Energy Efficiency in Wireless Sensor Networks

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Thesis Abstract

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Wireless Sensor Networks are an emerging area of Communication technology. These networks are made up of tiny wireless sensors that collect and transmit data toward a sink node(s). Energy efficiency in sensor networks is one of the most important considerations in network design. This is because of the low energy resources that can be supplied with these sensor nodes.

In this work, we describe methods to increase the lifetime of sensor networks using a hybrid routing scheme. Our routing scheme uses a probabilistic method of routing to transmit data from the sensor nodes to a sink. This scheme incorporates link usage probabilities and energy metrics to prevent failure of nodes due to their excessive usage. In addition, it also incorporates angular routing which forwards packets only to neighboring sensor nodes in assigned conical regions to prevent unnecessarily lengthy routes. Our scheme bounds routing delays in a predetermined manner to ensure that time critical data is not rendered obsolete.

There are regions of sensor networks that are more vulnerable to outages, called hotspots. We also propose a differential method of deployment of sensor nodes to prevent

network partitions around hotspots. This scheme ensures that there are no local outages that might create a network partition thereby isolating pockets of nodes from transmitting their data seamlessly to a central processor.

In summary, we demonstrate improved performance in comparison with other schemes. We also show that our scheme is more successful in delaying network partitions and in enhancing the lifetime of the network.

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Table of Contents

List of Figures xi

1 Introduction 1
- 1.1 Sensor Networks . . . 4
- 1.2 Applications of Sensor Networks . . . 9
  - 1.2.1 Military Applications . . . 9
  - 1.2.2 Environmental Applications . . . 10
  - 1.2.3 Domestic Applications . . . 10
  - 1.2.4 Other Commercial Applications . . . 11

2 Challenges associated with Sensor Networks 13
- 2.1 Scalability . . . 13
- 2.2 Deployment . . . 14
- 2.3 Environmental Conditions . . . 14
- 2.4 Energy Resources . . . 15
- 2.5 Topology and Connectivity . . . 15
  - 2.5.1 Network Dynamics . . . 16

3 Sensor Network Routing 17
- 3.1 Related Work . . . 17
  - 3.1.1 Flooding . . . 18
  - 3.1.2 Data Centric Routing . . . 18
  - 3.1.3 Hierarchical Routing . . . 20
  - 3.1.4 Energy Aware Routing . . . 21
- 3.2 Organization of the Thesis . . . 22

4 Sensor Network Model 23
- 4.1 Connectivity . . . 23
- 4.2 Problem Motivation . . . 25
- 4.3 Assumptions . . . 26
- 4.4 Routing Framework and Analysis . . . 27
  - 4.4.1 Probabilistic Routing . . . 27
  - 4.4.2 Angular Routing . . . 29

5 Simulation and Results 33
- 5.1 Simulation study . . . 33
- 5.2 Results . . . 35
- 5.3 Differential Sensor Node Deployment . . . 40

6 Conclusion 47

7 Proposed Future Work 49

Bibliography 51

List of Figures

1.1 A sensor node in comparison with a penny 3

1.2 Some popular commercially available commercial sensor nodes 3

1.3 A Crossbow sensor mote 4

1.4 Schematic Representation of a Sensor Field 6

1.5 Representation of a sensor network interacting with a real world network . 6

4.1 Variation of connectivity with density of the network 24

4.2 Conical sector routing. 30

4.3 Angular routing with sector angle θ. 31

5.1 Visualization of key network parameters 34

5.2 Sample topology used in the simulation 36

5.3 Variation of Delay with cone angle. 38

5.4 Variation of hopcount with and without angular routing. 38

5.5 Energy profile of the grid 39

5.6 Averaged energy profile of the grid for routing model proposed by Shah and Rabaey [45]. 41

5.7 Averaged energy profile of the grid of sensor nodes. 41

5.8 Effect of spatial node distribution on node failures 43

5.9 Histogram of traffic distribution on the nodes 43

5.10 Energy Profile of the nodes using gradient deployment 44

5.11 A snapshot of average energy over time 45

Chapter 1

Introduction

The networking revolution has grown from an ARPA project connecting isolated computers on different university campuses in the early 70s to the world wide web today. Along with the rapid advances in networking of computers, Moore's law has held true all the while helping the proliferation of faster and smaller chips in many electronic and networked devices. Wireless networking has been a revolution in the network world since the early 90s and has exploited advances in several areas such as communications, VLSI (Very Large Scale Integrated circuits), networking and software.

Mobile ad hoc networks(MANETs) are a class of wireless networks in which the network components are able to communicate with each without pre configured infrastructure. These components can form separate groups, auto-configure themselves and communicate on-the-fly with other devices. Some network interfaces may be cellular, some may be connected to the wired network and others through a wireless medium.

MANETs have come to be known as multi-hop networks. This is because the network components (referred to as nodes) not only function as source and destination, but also help in forwarding packets destined to other nodes. Hence they participate in relaying the information to the destination across multiple hops. Hence, even when the source and destination are out of each others' range, they can communicate with each other through the participation of other intermediate nodes.

Coupled with sensor technology on these chips and their shrinking sizes, it is now possible to design chips capable of sensing and computing information on these tiny chipsets.

Figure 1.1 shows how small the sizes of commercial sensors are shrinking with the advent of technology. Such tiny low power devices are possible only due to the VLSI chip design technologies. Figure 1.2 shows a variety of sensor nodes as developed by other academic universities and research labs for specific purposes.

For research and developmental purpose most researchers use sensor motes. A mote is a term used to describe a wireless sensor device which is a basic component in a wireless sensor network. Each such mote consists of a cpu, radio interface and sensor development board. It can form an ad hoc network with neighboring nodes. Because of the size of these nodes, they are also referred to as smart dust. One such developmental sensor mote is shown in Figure 1.3. Some of the prominent manufacturers of sensor motes are Crossbow Technology, Mica Mote, Sensi Net, etc.

The next revolution in the wireless networking world is sensor networks. Combining sensor devices with networking, it is now possible to network a number of these low cost sensor chipsets into a full fledged network. Capabilities of such networks include physical sensing of information, some local computing and transmission of the same to a central machine which is able to process and analyze such information. All this is possible in devices that are just a few centimeters in dimensions.

Advances in this direction have been made possible because of a huge number of researchers working in this field. There has been tremendous developments in the areas of low power chip design, improved protocols for networking sensors, etc. However, sensor networks are inherently different in a number of ways from traditional networks or even ad hoc networks. Their data transmission rate, communication range and battery life are some of the parameters that are considerably lower in comparison to traditional networks.

Figure 1.1: A sensor node in comparison with a penny

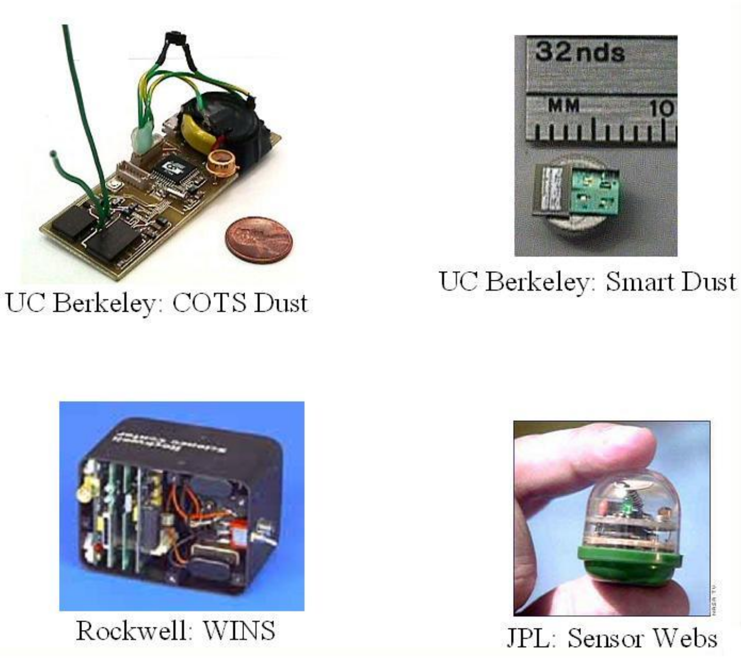

Figure 1.2: Some popular commercially available commercial sensor nodes

Figure 1.3: A Crossbow sensor mote

1.1 Sensor Networks

Deployment of sensor networks presents a wide range of advantages over traditional networks. The obvious advantage of size and low cost apart, they can easily be deployed in a wide variety of environments. They also provide many benefits over other existing schemes. Sensor nodes can be scattered in a given are and can sense the phenomenon and transmit wirelessly. Another advantage is that with large-scale deployment, they can be customized for various applications through hardware, software or a combination of both.

To effectively use the sensed data, the sensor nodes transmit the sensed information to one or more central processors, commonly referred to as sinks. For this, the sensors have to act collaboratively and co-operatively to transmit information [13]. The sinks collect such information from several sensors deployed in the field and collate the information, generate results and analyze to aid further monitoring of the phenomena or to take action. This whole process can be either centralized or distributed based on the network architecture and the underlying protocol.

Sensor networks are quite different from ad hoc networks. Though they are both autonomous networks and require no pre-configuration, they are set apart by certain features that make it hard to use the same techniques used for ad hoc networks. The number of nodes in a sensor network may be several orders of magnitude more than that in an ad hoc network. This makes non scalable protocols used for ad hoc networks unsuitable for sensor networks. Energy resource is one other feature that distinguishes these two networks. Sensors usually have a limited energy supply that are non rechargeable. However, ad hoc networks have much better batteries that can periodically be replenished. Sensor networks are more data centric, i.e., the focus is on nodes that have data satisfying certain conditions. Ad hoc networks are address centric in the sense that identifying individual nodes is important in delivering data.

A simple schematic diagram of a sensor network is shown in Figure 1.4.

Sensor networks can be connected to mainstream networks through the sink by making it act as a gateway. This enables monitoring of even individual sensors from remote locations. A representative diagram is shown in Figure 1.5.

Typically, wireless sensor nodes are deployed in thousands or hundreds of thousands. They can be deployed right inside or very close to the physical phenomenon that they need to sense. A larger number of sensor nodes usually provides greater accuracy, robustness, longer lifetime and speed of communication.

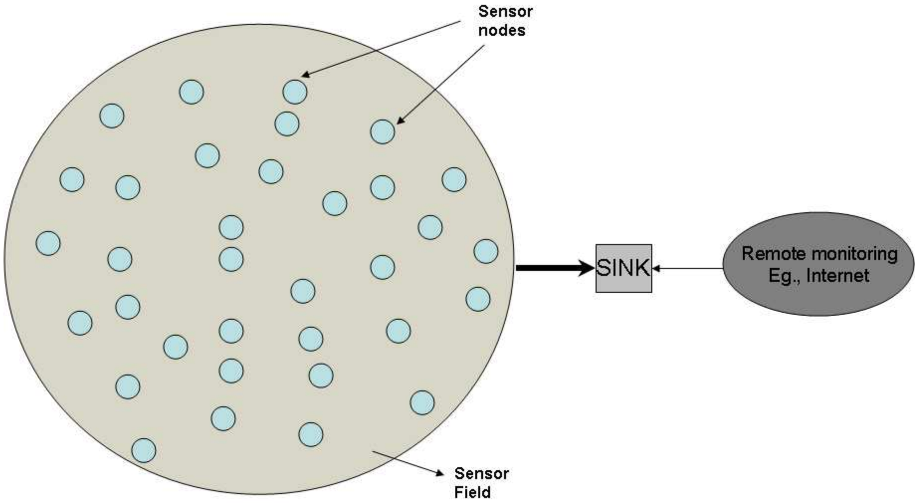

Figure 1.4: Schematic Representation of a Sensor Field

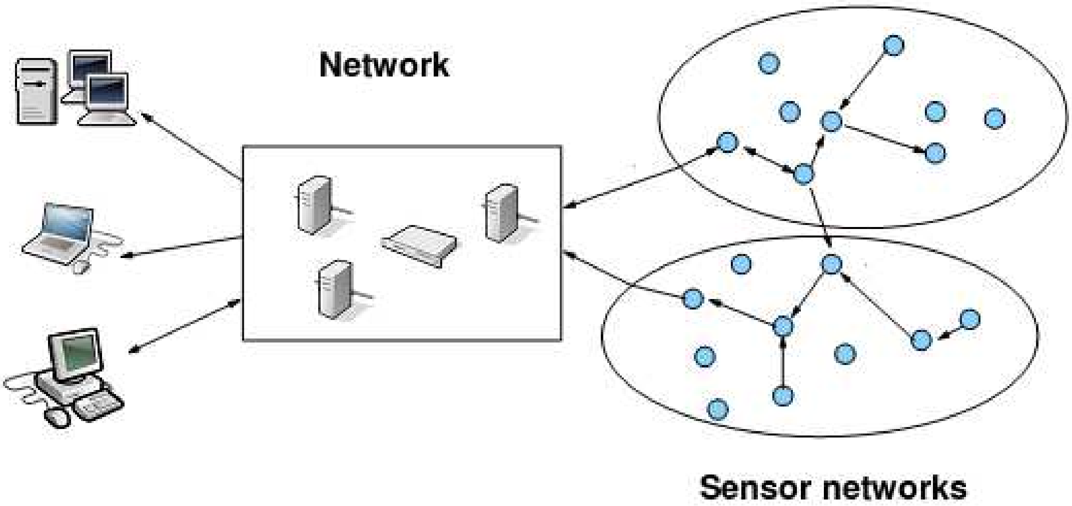

Figure 1.5: Representation of a sensor network interacting with a real world network

As much as they come with all the advantages, sensor networks also pose a plethora of problems. Sensor networks can usually be scattered randomly. Hence there is no need to pre-engineer their positioning scheme. However, they now have the problem of discovering their neighbors and configuring themselves to communicate with them. Their self-configuring capabilities must be extremely effective. Also, because of their large numbers, the protocols used in sensor networks must be highly scalable.

Irrespective of whether there is only one sink or several along the network periphery, the nodes closer to the sink expend comparatively more energy in relaying the information of other nodes to the sink rather than transmitting their own sensed information. This causes such nodes to fail more often due to energy depletion and might cause network discontinuity near the sink. This leads to network partitions and can create separate networks incapable of communicating with each other. In such a scenario, it may be infeasible to replace the energy sources of the sensor nodes or even replace them individually. For example, a sensor network deployed in the jungle for habitat monitoring [34] or perhaps monitoring an active volcano [52] barely permits constant energy replenishment.

Hence, energy conservation plays a prominent role in sensor network management. One energy saving tactic is to prevent the sensor nodes from transmitting information continuously. It may transmit sporadically only after being triggered by a particular threshold of the sensed phenomena or periodically based on a timer. This is not only to prevent rapid depletion of energy but also to conserve the bandwidth of the network by transmitting unnecessary duplicate packets. However, this might not always work since powering on a sleeping node repeatedly and frequently may consume a rather large amount of energy.

Sensor networks also face a wide variety of other problems that are different from wired, cellular, WLAN or ad hoc networks. This leads to new challenges in the network layer due to problems such as extremely limited battery life, constantly changing topology of the network, sheer size of the network, addressing problems etc. Moreover, there might be unpredictable wireless conditions leading to higher packet error rates (PER) [23]. Also, critical relaying nodes might fail causing network partitions. Movement of nodes might be too frequent or the remaining nodes might not be able to reconfigure themselves effectively to transmit information.

One of the primary problems of sensor networks [26], as we discussed earlier, is limited energy resource. There are various paradigms for conserving energy to make a sensor network last longer and within the upper bounds of the network lifetime [5]. Here, lifetime may refer to extending the time duration till the first node fails or to prevent a network partition. Energy efficient techniques have been proposed in almost all layers such as physical, MAC [54] and network layers. One way of effectively enhancing the collective lifetime of a sensor network is to use energy efficient routing protocols. There are several types of routing protocols which emphasize different methods of routing [2] [3]. They are geographic routing [24] [55] [14] [40], power-aware routing [47] [32], directed diffusion [21], data centric routing [27], semi-probabilistic routing for dynamic networks [10], probabilistic routing [44] [4], etc. There are others that suggest mobile sinks as an alternative to prolong the lifetime of these networks [33] [15]. Probabilistic routing [30] is one that focuses mainly on *network survivability* [45].

1.2 Applications of Sensor Networks

Deployment of large-scale sensor networks in real life scenarios is now a reality with several companies making customized sensors for practical applications. These large-scale deployments consist of sensors capable of detecting intruders in secure areas or sensing physical phenomena such as temperature, chemical leaks, water contamination, environmental conditions, radioactive leaks, pressure, etc. Often, manual deployment of sensor nodes is infeasible.

In practice, they are usually scattered by an aeroplane and based on a particular random distribution. There are also other methods suggested [2] such as delivery by artillery shells or using a robot to do the same. Such random deployment necessitates self-organization of the nodes. Since the network is usually inaccessible, it has to be made robust to overcome movement or failure of nodes.

Sensor networks are used for a wide variety of applications as mentioned above. Here, let us look at a few real-life examples of wireless sensor networks.

1.2.1 Military Applications

Sensor networks were primarily envisioned to serve the military. They can be used in a range of applications to help military personnel plan and fight wars better. Sensor networks can be deployed in battlefields to perform reconnaissance activities periodically. This will help in monitoring movements and re-deploying troops. They can be used to monitor NCBR (Nuclear, Chemical, Biological and Radioactive) attacks. This is very useful since these physical conditions cannot be monitored in person. Also, these kind of applications need to be planned much earlier, the network deployed and monitored from a far away place.

Such a scenario demonstrates an ideal use of sensor networks. Deploying sensors to sense these phenomena will help in maintaining personnel safety. Some of the other proposed applications in the military are in troop movements, battlefield surveillance, equipment status, etc.

1.2.2 Environmental Applications

This is an area of application of Wireless Sensor Networks that is extremely useful for the community. Deploying sensor networks for monitoring environmental conditions can help avert the community from coming in direct contact with natural disasters and other environmental forces [19] [8] [16] [18] [48] [42].

An excellent example of an environmental application of a sensor network is RIVER-SCOPE. This is a collaborative project by RPI and Columbia Universities. The project has deployed sensors along the Hudson river to monitor aquatic conditions. An underwater robot periodically traverses through the river to gather data from the sensors. This helps in keeping track of pollutants, salination, chemical additives let loose by industries, etc. There are several other environmental sensor network projects such as ALERT, COUGAR [53], etc that focus on flood detection.

Several other possible applications exist in monitoring humidity, weather stations, geo-physical monitoring, forest fire detection, etc.

1.2.3 Domestic Applications

Domestic applications abound for wireless sensor networks. Applications are only limited by imagination in the field of domestic/home applications. Sensor nodes can be embedded in various home appliances and networked to monitor them better [38] [19] [11].

They can be controlled from a central computer which can monitor their battery life, malfunctioning, etc.

Another interesting application is in making smart homes through the use of sensors. The sensors can be used in several devices and monitored over the internet. They can then be remotely given instructions based on the sensed phenomena. Also, intruder detection is a perfectly simple and feasible application involving just a few motion detection sensors. This saves the cost of installing hi-tech security devices and paying a security company to monitor those devices.

1.2.4 Other Commercial Applications

Commercial applications can exploit wireless sensor networks in many ways. Some of the common commercial applications are in robotics, inventory control and warehouse management, smart buildings, etc [1] [12] [22] [46] [51]. A very innovative usage is in vehicular sensor networks. Sensor networks in vehicles are used to see traffic congestion, traffic jams, etc on the web or on Global Positioning Systems (GPS). This helps other travelers avoid traffic jams, plan alternate routes, etc.

Large stores and warehouses can use sensors to keep track of shipments and inventories. They can be coupled with the vehicular GPS devices to provide information to the central warehouse. Also, large cities in the USA are now deploying vehicular sensor networks to help manage traffic better. Sensor nodes can be placed along the streets and highways which can monitor traffic conditions such as traffic jams, accidents, etc, and inform vehicles about alternative routes and delay times. This helps in decongesting and smoothing the traffic flow.

There are several other workplace applications [9] that are in the pipeline in becoming available commercially. Applications such as guiding guests in a new building through hand held devices or cellphones, helping employees to find empty conference rooms, etc are all practical applications that would be welcome in many large corporations. Such applications which improve the lifestyle and lead to more organization would definitely be a welcome improvement thanks to wireless sensor networks.

Chapter 2

Challenges associated with Sensor Networks

There are several challenges associated with sensor networks. Some of them are carried over from the wired and wireless ancestors whereas a few others are acquired from their characteristic differences from them. Also, sensor networks are quite different from their closest relatives, the MANET. One major problems associated with sensor networks is the customization required for each network. They cannot be deployed out of the box. Each application is different, the scale of operation, the management and the scenario totally different from other projects. This leads to a lot of customization and may increase the cost of the network.

In this section, we shall identify some of the challenges associated in the design of sensor networks.

2.1 Scalability

Scalability is one of the biggest problems associated with sensor networks. A distinguishing feature of a sensor network is the large number of network components associated with it. It is normally of the order of thousands or hundreds of thousands whereas MANETs consist of about tens to maybe a few hundred elements. The density of nodes also may vary depending on the application. It may be anywhere from a few nodes to a few hundred sensor nodes within a region of about 10 m in diameter [7]. Also, network density is given by [7] as

$$\mu(R) = \frac{N\pi R^2}{A}$$

where $\mu(R)$ is the number of nodes within the radio range R of each node in a region of interest of area A; N gives the total number of nodes scattered in the region.

Managing such a large network requires scalable protocols and extremely well planned deployment.

2.2 Deployment

Sensor nodes can be deployed in several ways. Due to the large number of nodes, it is impractical to manually deploy them by hand. Hence some of the methods resorted to are artillery shelling, scattering from an aeroplane, using a robot or in the worst case deploying manually [2]. Most protocols assume some kind of random distribution. Hence the deployment has to be in accord with such a distribution.

One advantage of such a deployment is that there is no necessity to plan for each node. This reduces the installation cost tremendously. However, monitoring individual sensors is very complex due to various factors such as size of network, accurate identification of each node, etc. The nodes themselves may be unreachable. In case of malfunctioning, it might be very expensive to replace a very small subset of scattered nodes in different geographical locations.

2.3 Environmental Conditions

Sensor nodes are typically deployed in regions with adverse climatic conditions. Underground sensor networks, underwater networks, volcanic and habitat monitoring sensor networks are some examples where they are tested to the extreme. In such scenarios, they have to sense the phenomenon and transmit information. The problem is usually associated with link quality and channel conditions. This might affect the radio range of the nodes or make them lose contact with immediate neighbors.

In busy commercial and workplace environments, they may face different problems such as unintentional jamming and noisy environments.

2.4 Energy Resources

Sensor nodes are tiny and hence so are their energy reserves. Most sensor nodes use tiny Lithium batteries. Hence they have to operate on low data rates and small radio ranges. Moreover, sensor nodes deployed in adverse environments are in no way individually replaceable or maintainable. This brings out a unique problem of managing whatever the scarce energy it has in a very efficient manner. They not only have to transmit their sensed information but also have to participate in relaying the information of other nodes.

Hence energy conservation and prudent management is one of the major challenges in sensor networks.

2.5 Topology and Connectivity

Sensor networks are usually deployed very densely so that coverage is not a problem. Such a dense network will initially not have problems discovering neighbors, finding connectivity, etc. However, as some nodes start to fail, there might be pockets of sparsely distributed nodes.

Wireless Sensor Networks can be analyzed theoretically by treating them as graphs [25]. The vertices can be treated as sensor nodes and the edges as links. The number of edges for any given vertex is called the degree. There will be connectivity problems in areas where the local degree is much lesser than the average degree of the graph. In such cases, connectivity may be lost and potentially create network partitions. Connectivity also depends on the distribution.

In sparse networks, it is obviously a much bigger problem.

2.5.1 Network Dynamics

Most scenarios of sensor networks consist of static nodes. However, there can be several cases such as fauna monitoring or vehicle tracking which may involve highly dynamic nodes. This creates a very mobile environment and hence a rapidly changing topology.

High mobility gives rise to a number of problems which cannot be handled by most protocols. Hence network dynamics can dramatically degrade overall sensor network performance.

Chapter 3

Sensor Network Routing

Routing in wireless sensor networks is quite different in many ways when compared to that in MANETs. This is primarily because of the challenges faced by wireless sensor networks as discussed in the previous section. The design of routing protocols for sensor networks will depend on many factors such as scalability, node deployment, transmission characteristics, delay tolerance, QoS, mobility, node heterogeneity, etc.

Coming up with efficient protocols when dictated by so many parameters is very difficult. One of the main objectives of a Wireless Sensor Network is to sense information and communicate it. However, it should also simultaneously take care of prolonging the lifetime of the network and reduce connectivity degradation by using excellent energy management.

There are various approaches to route packets based on the network characteristics. These approaches may use local information such as geographic location, neighbor movement or energy available in the nodes.

In the subsequent section, we investigate some of the approaches followed by various protocols. We also provide a critical survey of such protocols to determine what is the main feature lacking in a good sensor routing protocol.

3.1 Related Work

There are various paradigms in sensor network routing protocols. In this section, we shall classify some of the well known sensor routing protocols along with some of their shortcomings.

As discussed earlier, one of the most pressing problems in sensor networks is the scarce energy in the sensors. Hence, we emphasize the energy efficiency features adopted by previous methods.

3.1.1 Flooding

One of the simplest methods to disseminate information in sensor networks is to flood the network. Flooding is the process of forwarding of a packet from any node to every other node attached to the router except the node from which the packet arrived. This is an easy way to distribute routing information updates quickly to every node in a large network. However, it is also sometimes used to forward multicast packets.

It is obvious that such flooded information will reach every undesired corner of the network thereby wasting energy. There are other variants of full scale flooding such as constrained [56] and directed flood-routing [35] which reduce the overhead considerably. Constrained flooding uses techniques called differential delay mechanism and probabilistic retransmission policy. Using these techniques, it conserves energy by constraining retransmissions. Directed flood-routing has a flood routing engine that defines the routing policy. These policies specify the direction of flooding and how intermediate nodes rebroadcast messages. Also, there are global and local broadcast messages that are used to disseminate information to other nodes.

3.1.2 Data Centric Routing

One of the problems associated with sensor networks is that it is not practical to build a global addressing scheme which can compare with the classical IP-based addressing scheme. This is partly because of the sheer number of sensors deployed and also due to redundancy in regional data. Hence the data aggregation concept [27] [31] is more efficient in conserving energy. This concept involves combining regional data to eliminate redundancy and reduce the number of transmissions.

One of the first data centric routing protocols was SPIN [29]. This involves two features called *negotiation* and *resource-adaptation*. Negotiation involves a data advertisement scheme wherein sensors exchange descriptors called meta-data before transmission. Energy adaptation is controlled by the nodes when they are polled using a resource manager. This helps the nodes in deciding whether to participate in relaying third party information when battery resources are at a premium. These two features help in making it a better option than flooding.

Another important milestone in data centric routing was directed diffusion [21]. All data generated by the nodes is named by *attribute-value* pairs. For example, temperature and humidity may be two attributes in an environmental sensor. The values will be stored corresponding for the corresponding attribute. Hence the sink queries the nodes on an on-demand basis. The querying is done using attribute-value pairs. From a list of attribute-value pairs, a query (called *interest*) is generated by the sink and propagated through its neighbors. The neighbors cache these interests while forwarding them further. The source, receiving the interest, replies using the best gradient. A gradient is the information about the neighbor from which the interest was received. Hence, the source will be able to find an empirically best-performing path. The advantage of directed diffusion is that it is based on an on-demand model. This facilitates enormous saving of energy since there is no need to keep track of node movements. But this method would probably not work in a sensor network where the sink would need constant feedback from the sensors to function effectively.

Also, naming schemes for attribute-values are application dependent and occasionally each sensor might spend a lot of energy querying its own cache.

There are also other protocols such as gossiping [49] that avoid the problem of implosion. Implosion occurs when multiple copies of the same data reach a single destination leading to wastage of energy. This also causes delays in the propagation of valid data through the nodes. Rumor-routing [6] is a routing protocol which is a variant of directed diffusion which is used where geographic routing is not feasible. However, rumor routing performs well only when the quantity of sensed data is small.

3.1.3 Hierarchical Routing

One of the main network layer issues involved in sensor networks is scalability. This might cause the sink and the nodes near the sink to be engulfed with too much of traffic to handle. Due to the large number of sensors involved, some researchers have devised network clustering and then routing data through clusters to reach the sink. This creates a *multi-tiered* network.

LEACH [17] was one of the earliest routing schemes to involve cluster formation and many other routing protocols have been suggested based on this protocol. Some of the key features of LEACH are mentioned here. Small clusters are formed locally and cluster heads are elected in each cluster. Cluster heads are usually nodes with higher energy reserves. However, to balance the load evenly, cluster heads are rotated randomly. Also, all local data is compressed so as to reduce the number of packets.

In a cluster, the cluster head organizes all data aggregation and fusion. All transmissions are done only by the cluster heads. It has been shown that LEACH [17] reduces energy dissipation by a factor of about 7 compared to direct communication. Since clustering and election of cluster heads is dynamic, lifetime is increased and nodes die randomly. However, all nodes in a cluster need to be within a single-hop away from the cluster head. There might be overhead in electing a cluster head for certain sparse topologies which might mitigate the positive effects of adaptive clustering.

3.1.4 Energy Aware Routing

When energy conservation itself is the prime factor, the routing protocol has to be designed with focus on using the available energy of the nodes and preserving it for as long as possible. There are several protocols described in the literature where the main emphasis is on preserving the energy level of the network [45] [43] [55]. Shah and Rabaey propose a protocol [45] that concentrates on network survivability and tries to ensure that connectivity is maintained in the network as long as possible. It does not select the shortest path or a single path to route packets. Instead, it is a reactive protocol where each node makes a local decision based on available local metrics and computed probabilistic values to select a path. It is shown to provide a 44% increase in the lifetime of the network compared to directed diffusion for certain conditions.

In [43], the authors propose an energy efficient routing model to spread the traffic. This is done by a method called Gradient Based Routing where each node defines its height based on its energy.

3.2 Organization of the Thesis

In this work, we concentrate on an energy efficient packet routing technique for sensor networks [28] [43] and compare it with some of the existing routing methods. The remainder of this thesis is organized as follows. In Chapter 4, we propose a new probabilistic framework for routing. Chapter 5 deals with a simulation study and analysis of results. Finally, in Chapter 6, we provide a conclusion and propose some future work which could lead to improvements over the proposed method.

Chapter 4

Sensor Network Model

In this section, we propose a sensor network model which forms the basis for the simulation experiments performed. We briefly discuss some of the parameters that are involved in addressing the problem and

We propose a probabilistic framework for routing in wireless sensor networks [39]. Our method is based on [45] and is a considerable improvement over other proposals like [45] and [43]. Our model shows improvement in delaying the time of failure of the first node and also preserving more energy in the nodes near the sink.

The formation of *hotspots* in the network is caused by frequent routing through principally located nodes. Thus, an area in the proximity of a sink can be considered a hotspot. The main objective of this model is to enhance network lifetime (i.e., increase the time to the first node failure) as much as possible and also to mitigate the formation of hot-spots. This is done by spreading the energy consumption amongst as many nodes as possible.

4.1 Connectivity

Firstly, we discuss connectivity properties in the sensor network. We have to make sure that the sensor nodes in the network are connected with every other node. The notion of connectivity is explained as follows. If two sensor nodes are within each other's radio ranges, they are directly connected and can be called one-hop neighbors. If they are not within each other's radio ranges, then they can communicate with each other only by relaying information through other nodes that are their one-hop neighbors. These neighbors further

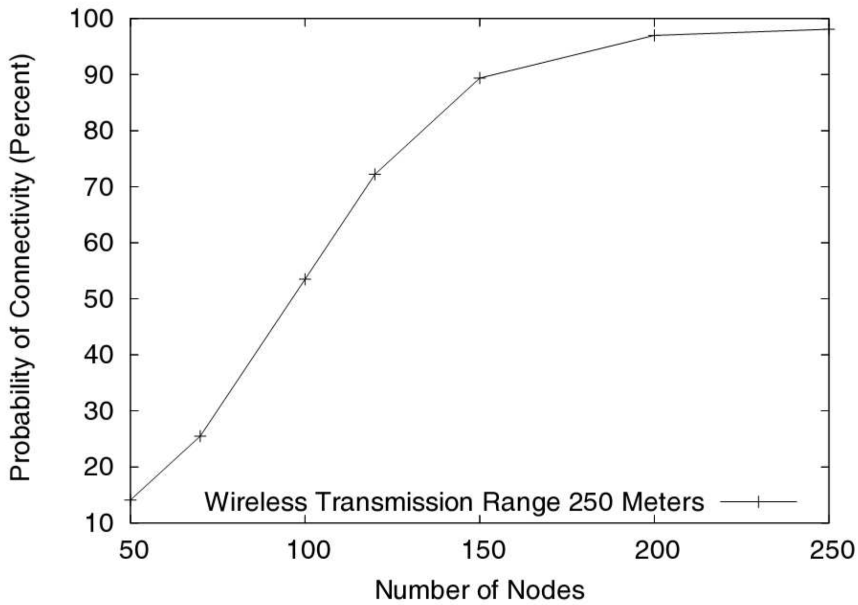

Figure 4.1: Variation of connectivity with density of the network

relay the information to their neighbors and finally reaches the destination over a *path*. It may so happen that for a particular distribution, there may be some nodes which are unreachable from any other node. They are said to be totally disconnected from the network. If a node is connected to all other nodes in the network, we can say that the entire network is connected.

Connectivity also depends on the radio range and sparsity or density of nodes in the network. For a sparse network, the radio range has to be long to establish connectivity. For a dense network, it suffices to have a short radio range to keep the network connected. As we increase the number of nodes, the connectivity also increases [36]. This is evident from the Figure 4.1 [36].

Based on the model used for connectivity in Figure 4.1, we decide on the number of nodes to be deployed in a planar region. Also, the radio range of the nodes are set to a value so as to get maximum connectivity in the network. It is better to deploy more nodes than to increase the radio range of the sensor nodes. Hence we cover the network by deploying additional sensors and decreasing the radio range.

To demonstrate connectivity, consider N sensor nodes deployed in a plane. We can model this as an undirected planar graph $G = (V, E)$. Here V denotes the set of vertices (nodes) and E the set of edges (radio links) between the nodes. An edge E exists between two nodes if the nodes are within each other's radio ranges and can directly communicate with each other.

Let the N nodes be in a region S of area A_s square units. Also, we suppose that the nodes are uniformly distributed over the planar region. To quantify connectivity, we define P_c as the probability that a node is connected to n nodes where $n \leq N - 1$.

It can be shown that there is a lower bound on P_c given by [50]

$$P_c > 1 - (1-a)^{n-1} - \sum_{k=1}^{n-1} \binom{n-1}{k} (1-x)^{n-1-k} (\frac{r^2}{A_s})^k \prod_{j=0}^{k-1} (\pi + 2j)$$

where $x = \dfrac{\pi r^2}{2A_s}$

This probability corroborates with the Figure 4.1 and ensures desired connectivity for a given number of nodes and a given area of deployment.

4.2 Problem Motivation

In a network of sensor nodes, the sensors produce data that has to be disseminated towards the sink. The data may be time sensitive and hence there may be a maximum tolerable delay of t_{max}. For a particular source S and destination d, we may assume that there are a total of P paths that exist in the network graph. Let us also assume that E_i and t_i denote the energy consumed and time taken along a particular path $P_i \in P$.

To obtain a path P' such that

$$P' \in P \text{ and } E' < E_j \forall P_j \in P^c$$

$$\text{where } P^c = P_i | P_i \in P and t_i < t_{max}$$

This problem of finding such a path P_i belongs to a class of constrained optimization problems. Hence it is NP-complete and we can only find heuristic solutions to obtain the solution for this problem.

One way of finding heuristic solutions to the above mentioned problem is to use probabilistic routing methods. This is explained in detail later.

4.3 Assumptions

In our study, we make a few assumption in the description of the sensor network. The assumption are listed below.

1. All nodes are assumed to be stationary and links with their neighbors are assumed to be bidirectional. The only unidirectional links belong to those nodes which are connected to the sink. There is no interfering traffic involved.

2. Nodes are deployed for sensing and transmission of information. They are homogeneous, i.e., they have the same capabilities and functions. They all cooperatively route the information to the sink.

3. Every node maintains a table which stores information required for routing. This table contains the node's location information, energy level, number of hops to a sink, one-hop neighbors, their locations, energy levels and their distance from the sink. The neighbors exchange energy level information through infrequent HELLO messages.

4. Based on this information, every node assigns routing link probabilities to each of its neighbors. This probability metric defines the possibility of a packet being forwarded through a particular neighbor. These probabilities are based on the energy level of neighboring nodes, their recent activity and distance from the sink. This will be discussed in more detail in the next section.

In our simulation study, except for the energy levels, most of the information is disseminated one-time only during the start of the simulation.

4.4 Routing Framework and Analysis

This section discusses the theory behind the routing framework. We discuss two methods called Probabilistic Routing and Angular Routing which are combined together to improve energy efficiency in the network.

4.4.1 Probabilistic Routing

Let us assume that nodes $y_1, y_2, ..., y_n$ are the n one-hop neighbors of x. The routing table of node x will have an entry $p_x(y_i)$ for every neighbor y_i where i $\in 1, 2, ..., n$ and denotes the probability of taking that link to reach a destination z. Hence, $p_x(y_i)$ indicates the probability of a packet being forwarded from node x to a neighboring node y_i.

It also follows that

$$p_x(y_i) \geq 0$$

$$\sum_{i=1}^{n} p_x(y_i) = 1$$

All nodes can access their energy levels e at any instant. Initially, every node computes the distances d_{y_i} and gets to know of the energy levels e_{y_i} where $i \in 1, 2, ..., n$ of all its n neighboring nodes through HELLO messages. They also advertise their distance from the sink in hops as h_{y_i}. Such information is stored as a vector in the form:
$< y_i, e_{y_i}, d_{y_i}, h_{y_i}, e_{av}, h_{xz}(y_i) >$.

Each node has a hop count to the sink h_{y_i} that is calculated during the initial phase. Since we have assumed that the network is stationary, the hop count computed once will remain the same throughout the lifetime of the network unless intermediate nodes die. This metric is useful because if a node's neighbor has a smaller hop count number, then that node is closer to the sink. Hence, it should be assigned a higher probability for forwarding the packet. In other words, the probability should be proportional to the weight determined by the hop count. Thus, a neighboring node, which is closer to the sink, relays a packet with a higher probability.

The average energy of a node e_{av} denotes the average of the energy levels of its neighboring nodes including itself. Ordinarily, e_{av} is used for all calculations. However, it may so happen that a node and one of its neighbors have quite ample reserves of energy but its average energy is very less. If $e_{av} \leq 0.5e_{y_j}$, then e_{y_j} is used for the calculation.

$h_{xz}(y)$ is initially not present but it is updated through feedback from the other nodes dynamically. This field denotes the distance in hop count from node x to z via the neighboring node y. This metric is not always used to compute the probability values since it converges only after sometime. However, if $h_{xz}(y)$ is comparable to the hop count of another neighboring node and also has comparatively the same energy, then it is used as a metric for computation.

The objective is to forward a packet to a neighbor with the maximum average energy and least hop count. This neighbor will have the maximum probability of receiving the packet. Also, the probabilities have to be recomputed after a certain number of transmissions so as to reflect the state of the node's and its neighbors' energy status.

We now compute the probability of forwarding a packet to a node as:

$$p_{xz}(y_i) = \frac{e_{av_{y_i}} h_{y_i}}{\sum_{i=1}^{n} e_{av_{y_i}} h_{y_i}}$$

This gives the probability of routing a packet to an adjacent node.

4.4.2 Angular Routing

When the network is deployed, the sensors configure and discover their neighbors. Thus, every node knows its position relative to the sink. It also knows its neighbors' positions. Using this information, we propose to route data with minimum number of hops. Hence, we introduce another parameter to the routing procedure called the *angle of routing*.

If routing is based only on probability, the packet might take a lengthy path if the energy metric outweighs the hop count metric. To prevent this, *sector based routing* as shown in Figure 4.2 helps in keeping the paths comparable to the shortest path. This procedure is explained below.

When nodes determine their localization information [37], they also exchange this information with their immediate neighbors. There is no necessity to have absolute location

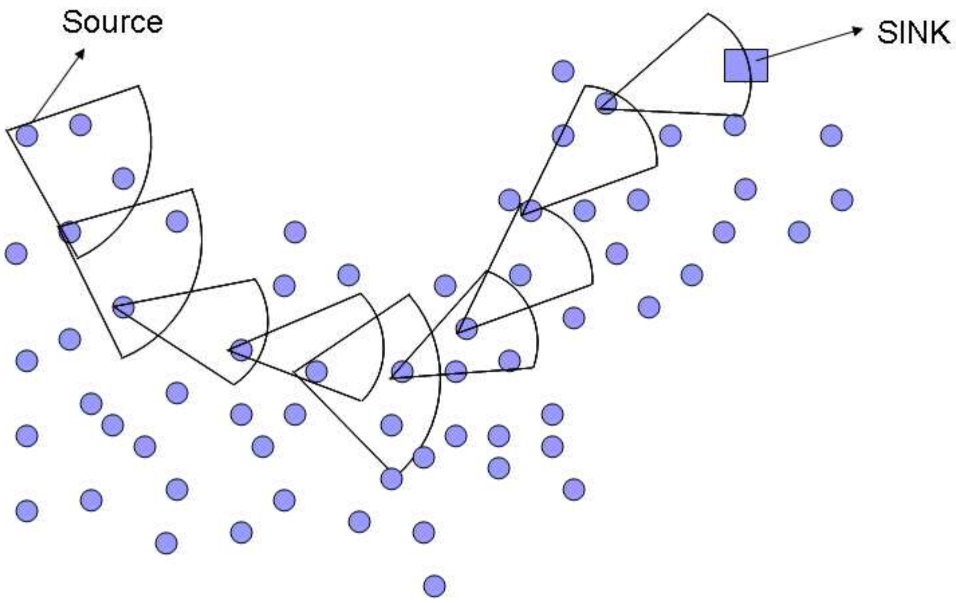

Figure 4.2: Conical sector routing.

information. This gives a relative location of a node with reference to its neighbors. We can use this localization information to direct packets towards the intended destination and reduce latency and energy consumption to some extent. In this work, since we assume that the destination is always fixed, all nodes have direction information about the sink. Initially, when a node has a packet to forward, it starts off by scanning only those neighbors within a θ° cone directed towards the sink. Hence the field of interest is reduced and the other neighboring nodes do not have to listen to the broadcast and expend their energy. Now, amongst the nodes selected, it forwards the packet to the neighboring node with the highest probability value. All the neighboring nodes which relay packets also update their recent activity fields. Hence, over a period of time, the probability values also change to reflect the current energy levels of the nodes.

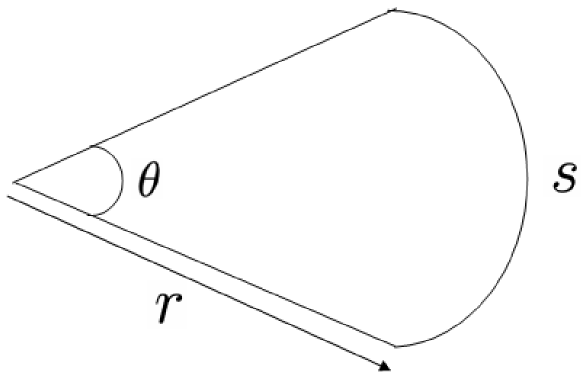

Figure 4.3: Angular routing with sector angle θ.

The nodes that come under the coverage of this cone are determined as follows. For the sake of analysis, this cone is approximated to a sector of a circle.

The sector is in the direction of the sink and the radio range r of the node is the radius and the length of the arc s can easily be determined as follows. The two end points of s on either sides of the center of the arc define the boundaries and the sensor nodes lying in this region can be identified for forwarding the packet.

$$s = r\theta$$

This can lead to a problem over time. As all the nodes towards the sink expend their energy reserves, the probability of forwarding a packet to any of them remains same since their energies are relative. However, when the battery level reaches the threshold, the source has to find alternative routes to the sink. Let us suppose that a node has to relay a packet and all its θ° cone neighbors have energy levels below a certain threshold. Then the sector angle is increased to $\theta + \epsilon$ so that there are more neighboring nodes that now come within its coverage. So the probability of forwarding a packet to one of these new nodes is now higher than the others. Hence, packets now find their way to the sink through other routes.

Summarizing, the routing model suggests spreading the packets across more nodes to conserve energy. This is done using a probability metric computed using hop counts to sink and average energy of the nodes. In addition, a sector for routing only to particular neighboring nodes is defined using θ.

As we demonstrate in the next section, we achieve considerable improvement in the conservation of energy and hence prevent the creation of hot-spots.

Chapter 5

Simulation and Results

In this section, we describe efforts to validate the proposed routing model. We perform a simulation study using realistic parameters to verify the claims that we have made for the proposed framework. The details are explained below.

5.1 Simulation study

To assess the performance of the routing model proposed above, we perform a MATLAB simulation study. Sensors are uniformly randomly deployed in a 100 X 100 grid as shown in Figure 5.1. All sensors are assumed to be homogeneous, i.e., they are assumed to have the same capabilities and functions. The deployment assumes that there is a high connectivity initially when deployed. Also, the sensors have to configure themselves, undergo localization and discover their neighbors. We assume that there is only one centralized sink with unlimited processing power and resources at the right edge of the grid. This is more practical than assuming a sink somewhere in the center which would be infeasible for most scenarios.

We assume a dense deployment of sensor nodes and the average node degree of the graph to be approximately 5. This facilitates high connectivity and thus permitting multiple routes to the sink. For every simulation run, we choose a sensor node in the field randomly. Then, we generate a packet to be routed to the sink using all the metrics proposed above and evaluate the energy consumed for each run. There is no other traffic in the network. The resource manager for each node also updates the energy usage for that node if it is

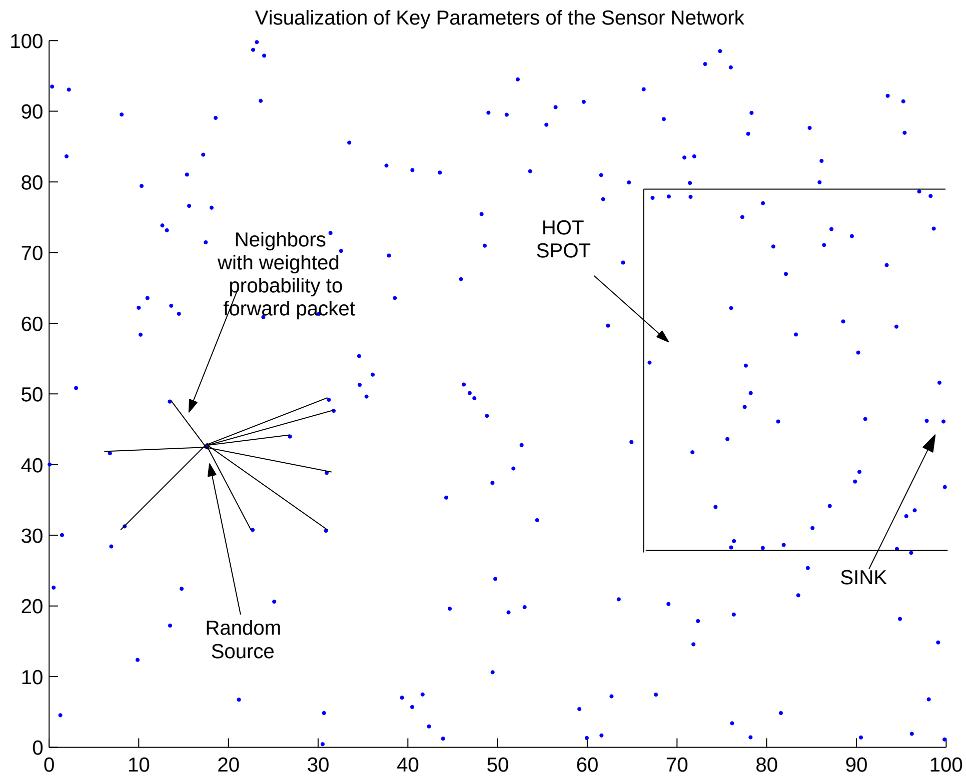

Figure 5.1: Visualization of key network parameters

used in either packet generation or relaying packets. The energy spent for receiving and transmitting a packet is assumed to be the same as that of Rabaey and Shah [45] which is 25nJ/bit. Also, all energy calculations are only for the network layer and do not take overheads of other layers into account.

Packets are numbered so that there is no looping and nodes do not receive the same packet multiple times. For comparison of the proposed routing method, we analyze the performance of the network for the routing protocol proposed in [45]. The packet transmitted from a node to the sink keeps track of the delay and the hop count. To obtain a statistical result, we run the simulation 100 times using different randomly generated network topologies and random sources.

5.2 Results

A sample topology in Figure 5.2 shows an instant of the simulation when the nodes have discovered their neighbors, formed links and updated their resource tables. Hence, location estimation, flooding, exchange of HELLO messages, etc. This connected graph shows that there is a high degree of connectivity with each node being connected to many neighbors.

Packets are generated randomly and transmitted. As described earlier, energy and probability metrics are updated regularly. As the energy of some of the nodes gets depleted, the sector angle as shown in Figure 4.3 needs to change. This has repercussions in the delay or the hop count. In such a case, the packets take longer paths to reach the sink for a wider sector angle than for a narrower angle. This is because as the angle increases, more candidate nodes are generated for packet forwarding. Hence, the packet might be routed

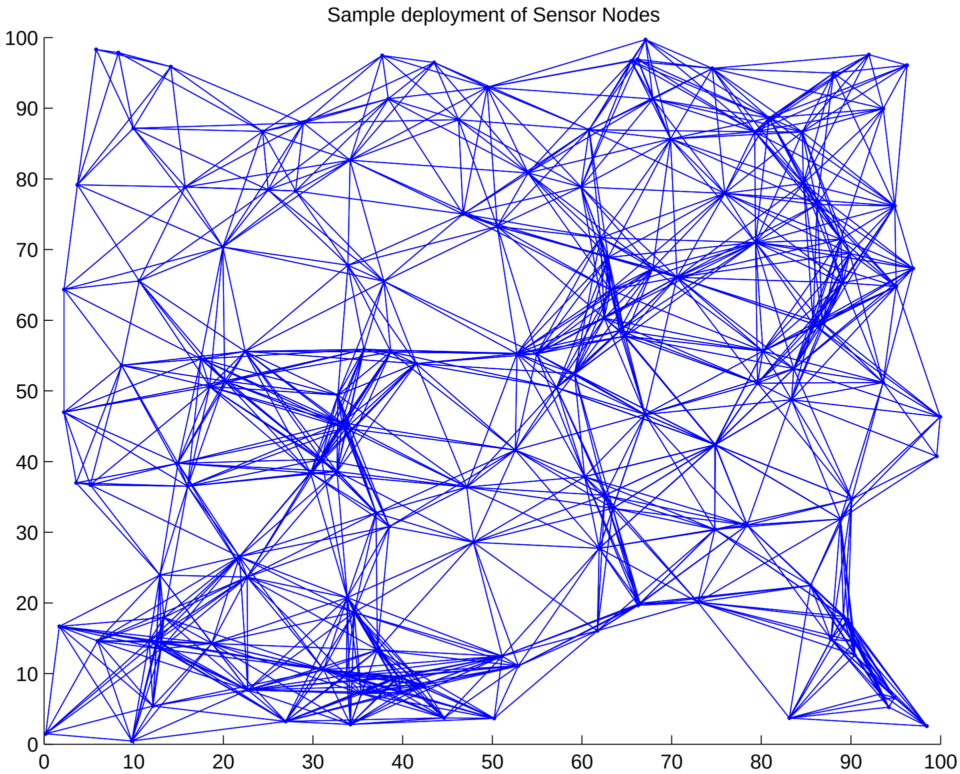

Figure 5.2: Sample topology used in the simulation

through a node which has more energy but would be farther from the sink. As a compromise, the maximum angle of the cone can be specified to prevent the longer path delays.

The simulation study shows the variation of path delay with the angle of the cone in Figure 5.3. As we observe, the sector angle has to be controlled to prevent the delay from getting too long. We notice that there is no variation in the delay when the angle is varied from $60°$ to $100°$. This is probably due to the fact that when the angle is varied above $60°$, the new candidate nodes would have almost the same hop count as the forwarding node. Hence, the sector angle can be increased up to $100°$ to obtain best effects of angular routing. For a given sector angle θ, we study the difference in the number of hops for a packet to reach the sink with and without angular routing. Figure 5.4 shows the difference in the average number of hops required for a packet to reach the sink. From the curves in Figure 5.4, we observe that using angular routing along with probabilistic routing has quite significant benefits. Though there is no major variation for shorter distances, we notice that for longer distances there is some advantage in using angular routing.

After a hundred rounds of simulations with different network topologies each with 1000 packet transmissions, the collective energy results collated and analyzed. An energy profile of the sensor nodes is shown in Figure 5.5. The colormap is also shown to the side. A region that has expended the maximum energy is shown in a reddish color and one with least energy spent in blue. We observe from Figure 5.5 that the energy is spread out and not many nodes die out in the routing process. In this figure, the energy consumption has been normalized.

As expected, there will definitely be more energy expended by the sensor nodes located near the sink than elsewhere. This is because even though they are not responsible for

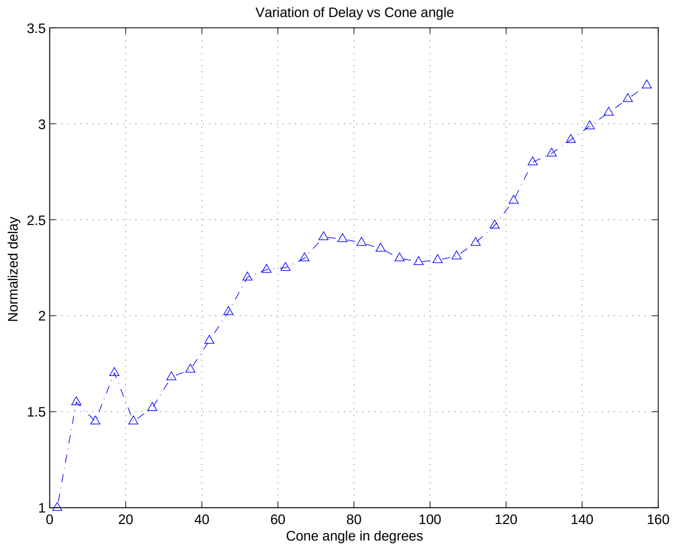

Figure 5.3: Variation of Delay with cone angle.

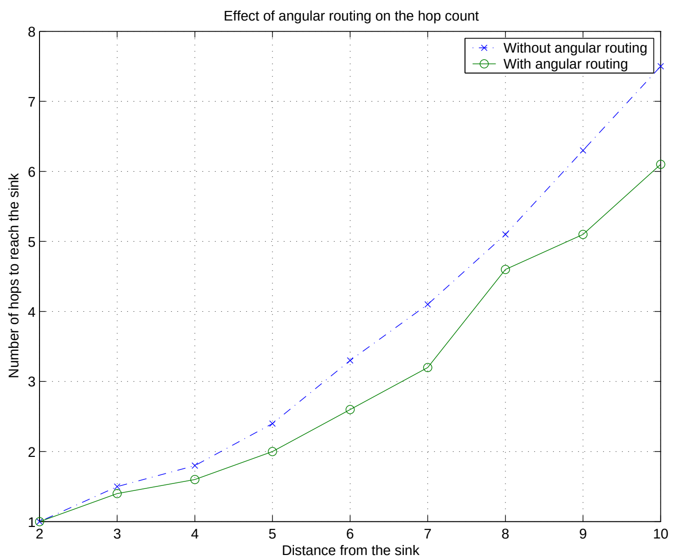

Figure 5.4: Variation of hopcount with and without angular routing.

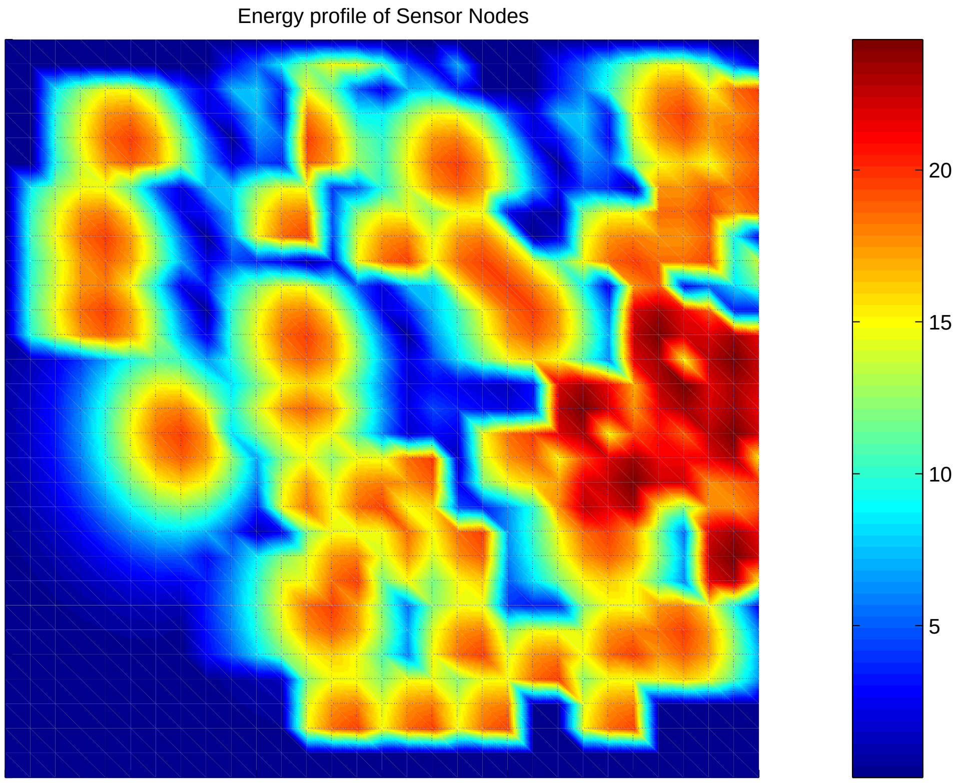

Figure 5.5: Energy profile of the grid .

generating packets, they are almost always relaying some other node's packets to the sink. However, it can be observed from Figure 5.5 that the formation of hot-spots near the sink is extremely slow. Hence the sensor nodes have conserved some amount of energy.

To demonstrate the robustness of our model, we compare our results with the one proposed by Rabaey and Shah [45]. We have simulated the energy aware routing protocol using the same network parameters. Then, we have averaged out the field of sensor nodes into a 10X10 grid. The energy profiles are shown in the Figure 5.6 and Figure 5.7. Though the energy plots look almost the same, we can calculate that there is an improvement in the conservation of average energy. We have obtained the difference in the energy values in the corresponding grids of the two figures. If we assume that the 25 grids near the sink as hot-spots, then we can show 11% efficiency of our routing model in distributing energy across the sensor nodes.

There is still potential cause of failure in the future since the nodes which are very close to the sink have depleted most of their stored energy. Their participation in the relaying process is extensively greater than other nodes.

To overcome some of the problems mentioned above, we suggest a differential deployment of sensor nodes. The details are explained in the subsequent section.

5.3 Differential Sensor Node Deployment

There are many ways in which we can conserve energy of the sensor nodes situated in hotspots. These include replacing or replenishing such nodes frequently, moving those nodes so that they exchange their locations with nodes that have expended less energy [41] or deploying more nodes in such regions to offset the traffic load. As we have already described,

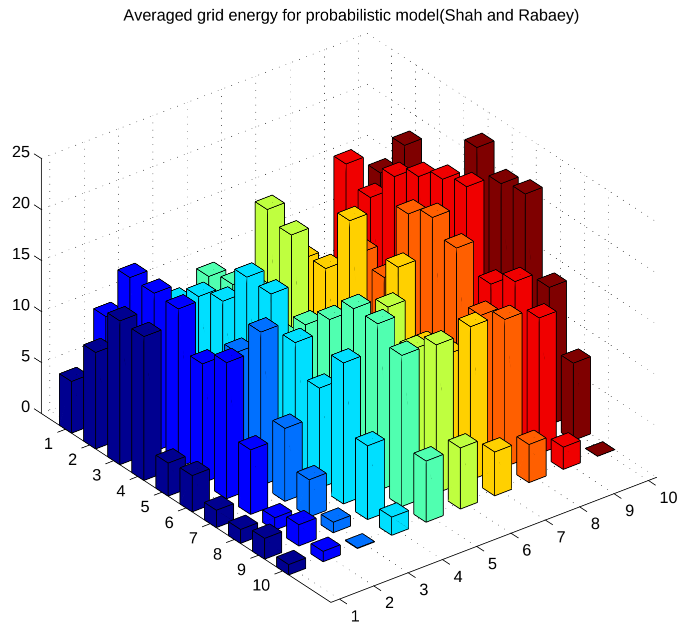

Figure 5.6: Averaged energy profile of the grid for routing model proposed by Shah and Rabaey [45].

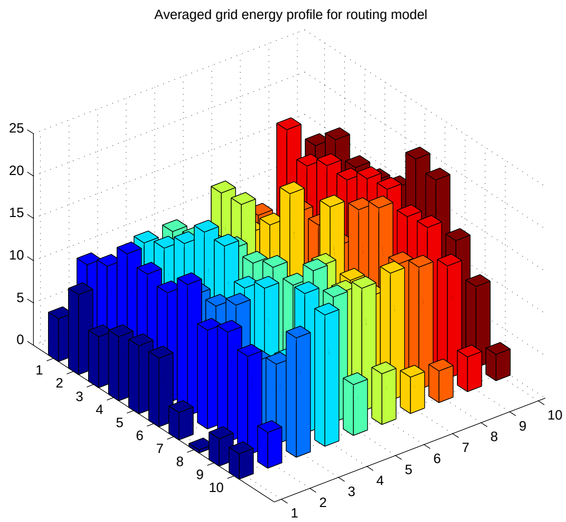

Figure 5.7: Averaged energy profile of the grid of sensor nodes.

it might not be feasible to recharge or replace nodes after deployment. Also, mobile nodes swapping their places might involve high end motes which have guided mobility and larger energy reserves. There has been some work in this area [20] on the effect of node density on data aggregation in sensor networks. Hence in this experiment, we have tried to demonstrate the effectiveness of the last option - i.e., deploying more nodes in such regions to see their effect on longevity of the network.

We do not consider the logistics of deploying a larger sample in hotspot regions. We shall assume that such a task is achievable and concentrate on performance analysis. We propose deployment of sensor nodes with differing densities in regions of extensive network usage. These differential deployments are made using a certain probability distribution. Since the purpose of deployment with different μ values is to aid the distribution of energy and hence prevent failure of nodes, we study how the variation of the mean will influence the hotspots. Figure 5.8 shows the sensor node failure rates for different distributions. We observe that for a particular distribution, the failure of nodes in the hotspot is particularly low. This depends on the routing protocol and the metrics used in the network such as the threshold e_{av}.

The whole purpose of using a gradient distribution is to spread the traffic load as uniformly as possible among nodes. We demonstrate this through a histogram in Figure 5.9. The histogram shows the distribution of data traffic on the nodes. We notice that this sensor node distribution coupled with the angular routing technique is quite successful in uniformly distributing the traffic. This, in fact, substantiates the energy profile of Figure 5.10 where we notice that most of the nodes in the hotspot have participated equally in the routing process. Though we still observe a few peaks in the histogram, these are not

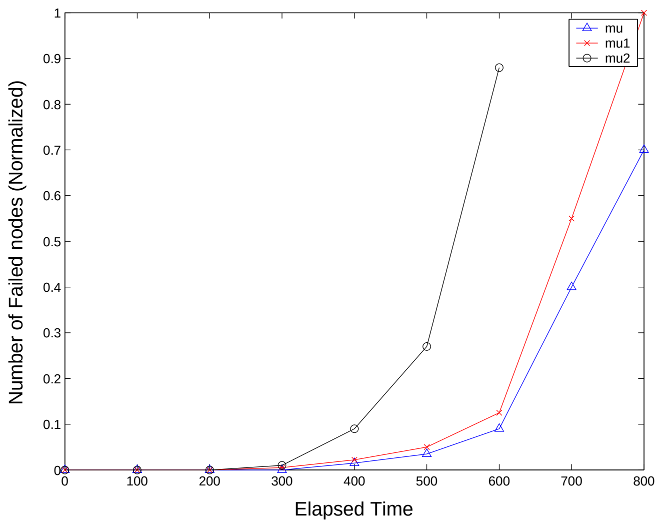

Figure 5.8: Effect of spatial node distribution on node failures

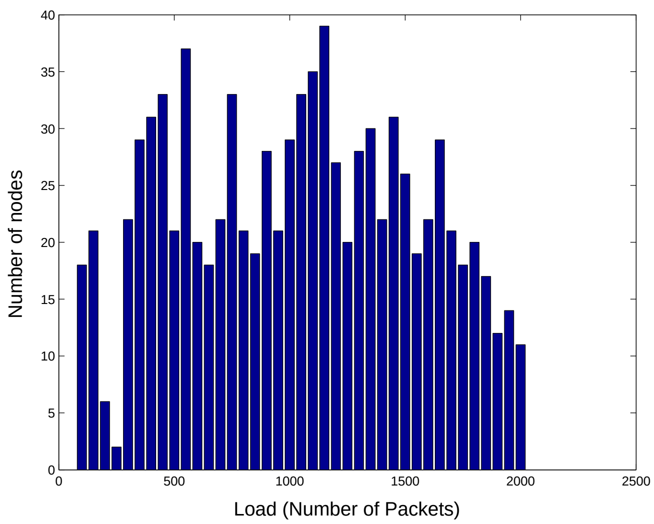

Figure 5.9: Histogram of traffic distribution on the nodes

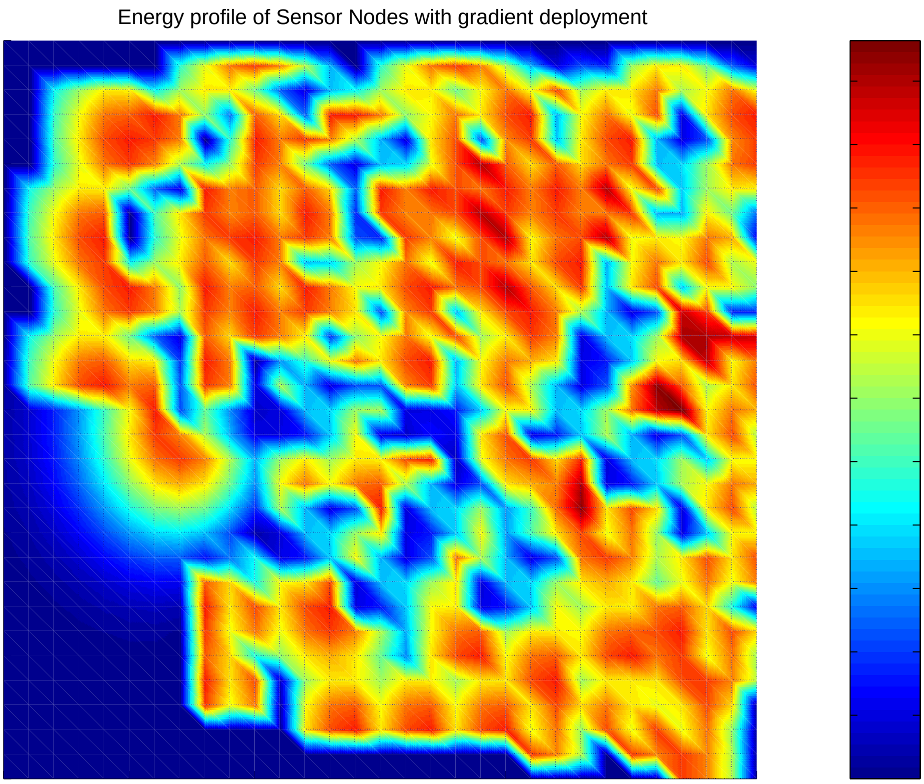

Figure 5.10: Energy Profile of the nodes using gradient deployment

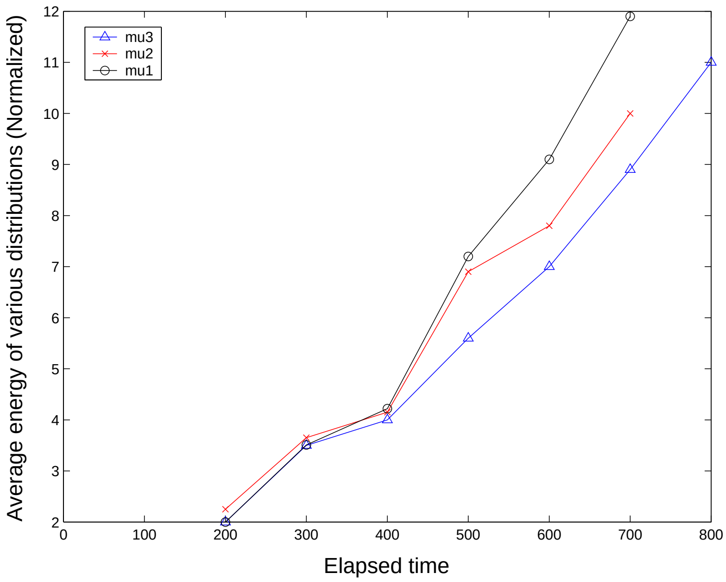

Figure 5.11: A snapshot of average energy over time

critical. This demonstrates that a majority of the nodes handle small to medium number of packets.

We also perform other studies from the simulation. Figure 5.11 shows the variation of average energy in the hotspot region over time. As we see, there is a noticeable difference in the energies consumed over time. The distribution with μ_3 corresponds to the least energy consumption and μ_1 to the highest among the three. It can be shown that the theoretical bound on the maximum energy consumed is closest to the curve corresponding to μ_3. From this figure, we conclude that difference in spatial distributions definitely influences the formation of hotspots and reduces failed nodes. Hence, finding the ideal distribution for any scenario will increase the lifetime of the network.

We can infer from Figure 5.11 that the energy consumption depends on the distribution of the nodes. Also, the gradient in deployment used to overprovision the network plays a significant role in preventing network partitions in the hotspots. Though initial energy consumption in the hotspot is almost the same for all distributions, we can see a notable difference during the later stages of the simulation.

Chapter 6

Conclusion

In this work, we set out to improve the energy efficiency of wireless sensor networks. We approached this problem through efficient routing methods.

We have proposed a routing framework for wireless sensor networks for avoiding the formation of *hot-spots* of energy depletion. This routing framework incorporates assigning probabilities to the links to neighboring sensor nodes.

To incorporate the changing energy profile of the network, we re-evaluate the network parameters frequently. We have used the idea of changing routes over time depending on the probability. This is based on computing probability with parameters such as remaining energy of the sensor nodes, recent activity, etc.

To prevent increased latency and extremely long routes, we bring in the idea of angular routing. This prevents taking paths that are in the opposite direction from the sink and thereby elongating routes. We have also demonstrated via simulations that probabilistic routing using energy and angular metrics can increase the lifetime of the network. There is also evidence of this fact by the reduction of *hot-spots*.

It is true that to extend the lifetime of the network, we have employed data forwarding through suboptimal paths. Viewed in isolation, these look bad since they not only increase the latency for the packet but also increase the average energy consumed for a packet. However, if we look at the big picture, we have been successful in spreading the energy consumption over a larger area thereby reducing node failures.

In spite of these methods to tackle the problem of hot-spots in networks, there is still increased activity in regions near the sink. To overcome the energy depleting effects, we also propose a method to differentially deploy more nodes in such regions. This will spread the traffic in such regions and extend the life of such networks.

Probabilistic angular routing method may not be optimal for all network topologies. Topological changes induced by mobility might have different effects on the energy profiles and network lifetime.

Chapter 7

Proposed Future Work

The proposed framework has been validated by extensive simulations using MATLAB. The parameters used are quite realistic and map closely to real time scenarios. In future, we propose to use real sensor nodes and program them with this routing framework. This will help take into consideration many other factors that had been previously neglected. A real emulation using sensor motes would involve cases of channel fading, co-channel interference, congestion, hidden terminal problems, environmental influences on the sensor nodes, etc. This would also bring out some of the deficiencies of the packet format used, the need for effective data aggregation, cluster formation, heterogeneous sensors, etc. Also, in future, we propose to extend this work with a network simulator that tries to take care of at least a few of these parameters. All this would substantiate the effectiveness of the proposed methods ever better.

We have proposed a routing framework that tries to elongate the lifetime of wireless sensor networks. However, it is not without some minor loopholes.

Probabilistic angular routing method may not be the most optimal routing framework for all kinds of network topologies. Moreover, topological changes induced by mobility might have different effects on the energy profiles and network lifetime. As future work, we propose to extend this work to incorporate the effect of node densities throughout the network. The objective of such architectures is to deploy nodes according to the energy usage profiles in the network. We also propose to investigate this in comparison with other network architectures such as multi-tier (clustered) networks, data aggregation models, etc which represent a paradigm difference in architecture.

In this work, we have considered a stationary sensor network and a stationary sink. In future, we propose to investigate mobility in the network and also mobility of the sink. This might be a realistic scenario in some specialized applications.

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