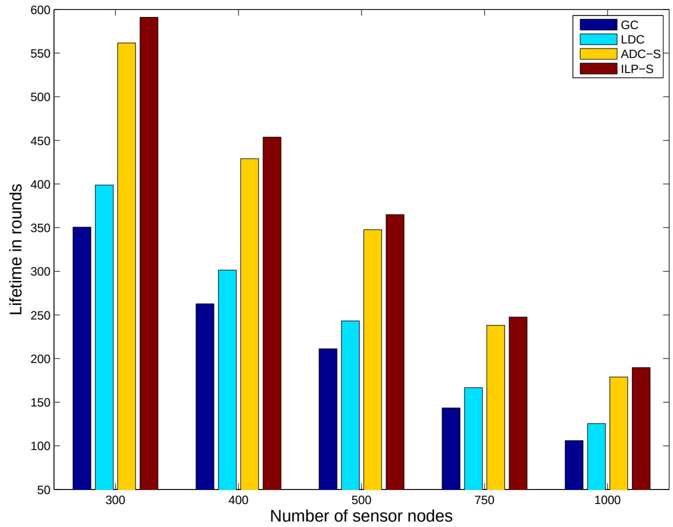

Figure 6.2: Network lifetimes using single-hop routing for a 24 node network.

determines how quickly the clustering algorithm terminates. A low value of w is likely to give better clusters (with a lower value of F_{max}), since the clustering is based on more accurate information about the critical energy Q_j in each relay node. However, the clustering algorithm would need more iterations (i.e., involve more penalty) so that the residual energy of the relay nodes, when the clustering is completed, would be less if w is smaller, and this would adversely affect the operating lifetime of the network. In other words, there is a trade off - a lower value of w means that the value of F_{max} would be lower but the value of $E_{initial}$ would be lower by the amount of penalty as well. Fig. 6.5 shows how the operating lifetime, $(E_{initial} - penalty)/F_{max}$, of the network with 24 relay nodes network, on 4 randomly generated datasets with 750 sensor nodes each, initially increases with w, and then decreases. A choice of $w = 30$ should be a good value for this particular configuration of the network.

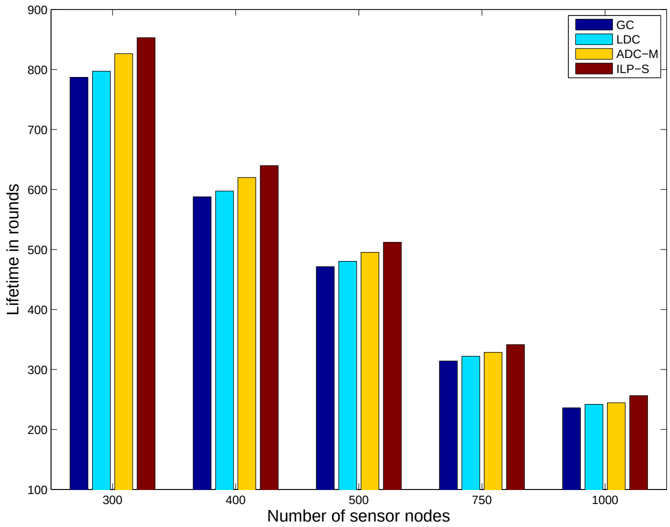

Figure 6.3: Network lifetimes for a 24 node network using MTE routing.

6.4 Discussion

In this chapter, we have presented a distributed algorithm for load balanced clustering to extend the lifetime of a hierarchical two-tiered sensor networks. An interesting and novel aspect of this research was to develop a "routing-aware" clustering heuristic, that can take into consideration the effect of different routing strategies and form the clusters accordingly. The results presented in this chapter demonstrate that such an approach can lead to significant improvements over existing clustering algorithms, which do not consider the routing schemes used for data communication.

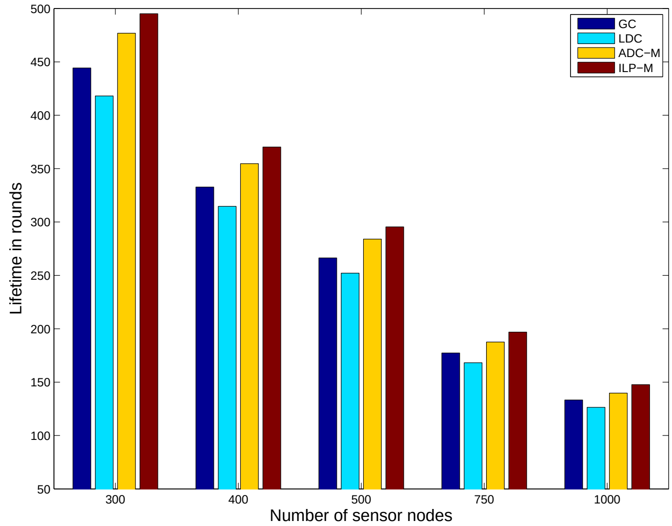

Figure 6.4: Network lifetimes for a 24 node network using MH routing.

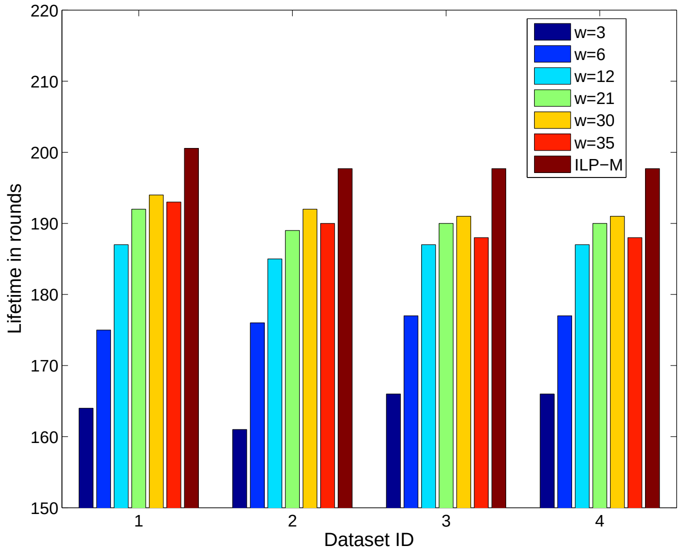

Figure 6.5: Effect of w for a 24 node network using MH routing.

Chapter 7

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

In this dissertation, we have considered a hierarchical two-tiered sensor network architecture that uses relay nodes, provisioned with higher initial energy, as cluster heads, and have proposed algorithms to design the upper-tier network. When designing such networks it is necessary to consider the placement of the relay nodes, the allocation of sensor nodes to clusters, and the routing scheme used by the network of relay nodes. These problems are interrelated and, for an optimal solution, should be solved simultaneously. However, each of the problems is known to be a computationally difficult optimization problem. Hence, researchers have treated the placement problem, the clustering problem and the routing problem as stand-alone problems. We have proposed novel solutions for each of these problems and have shown that, for small networks, the clustering problem and the routing problem can be solved simultaneously.

In summary, in this dissertation, we have presented:

i. Placement strategies for the relay nodes that can provide any desired level of fault tolerance in both the upper-tier and the lower-tier of the network, using a minimum number of relay nodes.

ii. Centralized strategies for optimal clustering of sensor nodes under any given routing scheme.

iii. An optimal strategy, as well as, a heuristic for integrated clustering of sensor nodes and routing through the upper-tier network of relay nodes.

iv. A distributed strategy for clustering of sensor nodes, using only the local information.

Our ILP-based placement strategy is able to handle the general case of fault tolerance, and can optimally select positions of the relay nodes from a supplied set of possible locations. In our formulation, both the lower and the upper tiers can be provided with the desired level of fault tolerance, which can be different in the different tiers.

We have proposed ILP formulations that can maximize the lifetime of the relay node network by distributing the sensor nodes in the clusters of the relay nodes in an energy-efficient way, under a given routing strategies. ILP-M is a generalized formulation that can be used with any specified multi-hop routing strategy. We have also proposed a distributed approach for the same clustering problem, where the relay nodes take decisions based on local information only.

Our integrated clustering and routing approach jointly optimizes both problems. Our heuristic, based on a LP relaxation, can quickly generates solutions for large networks, even with thousands of sensor nodes. Simulation results demonstrate that our combined ILP based approach significantly increases the lifetime of a network using the non-flow-splitting model. Our heuristic clearly outperforms traditional routing schemes, such as the minimum-hop routing and the minimum-transmission-energy routing, for large networks.

7.2 Future Work

In this dissertation, we have proposed integrated clustering and routing strategies in Chapter 5. The simulation results indicate that it is worthwhile to carry out routing and clustering together. However, our approach is centralized, and it will be interesting to develop distributed algorithms for the joint problem of clustering and routing, and compare the results with the optimal, ILP based approach proposed in chapter 5.

As the next step in the evolution of algorithms for two-tiered networks, we need an algorithm that can solve the placement problem, the clustering problem and the routing problem simultaneously. It is possible that, if these problems are considered together, we may get substantial performance improvements.

Recently, it has been shown that the deployment of a mobile data collector

(MDC), which visits each relay node and collects data, can improve the performance of the network in a number of ways. Each relay node buffers the data it receives from the sensor nodes in its cluster, until it is visited by the MDC. In this context, it would be interesting to study the computation of the trajectory of the MDC, the impact of the length of the trajectory on the Quality of Service (QoS) of the network, and compute the requisite buffer sizes of the relay nodes.

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