EFFICIENT COMMUNICATION IN STATIONARY WIRELESS SENSOR NETWORKS

by

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Dedication

To my father for his encouragement.

To my mother for her love.

To my wife for being there.

To my children for their future.

Acknowledgments

It has been almost three and half years since I started my Ph.D education at Wayne State University, and when I sit back and think about the number of people who influenced me and helped me complete this dissertation, I am overwhelmed! There is no doubt that this would have been impossible without their help. I hope that I can remember everyone who helped me through this difficult yet rewarding process.

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Chapter 1

Introduction

Wireless Sensor Networks (WSN) have wide and varied applications. A smart sensor is a collection of integrated sensors and electronics. When these types of sensors are used in WSNs, very powerful, versatile networks can be created and used in situations where traditional wired networks fail. These sensor networks can be used for emission monitoring systems in the harsh environment of automobile exhaust systems or in large buildings for more consistent climate control. Research is already being conducted with respect to low-power dissipation for deep space missions (Patel, Chai, Yalamanchili, and Schimmel 1997). While the space station research has been concentrating on direct networks, this would be an excellent case were the flexibility of wireless networking could be aptly applied.

Some of these networks can be installed in a building to monitor the building or in an assembly plant, where the use of regular topology will have better advantage than mobile. In a fixed topology we can place the nodes so they can give better coverage. Node also functions as a router and can relay messages for its neighbors. Regular topologies such as the mesh offer multiple redundant communications paths throughout the network. If one node dies or fails other nodes can be use to reroute the message. Regular topologies also enhance the overall reliability of the network by providing an alternative paths.

There are also countless medical applications, including monitors and implantable devices, such as a retinal prosthesis (Schwiebert, Gupta, Weinmann, et al. 2001). Biomedical WSNs have unique constraints that must be addressed before they are feasible for human use. These implants are intended for long-term placement in the body and, therefore, cannot dissipate amounts of heat that would damage the surrounding tissue. They would also require a constant, renewable source of energy. This alleviates many constraints placed on other WSNs that have finite amounts of non-renewable energy. Uses such as these, where the network topology is nominally fixed, are of particular interest.

A sensor network is composed of a large number of sensor nodes, which are densely deployed either inside the phenomenon or very close to it. Since large numbers of sensor nodes are densely deployed, neighboring nodes may be very close to each other. Hence, multihop communication in sensor networks is expected to consume less power than the traditional single hop communication. Furthermore, the transmission power levels can be kept low, which is highly desired in covert operations. Multihop communication can also effectively overcome some of the signal propagation effects experienced in long-distance wireless communication.

One of the most important constraints on sensor nodes is the low power consumption requirement. Sensors nodes carry limited, generally irreplaceable, power sources. Therefore, while traditional networks aim to achieve high quality of service (QoS) provisioning or high bandwidth, sensor network protocols must focus primarily on power conservation. They must have built-in trade-off mechanisms that give the end user the option of prolonging network lifetime at the cost of lower throughput or higher transmission delay.

Wireless devices must operate for a long period of time, relying on their battery power. Although many developers have looked at extending the life of a wireless system from a hardware point of view, such as directional antennas and improving battery life, power-aware routing is a relatively new concept in wireless networking.

Until recently, most routing protocols in wireless networks have concentrated mainly on establishing routes, and maintaining these routes under frequent and unpredictable changes in network topology. The concept of using routing to minimize power usage has only recently been looked at and it has been shown to be moderately successful. It has been proposed that routing packets in a power-aware method will complement hardware-based methods of extending the network's life. The metrics that have so far been devised to minimize power can be grouped into two main categories, power-aware and cost-aware metrics. Power-aware metrics aim to minimize the total power needed to route a message between two different locations while cost-aware metrics look at methods that extend the nodes' battery lifetime.

Due to the high cost of communication and low battery power, it is natural to seek decentralized, distributed algorithms for wireless sensor networks. This means that instead of relaying data to a central location that does all the computing, the nodes process information locally. By locally, we mean that the computation of routes should be based on local information that is available to the node from its neighbors only. By doing so we limit the number of messages that need to be sent in the network to discover routes or to make a decision for routing.

However, centralized algorithms have the advantages of obtaining global information about the network and obtaining an optimum solution for routing. But due to the limitation of power, the large number of nodes in a sensor network, and the change of power available at the nodes, this is not an efficient way of obtaining information and some of the information will be outdated.

1.1 Contribution and Scope of the Dissertation

This dissertation primarily addresses several issues related to designing a power efficient protocol for extending the life of the nodes and the overall network. First, we address the issue of localizing the information in sensor networks. Second, we address the effect of fixed topology on the power efficiency of designing protocols. Third, we address the issue of power aware metrics and their role in the design of a local routing protocol. Finally, we address the issue of communicating internally and externally with a base station.

In this dissertation, we focus on designing protocols for stationary regular topologies that increase the life of nodes as well as the overall network. In doing so, we have restricted our protocols to deal with only local information that is available to nodes from their neighbors. The main idea is to request and process data locally and gather information from neighbors on a demand basis. So, a wireless protocol for sensor networks should consider the constraints the network will operate under, such as limited power and only local information available to each node in the network. By using local information, we limit the number of messages that the network needs to send to update the changes in the network.

Basing a routing protocol on these items only is not enough. Routing paths must be defined. Producing a routing table involves many control messages and also involves route discovery. But with the kind of information that is available and the limited resources that we have, we cannot have control messages to do route discovery and continually update the routing table. Instead we base the routing protocol on the local information only without using a routing table. In order to achieve this idea we introduced the idea of Directional Value (DV) (Salhieh, Weinmann, Kochhal, and Schwiebert 2001). Each node knows from the request which direction to send the packet. So the node just computes which neighbor is the most suitable to forward the message to and the neighbors on their own will determine the rest of the route. This idea requires the node to contact its neighbors only and saves many control messages throughout the whole network. This provides a routing protocol that will scale with a large number of nodes.

The idea of directional routing, requires only that each sensor know its location within the network relative to the sending node and the destination. This allows for the use of simple directional routing based on local information only. However, sensors are energy-constrained devices, so selecting paths within this network could benefit from an energy-aware routing process.

In extending the life of the network, we will examine the relationship between power usage and the number of neighbors in a wireless sensor network. The study of wireless network topology must be approached from a different point of view than for wired networks. In a wired network, we examine how nodes are physically connected and the resulting available routing paths. In a WSN, the definition of the network topology is derived from the physical neighborhood and transmission power, so we must determine which topology gives the optimal number of neighbors that a node can handle to transmit to or receive from. Many of the topologies proposed for wired networks cannot be used for wireless networks, for in wired networks, a higher dimension can be implemented by connecting the nodes in some fashion to simulate higher dimensions. In WSN, however, we are dealing with three dimensions in the physical world and are thus restricted in our choice of topologies. Therefore, we concentrate on 2D and 3D mesh topologies.

One question we are seeking to answer is what is the best topology for a wireless network of sensors, assuming we can control the placement of these sensors and the sensor locations are fixed relative to each other. Since we assume control over the placement of these sensing nodes and do not require mobility of the sensors relative to each other, the research problem changes. Instead of considering self-organization of the sensor nodes into a network, we address efficient placement of fixed nodes.

The design of these protocols must be power aware to take advantage of the information that is available from the neighbors. In (Salhieh, Weinmann, Kochhal, and Schwiebert 2001) the authors have shown that using a power aware protocol distributes the power usage evenly among the nodes of the network. When considering a routing metrics for sensor networks, we need to see what kind of information is available for routing. If we consider only the local point of view then there is limited information that each node can get from its neighbors. These items are listed below:

- Cost of communication and distance between a source and its neighbors.
- Cost of communication and distance between a node and the base station.
- Number of neighbors.
- Power remaining at the neighbors.

From the above list we have created several types of power aware metrics that depend only on the local information. We list these algorithms that will be discussed in detail in a later chapter:

1. Power Only.
2. Directional Value Only.
3. Directional Value and Power.
4. Directional Value and Sum of Power.
5. Number of Hops Only.
6. Hop and Cost.
7. Hop, Cost, Directional Value, and Sum of Power.

The idea here is to localize everything in the protocol. We mean that each algorithm is applied locally on a hop-by-hop basis from the source to the destination.

The use of local information for making routing decisions may not lead to an ideal path. The lack of global knowledge could result in the choice of less efficient paths or even paths that require significant backtracking to reach the destination. Global knowledge of the nodes and their properties, such as available power, along with knowledge of the current traffic in the network could allow for optimal path selection for whatever goals we are attempting to achieve. However, the overhead and delay of accumulating and using global information is prohibitively expensive especially for sensor networks. Because network conditions, including each sensor node's power and availability, are dynamic properties, this global information is likely to be obsolete before it is accumulated, so the advantages of using global information are reduced or lost. Despite the fact that routing based on global information is not practical, it provides a good basis for determining how efficient routing based on only local information performs. In this paper, we evaluate several global metrics and compare these with the corresponding local metrics, showing that the local routing metrics perform reasonably well given the limited overhead.

Routing packets within in a large scale wireless sensor network without storage overhead and routing table updates is a challenging problem. With a large number of sensors, however, the overhead plays a significant role in the scalability of the routing protocol. In order to constrain this communication overhead, sensor network routing demands new and efficient methods for routing packets. In order to do remove or reduce this overhead, the routing protocol needs some way of implicitly, rather than explicitly, defining paths. We mean that the protocol need to base its decision on the local information and decide which of its neighbors is the most eligible to receive and forward the message. This can be accomplished by using our protocol DSAP which is based on local information and also based on the idea of directional routing. Meaning that the source need to know the direction of the destination and it will forward to the best node that can forward the message toward the final destination.

1.2 Overview of Dissertation

In this dissertation, our primary focus has been on extending the life of the network from a local point of view. We addressed several fundamental problems. First, the relationship between power usage and the number of neighbors in a wireless sensor network. Second, which power aware metric will extend the life of the network. Third, do we need global information or is local information enough to choose the next hop. The answer to these problems will be discussed throughout the dissertation as follows:

In chapter 2, we present the related work and explain the problem statements in more detail. We also present the assumptions that are used throughout our simulations.

In chapter 3, we introduce the routing protocol Directional Source Aware Protocol (DSAP). DSAP is a power aware protocol that is based on the idea of Directional Value (DV), where the node needs only to know the direction of the destination. From the DV of the destination, the source decides which node of its neighbor will be the most eligible to receive the packet and forward it toward the destination. Every node that receives a packet should be closer to the destination if we use the DV as metric for routing.

In chapter 4, we study the relationship between power usage and the number of neighbors. The number of neighbors dictate which topology to use. In this chapter we answer the question of which topology is the most efficient to use if we have control over placing the nodes in wireless sensor networks? Or what is the optimal number of neighbors that can be used in a wireless sensor network?

In chapter 5, we introduce different power aware metrics that could be used to route the packet toward the destination. In order to extend the life of the network, power has to be a major factor in deciding the next hop. So we developed several techniques that will incorporate power as a metric for routing packets from source to destination. In this chapter, we analyze these metrics and show how each one will effect the number of hops and how much it extends the life of the network.

In chapter 6, we present an evaluation between the local routing and global routing. The use of local information for making routing decisions may not lead to an ideal path. The lack of global knowledge could result in the choice of less efficient paths or even paths that require significant backtracking to reach the destination. Despite the fact that routing based on global information is not practical, it provides a good basis for determining how efficientty routing based on only local information performs.

In chapter 7, we present an implementation of DSAP on the mote using the TinyOS operating system. This implementation will show how effective is the idea of directional routing.

In chapter 8, we briefly summarize the work contained in this dissertation. Future extensions to this work are also described.

Chapter 2

Background and Assumptions

2.1 Background

Much of the related research addresses WSN that are battery powered. Because of these requirements, most of the literature is concentrated on finding solutions at various levels of the communication protocol, including being extremely energy efficient. Energy efficiency is often gained by accepting a reduction in network performance (Patel, Chai, Yalamanchili, and Schimmel 1997). Although we do not wish to waste energy, our system does have a constant, renewable energy source. We are constrained, however, by a very low-power dissipation allowance, which fits nicely with an energy-efficient scheme. Popular power saving ideas include specialized nodes, negotiation, and data fusion, and are discussed below.

The literature review will be discussed with respect to three areas.

1. Study of the Topologies and Routing.
2. Power Aware from a local point of view.
3. Directional Routing.

2.1.1 Topology and Routing

Limited research has been conducted on the effect that topology has on wireless networking (Hu 1993; Ramanathan and Rosales-Hain 2000; Tang and Garcia-Luna-

Aceves 1999). The concentration, however, has been on mobile networks rather than ones with fixed node placement. While novel approaches have been thought of, none of them would be appropriate in the biomedical arena, for example, where a surgeon places the nodes, giving a nominally fixed topology. Although much research has been completed in the area of WSN, nothing has sufficiently answered the question of fixed topology's impact on low-power requirements.

Routing has been an active research area in the context of sensor networks. SPIN (Heinzelman, Kulik, and Balakrishnan 1999; Kulik, Heinzelman, and Balakrishnan 99), Directed Diffusion (Estrin, Govindan, Heidemann, and Kumar 1999; Intanagonwiwat, Govindan, and Estrin 2000), PEGASIS (Lindsey and Raghavendra 2002), and LEACH (Heinzelman, Chandrakasan, and Balakrishnan 2000; Heinzelman, Sinha, Wang, and Chandrakasan 2000) are four recent routing protocols for wireless sensor networks.

SPIN (Heinzelman, Kulik, and Balakrishnan 1999; Kulik, Heinzelman, and Balakrishnan 99) (Sensor Protocols for Information via Negotiation) is a unique set of protocols for energy-efficient communication among wireless sensors. The authors propose solutions to traditional wireless communication issues such as network implosion caused by flooding, overlapping transmission ranges, and power conservation. The SPIN protocols incorporate two key ideas to overcome implosion, overlap, and resource blindness: negotiation and resource-adaptation. Using very small meta-data packets to negotiate, SPIN efficiently communicates with fewer redundancies than traditional approaches, dealing with implosion and overlap. The meta-data is application specific, which means that we could use them to describe the amount of power dissipated, for instance. To solve the resource blindness issue, each node has an individual resource manager, allowing the node to limit activity when power is low.

SPIN (Heinzelman, Kulik, and Balakrishnan 1999; Kulik, Heinzelman, and Balakrishnan 99) also addresses the deficiencies of classic flooding by negotiation and resource adaptation. SPIN disseminates all the information at each node to every node in the network. This protocol makes use of the property that nearby nodes have similar data and thus distribute only the data that the other nodes don't have. This protocol works proactively and distributes the information all over the network, even when a user does not request any data.

LEACH (Heinzelman, Chandrakasan, and Balakrishnan 2000; Wang, Heinzelman, and Chandrakasan 1999) (Low-Energy Adaptive Clustering Hierarchy) is a new communication protocol that tries to evenly distribute the energy load among the network nodes by randomly rotating the clusterheads among the sensors. This assumes that we have a finite amount of power and aims at conserving as much as possible despite a dynamic network. LEACH uses localized coordination to enable scalability and robustness for dynamic networks, as well as data compression to reduce the amount of data that must be transmitted to a base station. Performing some calculations and using data fusion locally conserves much energy at each node. In LEACH, they suggest two schemes, distributed and centralized. Data collection is centralized and done periodically. This can be appropriate for constant monitoring of a network. The user may not always need the data. So, periodic data transmissions maybe unnecessary, which drains the limited energy from the sensors.

PEGASIS (Lindsey and Raghavendra 2002) is an optimization of LEACH (Heinzelman, Chandrakasan, and Balakrishnan 2000; Heinzelman, Sinha, Wang, and Chandrakasan 2000), PEGASIS uses a greedy algorithm to form clusters by assuming each node have a global view of the network. Each node communicates only with a close neighbor. Nodes take turns to transmit so that the average energy spent by each is reduced.

Directed Diffusion (Estrin, Govindan, Heidemann, and Kumar 1999; Intanagonwiwat, Govindan, and Estrin 2000) is a data-centric paradigm and is applied to query dissemination and processing. Each query is disseminated (flooded) throughout the network and gradients are set up to draw data satisfying the query toward the requesting node. More generally a gradient specifies an attribute value and a direction. Events start flowing toward the requesting node from multiple paths. A small number of paths can be reinforced to prevent flooding. This type of protocol is suited only for persistent queries where requesting nodes are expecting data that satisfy a query for some duration of time. This makes it unsuitable for historical or one-time queries, as it is not worth setting up gradients, etc. for queries that employ the path only once.

Design issues and trade-offs that need to be considered for power-constrained wireless sensor networks with low data rate links have also been studied (Pottie 1998). Pottie advocates, “aggressive power management at all levels,” noting that the communication protocol is more helpful in reducing the power consumption than optimizing the hardware is. Local processing of information is key to reducing the amount of communication between nodes, and hence, reducing the amount of power consumed by the network.

There has also been a useful comparison of multiple protocols used for wireless sensor networks (Chen, Sivalingam, and Agrawal 1999). Although the authors’ main focus is on energy efficiency due to battery power, they provide very useful guidelines for designing access protocols for wireless networks. Specifically, the authors recommend that “protocols should reduce the number of contentions to improve power conservation,” as well as using shorter packet lengths. The receiver usage time, however, tends to be higher for protocols that require the mobile nodes to sense the medium before attempting transmission.

2.1.2 Power Aware

Existing routing protocols can be classified into three categories: proactive, reactive, and a hybrid of the two. Proactive routing maintains routes to every other node in the network, thus a route can be provided immediately when requested. Regular routing updates impose large overhead, thus proactive routing is suitable for high traffic networks. Reactive routing maintains routes to only those nodes that are needed, in other words, on-demand. Each host computes routes for a specific destination only when necessary. Thus, the cost of finding routes is expensive since flooding is involved. This kind of protocol is good for low/medium traffic networks. Traditional reactive protocols find the best route and then always use that, but that is not the best solution. This kind of routing is not an efficient way of routing, since we want the protocol to be power aware and source aware. The third category maintains partial topology information for local hosts. Routing decisions are made either proactively or reactively.

In most routing protocols, the paths are computed based on minimizing hop count or delay. When the transmission power of nodes is adjustable, hop count may be replaced by a power consumption metric. Some nodes participate in routing packets for many source-destination pairs and the increased energy consumption may result in their failure. A longer path passing through nodes that have plenty of energy may be a better solution (Singh, Woo, and Raghavendra 1998).

Singh et al. (Singh, Woo, and Raghavendra 1998) propose several algorithms for power-aware routing in mobile ad hoc networks. The algorithms in (Singh, Woo, and Raghavendra 1998) propose to use a function, *f(A)*, to denote node A's reluctance to forward packets and to choose a path that minimizes the sum of *f(A)* for nodes on the path. This routing protocol (Singh, Woo, and Raghavendra 1998) addresses the issue of energy critical nodes. As a particular choice for *f*, (Singh, Woo, and Raghavendra 1998) propose *f(A)=1/g(A)*, where *g(A)* denotes the remaining lifetime of the node. The other metrics used in (Singh, Woo, and Raghavendra 1998) are aimed at minimizing the total energy consumed per packet. However, (Singh, Woo, and Raghavendra 1998) merely observe that the routes selected when using this metric will be identical to routes selected by shortest hop count routing, since the energy consumed in transmitting (receiving) one packet over one hop is considered constant.

In (Stojmenovic and Datta 2002) and (Stojmenovic and Lin 2001) the authors describe several localized routing algorithms that try to minimize the total energy per packet and/or lifetime of each node. The proposed routing algorithms are all demand-based. These methods use control messages to update the positions of all nodes to maintain the efficiency of the routing algorithms.

In other protocols (Akyildiz, Su, Sankarasubramaniam, and Cayirici 2002), they use the idea of minimizing the energy consumed per packet along the whole path. And others use the idea of minimizing the cost for all packets, also others use the idea of minimizing variance in node power levels. All of these are good to use but we have one problem with these metrics . The problem is that if we want to use these metrics we have to assume that every node must maintain the information of the whole network topology. Otherwise, we are impossible to select the optimal routes. But in sensor network, frequent topology updates will result in higher message overhead and the system can not afford so much energy to meet that.

We are using similar ideas that use power-aware routing but from a local view of the network without sending control messages to request information. Each neighbor will gather local information about each neighbor whenever there is communication with its neighbor and use this information to calculate the possible routes. By doing so the protocol limits the energy consumption because energy consumption occurs in three domains: sensing, data processing, and communication. Communication is the major consumer of energy in a WSN. Pottie and Kaiser (Pottie and Kaiser 2000) showed that communication costs significantly more than processing. So, it is possible to make trade-offs between data processing and wireless communication. Hence, local data processing is crucial in minimizing power consumption in a multihop wireless sensor network (Sohrabi, Gao, Ailawadhi, and Pottie 2000).

2.1.3 Directional Routing

Most of the above protocols are based on the idea of flooding, or improved flooding or using a centralized approach. The idea of directional routing is to eliminate any kind of flooding or overhead used in the routing. Instead base the bath on directional routing. Similar ideas were introduced in (Nath and Niculescu 2002). In (Nath and Niculescu 2002), the basic idea is to embed a trajectory in the packet and let the intermediate nodes forward the packet to those that lie more or less on this trajectory.

Here we present an idea similar to trajectory based routing, but based on the directional value of the destination. Each node receiving the packet obtains the destination directional value and computes the new direction according to the local information available from its neighbor and chooses the most suitable neighbor to forward the packet to the next neighbor.

2.2 Assumptions

In this dissertation we present the assumptions that have been used throughout the dissertation. These assumptions have been divided into two major areas. First, without the use of a base station, means to route the packets internally in the network from source to destination. Second, with a base station in consideration, so we have to route to nodes that are closer or have more power to transmit to the base station. For both of them we have used the same radio model.

2.2.1 Radio Model

In our work, we assume a simple model where the radio dissipates $\mathrm{E}_{elec} = 50\, nJ/bit$ to run the transmitter or receiver circuitry and $\mathrm{E}_{amp} = 100\, pJ/bit/m^2$ for the transmit amplifier to achieve an acceptable E_b/N_0 (see Figure 2.1 and Table 2.1) (Heinzelman, Chandrakasan, and Balakrishnan 2000). We also assume that the packet size is $k = 512$ bits.

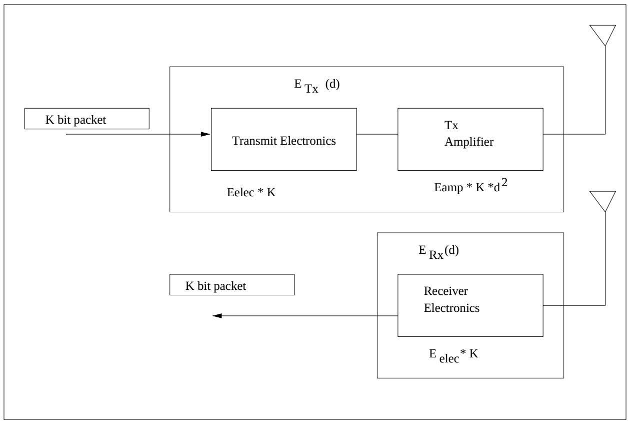


Figure 2.1: First Order Radio Model

Table 2.1: Radio Characteristic

Operation	Energy Dissipated
Transmitter Electronics (E$_{Tx-elec}$) Receiver Electronics (E$_{Rx-elec}$) (E$_{Tx-elec}$ = E$_{Rx-elec}$ = E$_{elec}$)	50 nJ/bit
Transmit Amplifier (E$_{amp}$)	100 $pJ/bit/m^2$

To transmit a k-bit message a distance d meters using this radio model, the radio expends:

$$\begin{aligned} E_{Tx}(k,d) &= E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \\ &= E_{elec} * k + E_{amp} * k * d^2 \end{aligned} \tag{2.1}$$

To receive this message, the radio expends:

$$\begin{aligned} E_{Rx}(k) &= E_{Rx-elec}(k) \\ &= E_{elec} * k \end{aligned} \tag{2.2}$$

2.2.2 Number of Nodes

Two sets of nodes were used, first 36 nodes for the theoretical study and deriving equations in the study of topologies. And because it works nicely for 2D and 3D networks with the different topologies we consider. This also represents an intermediate value between 16 and 64 node networks, which have been used in other studies (Patel, Chai, Yalamanchili, and Schimmel 1997). Secondly, we used a set 100 nodes for the simulations to show or explain the simulation results.

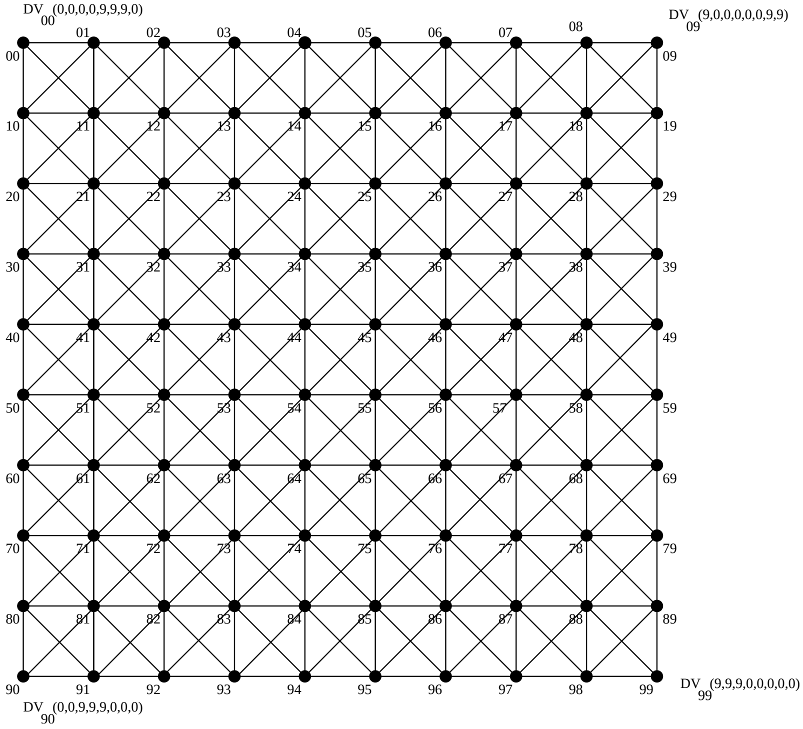


Figure 2.2: 10 × 10 2D Topology with up to 8 Neighbors

2.2.3 Distance Between Nodes

For simplicity of calculation we will assume for local routing between nodes that the transmission range of neighboring nodes is equal to each other on the condition that the value of this transmission range should reach the number of neighbors that is allowed for each network (maximum number of neighbors). Also assume that all data packets contain the same number of bits. So we assume a maximum distance $d = 15$m. The topology that we are going to evaluate is a 10×10 2D mesh with a maximum of 8 neighbors (Figure 2.2).

On the other hand we assume that each node will increase its transmission range beyond the 15 m if needed to transmit to the base station. When we assume the existence of the base station, we will assume that the whole topology falls in a grid of $200m \times 200m$, the first node is located at position (x=55, y=55), and the base station is located at position (x=0, y=100) with a transmission range of 90m.

Each sensor in the network knows its position with respect to the network. The location of each node will be determined by using the directional value system. The base station will have a fixed position. The Base Station (BS) will broadcast to the network, so nodes can know how to adjust their transmission range to transmit to the BS.

For these parameter values, receiving a message is not a low-cost operation; the protocol should thus try to minimize not only the transmit distance but also the number of transmit and receive operations for each message. Next we will present the general equations that can be used to estimate the total power used to transmit a message from source to destination.

2.3 Problem Statement

Wireless sensor networks typically have power constraints. The small size and absence of wires implies the lack of an external power supply such as battery packs. Although photovoltaic or other passive energy gathering techniques are possible, these approaches typically provide only a modest amount of operating power. Therefore it is necessary to extend the battery life of individual sensors so that the network can remain functional as long as possible.

Due to the limited power that nodes have, we restrict the routing to the local information available to the nodes from their neighbors only. Consider the following network scenario where

- All sensor nodes are identical and have the same limited energy capacity.
- Each sensor knows the location of its nearest neighbors with whom it can communicate.
- Each sensor knows the power available at each neighbor.
- Each sensor knows the direction in which to send the message.

From this scenario we want to design protocols that will increase the life of the nodes as well as the overall network. In order to do that we need to consider three points in resolving this problem:

1. Local Information.
2. Topology.
3. Power Awareness.

The first problem is to develop a protocol that can be used to route a message from a source to a destination with the aid of local information only. The idea is to evaluate the routing according to this local information without the aid of global information.

The second problem is to answer this question: what is the best topology for a fixed wireless network of sensors. The answer to this question will lead to the optimal number of neighbor that a node can choose in order to conserve power, whether this optimal number is for broadcasting or for gathering information from the neighbors.

The final problem is that we need to design a protocol that can take the power available at the neighbors in consideration when implementing the routing. In other words, the need to make the routing protocol power-aware from a local point-of-view.

In the next chapter we will address the design of the Directional Source Aware Protocol (DSAP). This protocol will address the issue of local information and the power aware.

Chapter 3

Directional Source Aware routing Protocol (DSAP)

3.1 Introduction

One of the challenges of designing a routing protocol for wireless sensor networks is how to find the final destination and which path to take that will be the most reliable path to deliver the packets without retransmitting or discovering a new path. Most of the existing routing protocols can be classified into three categories: proactive, reactive, and a hybrid of the two. Proactive routing maintains routes to every other node in the network, thus a route can be provided immediately when requested. Regular routing updates impose large overhead, thus proactive is suitable for high traffic networks. Reactive routing maintains routes to only those nodes that are needed, in other words on-demand. Each host computes routes for a specific destination only when necessary. Thus, the cost of finding routes is expensive, since flooding is involved. This kind of protocol is good for low/medium traffic networks. Traditional reactive protocols find the best route and then always use that route, but that is not the best solution for a wireless sensor network. This kind of routing is not an efficient way of routing, since we want the protocol to be power aware and source aware. The third category maintains partial topology information of local hosts. Routing decisions are made either proactively or reactively.

In order to overcome these problems of routing and maintaining efficient routes, we have developed a routing protocol that depends on the local information that is available from the neighbors of the transmitting node. The idea is to collect the information from the neighbors and based on this information, the routing protocol decides which neighbor should receive the packet. The protocol that we have developed is based on the idea of *directional routing*.

In *directional routing* each node needs to know the direction of the destination so it can forward the packet in that direction. All the node has to do is forward the packet to the nearest neighbor that will be capable of transmitting the packet one hop closer to the final destination. Then the responsibility will be on the new node to find one of its neighbors that can forward the packet toward the final destination.

In the next section we will introduce the Directional Value (DV) system and explain how the DV will help in solving the problems of routing and maintaining the paths to forward the packets.

3.2 Directional Value (DV)

In order to resolve the problem of routing we have developed a unique identification system for the networks that we are using. The idea behind this identification system is to identify the location of each node in the network, which will help in the routing of the packets. The system has the following properties:

- Each node has a unique ID.
- Each ID gives how far the node is from the network perimeter in each direction.
- Each node can compute the relative direction of another node from its ID.

To construct the directional value, each node in each topology that has been used has a fixed number of neighbors. Each neighbor represents a direction that the node can route through it, as shown in figure 3.1. How far the node is from the edge of the network in each direction represents the directional value of each node. This number is unique for each node and can be used as the ID number for each node for the purposes of routing.

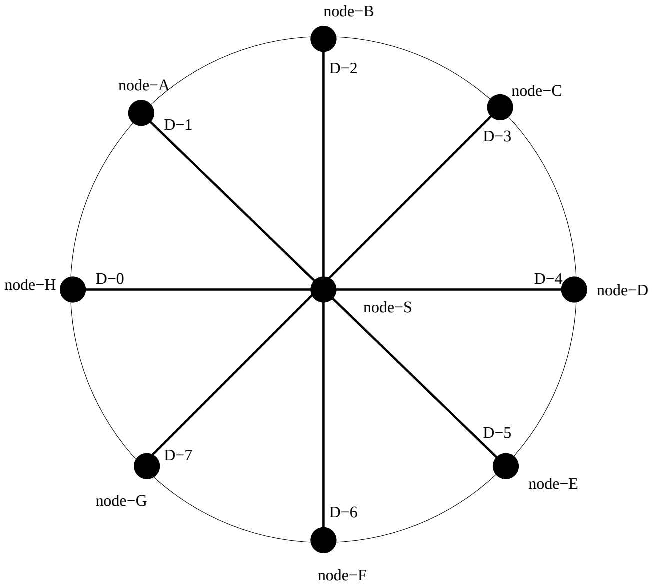


Figure 3.1: Directional 8 Neighbor node

Each topology was constructed from figure 3.1 by eliminating the directions that are not used in that topology. For example, constructing a 7 neighbor topology from a 8 neighbor is done by eliminating $D-7$ in one node and also eliminating the corresponding direction from the other node. Each direction has a corresponding or an associate direction. $D-7$ has $D-3$, $D-6$ has $D-2$, $D-5$ has $D-1$, $D-4$ has $D-0$, and vice versa.

In figure 3.1, node S would have an identifier of $(DV_0, DV_1, DV_2, DV_3, DV_4, DV_5, DV_6, DV_7)$. This means that there are DV_0 nodes to the edge in direction D-0, DV_1 in D-1, DV_2 in D-2, and so on. This figure is a logical representation of the networks that will be used in this dissertation. Figure 3.2 shows the possible number of neighbors that can be created from figure 3.1.

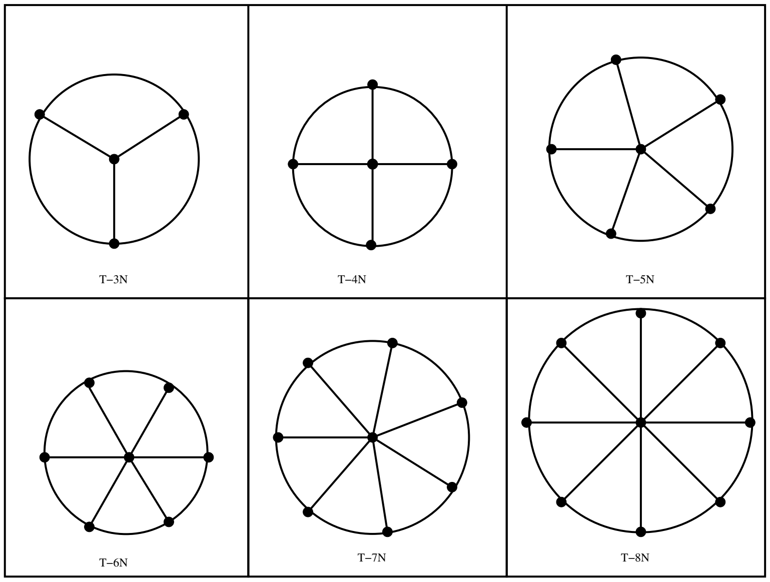


Figure 3.2: Possible number of Neighbors

For instance, in the four-neighbor case of Figure 3.3, node 31 would have an identifier of $(1, 0, 3, 0, 4, 0, 2)$. This means that there is 1 node to the edge in direction 0 (left), 3 in direction 2 (up), 4 in direction 4 (right), and 2 in direction 6 (down). Since we have control over the placement of the nodes, as well as a fixed topology, we can hard-code this information into each node with relative ease. But, if we have a random topology then we have to discover the directional values of each node in the network.

From this directional value we have developed a Directional Source-Aware routing Protocol (DSAP) (Salhieh, Weinmann, Kochhal, and Schwiebert 2001). In the next section we explain the basic scheme behind DSAP (Salhieh, Weinmann, Kochhal, and Schwiebert 2001) and how DSAP (Salhieh, Weinmann, Kochhal, and Schwiebert 2001) can incorporate power into its routing scheme.

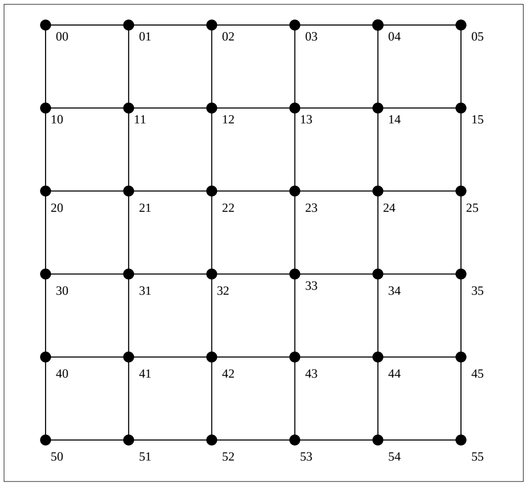


Figure 3.3: 2D Topology with up to 4 Neighbors

3.3 Algorithm of DSAP

In this section we will introduce two algorithms for DSAP. The first one deals with the directional value as a metric to be used to find the final destination. The second one uses the directional value and a power aware metric to route the packet to the final destination. Later we will show the difference between using these two methods and also introduce some other power aware routing metrics that can improve the routing and extend the life of the network.

As shown in the algorithm of DSAP in figure 3.5 when transmitting a message, the destination node identifier is subtracted from the source node identifier. This yields at most five nonnegative numbers (for a 2D topology with 8 neighbors) that describe in which way the message needs to move. Negative numbers are ignored. The decision to move in any positive direction is determined by the *directional value* of the nodes in question. Taking each of the neighbor's identifiers and subtracting them from the destination node's identifier computes the directional value (DV). These eight directional numbers are added together and the one with the smallest total is chosen. If both nodes have the same DV, then one is picked randomly. This is the basic scheme developed for routing the messages.

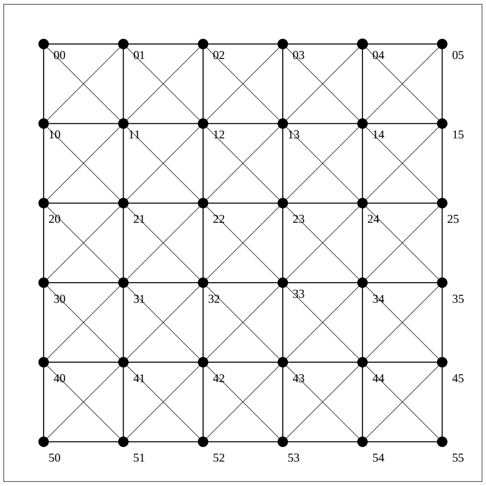


Figure 3.4: 2D Topology with up to 8 Neighbors

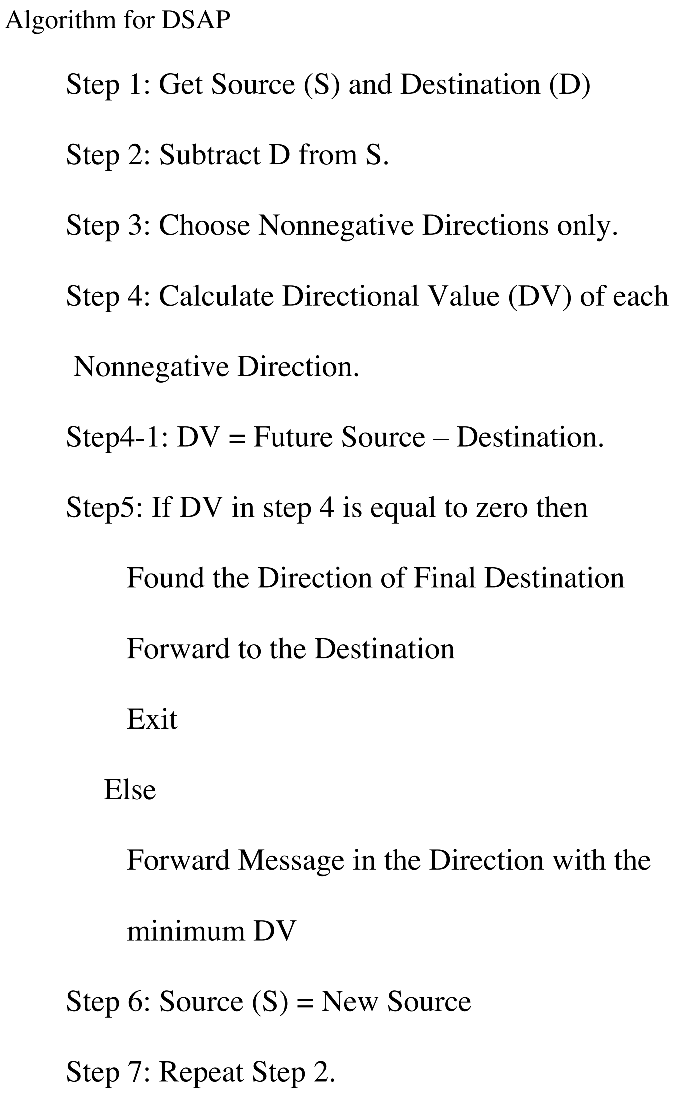
For example, in figure 3.4, consider the source node S_{11} with DV_{11}=$(1, 1, 1, 1, 4, 4, 4, 1)$ and destination node D_{44} with DV_{44}=$(4, 4, 4, 1, 1, 1, 1, 1)$. According to the algorithm of DSAP (Salhieh, Weinmann, Kochhal, and Schwiebert 2001), S-D = $(-3, -3, -3, 0, 3, 3, 3, 0)$, which produces D-3, D-4, D-5, D-6, and D-7 as possible nonnegative directions that the message can be forwarded to, then computes the directional value of each nonnegative direction to find which route to take. By doing so, we get the following values for each direction: 20, 17, 14, 16, and 20, respectively. By choosing the minimum directional value, the message is forwarded in direction D-5, which is obvious from figure 3.4. Then the protocol repeats until reaching the final destination, which will have a DV of 0.

This is the basic scheme developed for routing messages. However, the objective is to incorporate energy efficiency as well. This is achieved by considering the maximum available power and minimal directional value when picking which node route to take. Instead of simply picking the node with the lowest directional value, the directional value is divided by the power available at that node. The smallest value of this power-constrained directional value is the path that is chosen. This allows for a least-transmission path that is also cognizant of power resources, although in some cases a longer path may be chosen if the available power dictates that choice.

In (Salhieh and Schwiebert 2002) the authors presented several power aware metrics that can be incorporated with DSAP. The idea in this chapter is to show that using power aware methods will extend the life of the network and yield a fair load balance among the nodes. In chapter 5 we study and analyze different power aware methods that can be incorporated into DSAP as a routing mechanism. These methods are as follows:

1. Power Only.
2. Directional Value Only.
3. Directional Value and Power.
4. Directional Value and Sum of Power.
5. Number of Hops Only.
6. Hop and Cost.
7. Hop, Cost, Directional Value, and Sum of Power.

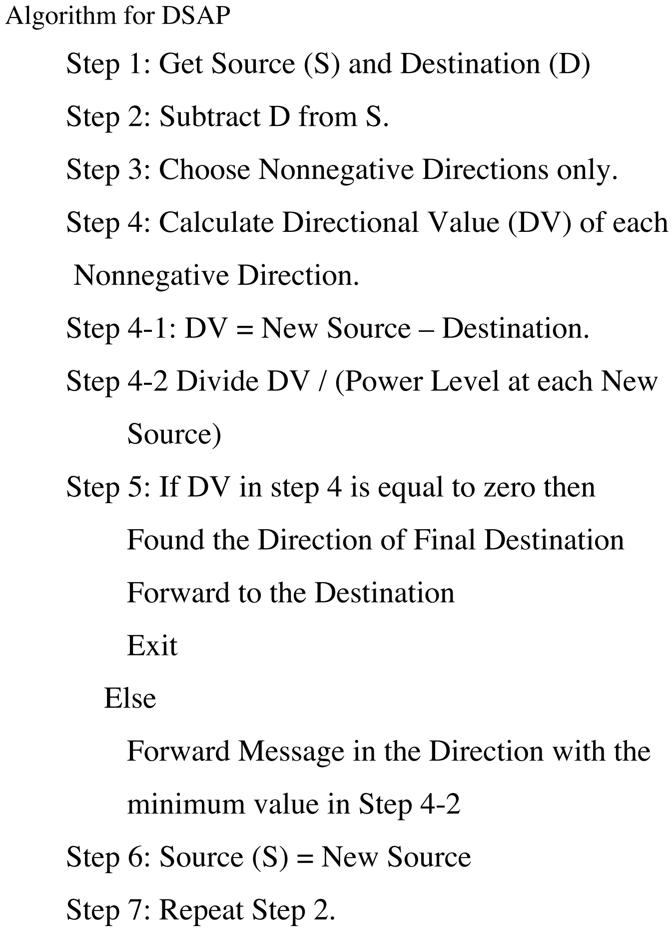
Studying these methods will show the effect of using some kind of power aware metric rather than using only shortest path metrics.



Algorithm for DSAP

```
Step 1: Get Source (S) and Destination (D)
Step 2: Subtract D from S.
Step 3: Choose Nonnegative Directions only.
Step 4: Calculate Directional Value (DV) of each
 Nonnegative Direction.
Step4-1: DV = Future Source – Destination.
Step5: If DV in step 4 is equal to zero then
        Found the Direction of Final Destination
        Forward to the Destination
        Exit
     Else
        Forward Message in the Direction with the
        minimum DV
Step 6: Source (S) = New Source
Step 7: Repeat Step 2.
```

Figure 3.5: Algorithm for DSAP



```
Algorithm for DSAP
    Step 1: Get Source (S) and Destination (D)
    Step 2: Subtract D from S.
    Step 3: Choose Nonnegative Directions only.
    Step 4: Calculate Directional Value (DV) of each
     Nonnegative Direction.
    Step 4-1: DV = New Source – Destination.
    Step 4-2 Divide DV / (Power Level at each New
        Source)
    Step 5: If DV in step 4 is equal to zero then
        Found the Direction of Final Destination
        Forward to the Destination
        Exit
      Else
        Forward Message in the Direction with the
        minimum value in Step 4-2
    Step 6: Source (S) = New Source
    Step 7: Repeat Step 2.
```

Figure 3.6: Algorithm for DSAP Power Aware

Chapter 4

Power Efficient Topologies for WSN

4.1 Introduction

In this chapter, we will examine the relationship between power usage and the number of neighbors in a wireless sensor network. The study of wireless network topology must be approached from a different point of view than for wired networks. In a wired network, we examine how nodes are physically connected and the resulting available routing paths. In a WSN, the definition of the network topology is derived from the physical neighborhood and transmission power, so we must determine which topology gives the optimal number of neighbors that a node can handle to transmit to or receive from. Many of the topologies proposed for wired networks cannot be used for wireless networks, for in wired networks, a higher dimension can be implemented by connecting the nodes in some fashion to simulate higher dimensions. In WSN, however, we are dealing with three dimensions in the physical world and are thus restricted in our choice of topologies. Therefore, we concentrate on 2D and 3D mesh topologies.

In this chapter, we are analyzing the performance issues associated with different network topologies. The question we are seeking to answer is what is the best topology for a wireless network of sensors, assuming we can control the placement of these sensors and the sensor locations are fixed relative to each other. Since we assume control over the placement of these sensing nodes and do not require mobility of the sensors relative to each other, the research problem changes. Instead of considering self-organization of the sensor nodes into a network, we address efficient placement of fixed nodes.

Some of these networks can be installed in a building to monitor the building or in an assembly plant, where the use of regular topologies will have advantages over random deployments. In a fixed topology we can place the nodes so they can give better coverage. A node also functions as a router and can relay messages for its neighbors. Also the use of regular topology or mesh topologies offers multiple redundant communications paths throughout the network. If one node dies or fails, other nodes can be used to reroute the message. Thus, regular topologies enhance the overall reliability of the network.

In this chapter, we do not consider the effects of communication with a base station. Since the topology is fixed and known, we assume that the base station can be placed at an appropriate place for each topology. Thus, the power requirements for communicating with the base station should be essentially independent of the topology. This enables us to concentrate on the effects of the topology on the communication among the network nodes only.

4.2 Issues for Topology Design

In this section, we are analyzing the performance issues associated with different network topologies. Unlike previous studies of these issues, mobility is not an issue. The question we are seeking to answer is, what is the best topology for a wireless network of sensors, assuming we can control the placement of these sensors and the sensor locations are fixed relative to each other? One factor in the choice of topology is the amount of contention for the wireless media. The level of contention will vary with the application, since the message pattern and overall message generation rate are functions of the application. However, our study should provide some insights that can be used along with knowledge of the application to select an appropriate topology. Again, the goal is not to find a single topology that is appropriate for all applications, but rather provide a structured analysis of the options and give guidance on the best choices so that a more informed decision is possible.

Next we will define the different topologies that will be used in this chapter. Each of these topologies will be considered as a grid of nodes either in two or three dimensions. The vertices of this grid are the nodes that will transmit the packets and the edges are the neighbors of each node that will receive the transmissions. According to the mesh topologies that will be used in this section we can find the optimal path between a source (S) and a destination (D) or the shortest path between them. We will introduce this optimal path and use it later to show how much power is used in the network using each topology to send a packet from S to D.

The Wireless Sensor Network, WSN(m,n), is an $m \times n$ grid, where $m \times n$ represents the number of nodes in the network. Each node is represented as (y, x), for $0 \leq y \leq m-1$ and $0 \leq x \leq n-1$. For each of the topologies we will assume the following:

- $S = (y_s, x_s)$
- $D = (y_d, x_d)$
- $\triangle y = \|y_s - y_d\|$
- $\triangle x = \|x_s - x_d\|$

Each network will be defined by identifying the neighbors of each node according to the different number of neighbors as shown in figure 4.1 and presenting the optimal number of hops from a source to a destination. Next we will define how to identify if two nodes are neighbors and what is the optimal number of hops between a source and a destination for each topology.

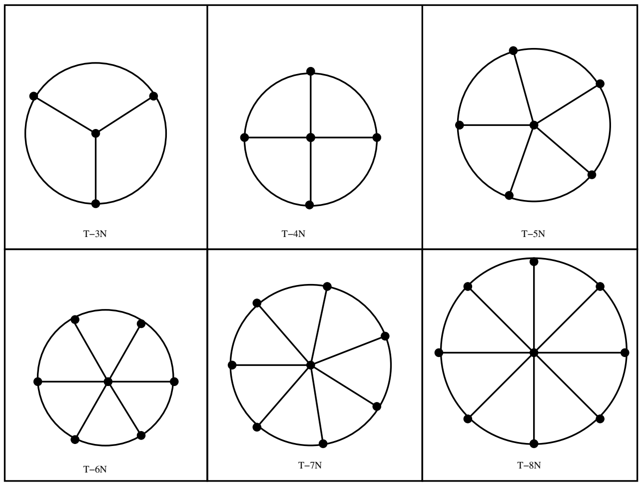


Figure 4.1: Possible Number of Neighbors

4.2.1 Three Neighbors WSN

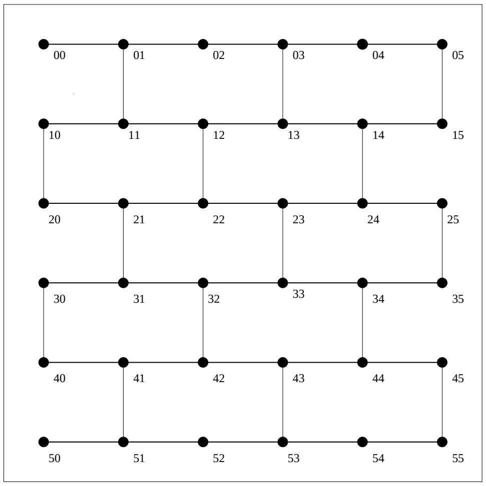


Figure 4.2: 2D Topology with up to 3 Neighbors

According to figure 4.2 we note the following:

1. Two nodes are neighbors if:
    - $\langle (y, x), (y, x + 1) \rangle$ for $x < n - 1$
    - $\langle (y, x), (y + 1, x) \rangle$ for even (y, x) and $y < m - 1$
2. Two nodes are not neighbors if $\langle (y, x), (y + 1, x) \rangle$ for odd (y, x) and $y < m - 1$

3. Optimal Number of hops (s, d) = $\begin{cases} \triangle x + \triangle y & \text{if } \triangle x \geqslant \triangle y \\ 2\triangle y \pm 1 & \text{if } \triangle x < \triangle y \end{cases}$

4.2.2 Four Neighbors WSN

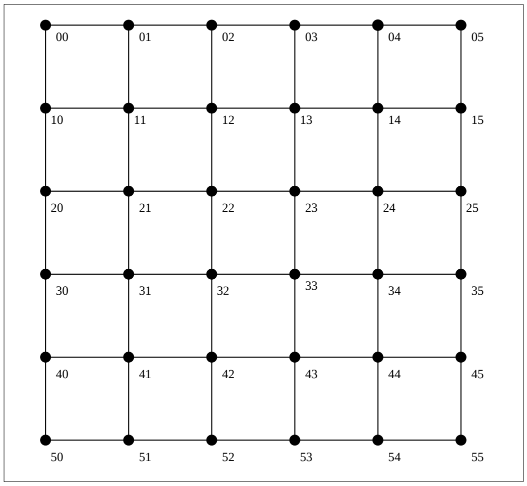


Figure 4.3: 2D Topology with up to 4 Neighbors

According to figure 4.3 note the following:

1. Two nodes are neighbors if:
    - $\langle (y, x), (y, x+1) \rangle$ for $x < n-1$
    - $\langle (y, x), (y+1, x) \rangle$ for $y < m-1$
2. Optimal Number of hops (s, d) = $\triangle x + \triangle y$

4.2.3 Five Neighbors WSN

According to figure 4.4 note the following:

1. Two nodes are neighbors if:
    - $\langle (y, x), (y, x+1) \rangle$ for $x < n-1$
    - $\langle (y, x), (y+1, x) \rangle$ for $y < m-1$

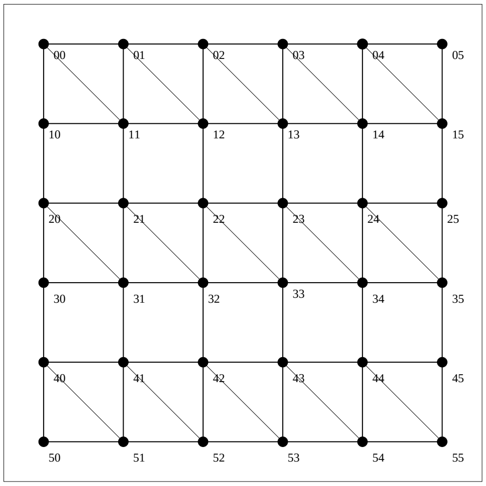


Figure 4.4: 2D Topology with up to 5 Neighbors

- $\langle (y, x), (y+1, x+1) \rangle$ for even x.
- $\langle (y, x), (y-1, x-1) \rangle$ for odd x.

2. Optimal Number of hops (s, d) $= \begin{cases} \triangle x + 2 & \text{if } x_s \geqslant x_d \text{ and } y_s > y_d \\ & \text{or } x_s \leqslant x_d \text{ and } y_s < y_d \\ \triangle x + \triangle y & \text{Otherwise} \end{cases}$

4.2.4 Six Neighbors WSN

According to figure 4.5 note the following:

1. Two nodes are neighbors if:

- $\langle (y, x), (y, x+1) \rangle$ for $x < n-1$
- $\langle (y, x), (y+1, x) \rangle$ for $y < m-1$
- $\langle (y, x), (y+1, x+1) \rangle$ for every $y < y+1$ and $x < x+1$
- $\langle (y, x), (y-1, x-1) \rangle$ for every $y < y-1$ and $x < x-1$

2. Optimal Number of hops (s, d) $= \begin{cases} \triangle x + \triangle y & \text{if } x_s > x_d \text{ and } y_s < y_d \\ & \text{or } x_s < x_d \text{ and } y_s > y_d \\ \max(\triangle x, \triangle y) & \text{Otherwise} \end{cases}$

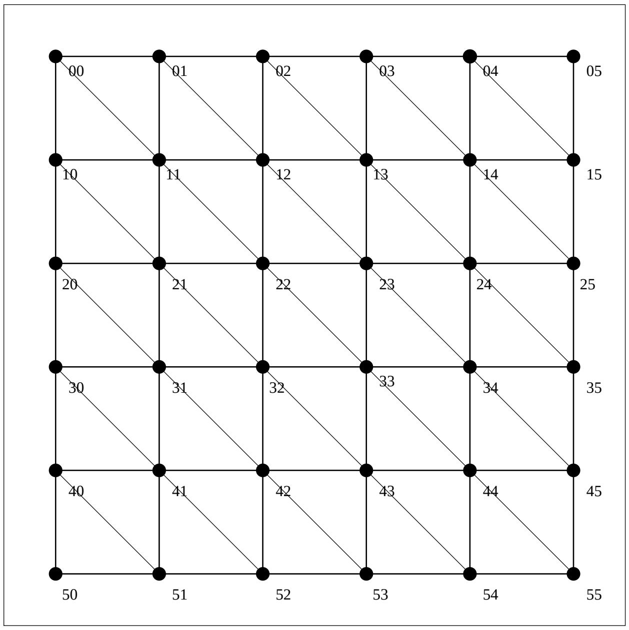


Figure 4.5: 2D Topology with up to 6 Neighbors

4.2.5 Seven Neighbors WSN

According to figure 4.6 note the following:

1. Two nodes are neighbors if:
    - $\langle (y, x), (y, x+1) \rangle$ for $x < n-1$
    - $\langle (y, x), (y+1, x) \rangle$ for $y < m-1$
    - $\langle (y, x), (y+1, x-1) \rangle$ for $x = 0$ or x is even.
    - $\langle (y, x), (y-1, x+1) \rangle$ for $x = 1$ or x is odd.
    - $\langle (y, x), (y+1, x+1) \rangle$ for every $y < y+1$ and $x < x+1$
    - $\langle (y, x), (y-1, x-1) \rangle$ for every $y < y-1$ and $x < x-1$
2. Optimal Number of hops (s, d) = $\begin{cases} \triangle x + 2 & \text{if } x_s > x_d \text{ and } y_s < y_d \\ & \text{or } x_s < x_d \text{ and } y_s > y_d \\ \max(\triangle x, \triangle y) & \text{Otherwise} \end{cases}$

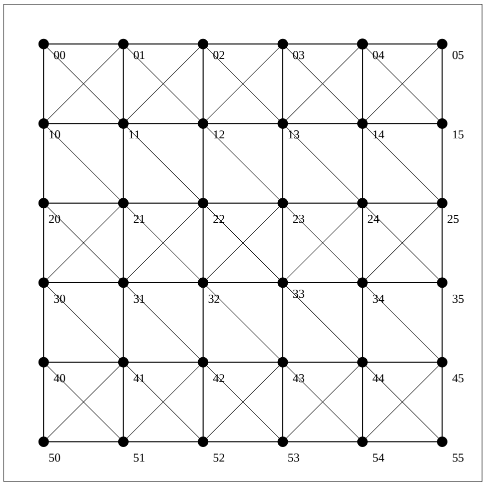


Figure 4.6: 2D Topology with up to 7 Neighbors

4.2.6 Eight Neighbors WSN

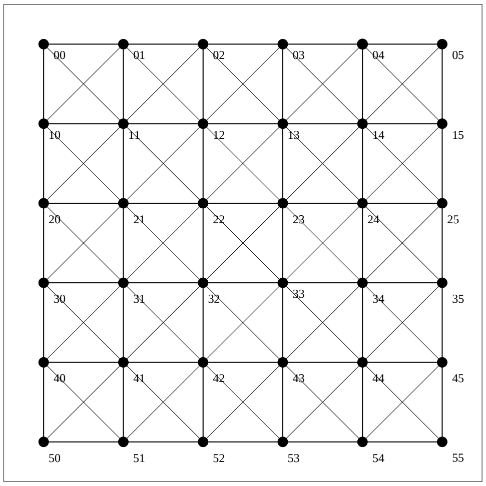


Figure 4.7: 2D Topology with up to 8 Neighbors

According to figure 4.7 note the following:

1. Two nodes are neighbors if:

    - $\langle (y, x), (y, x+1) \rangle$
    - $\langle (y, x), (y+1, x) \rangle$
    - $\langle (y, x), (y+1, x-1) \rangle$

- $\langle (y, x), (y-1, x+1) \rangle$
- $\langle (y, x), (y+1, x+1) \rangle$
- $\langle (y, x), (y-1, x-1) \rangle$

2. Optimal Number of hops (s, d) = $\max(\triangle x, \triangle y)$

4.2.7 Six Neighbors for 3D

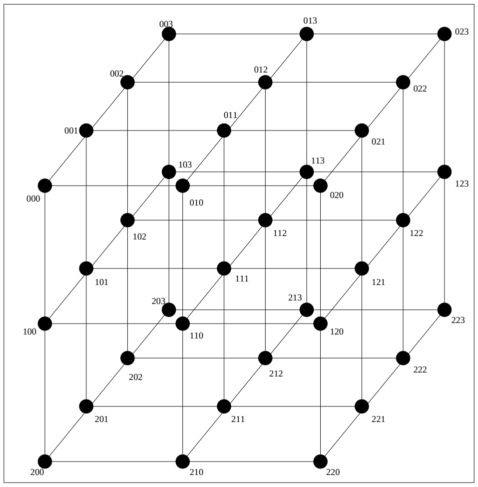


Figure 4.8: 3D Topology with up to 6 Neighbors

The WSN(m, n, k) is an $m \times n \times k$ grid where a node is represented as (y, x, z) for $0 \leq y \leq m-1$, $0 \leq x \leq n-1$, and $0 \leq z \leq k-1$.

For 3D topology assume the following:

- $S_{3D} = (y_s, x_s, z_s)$
- $D_{3D} = (y_d, x_d, z_d)$
- $\triangle y = \|y_s - y_d\|$
- $\triangle x = \|x_s - x_d\|$
- $\triangle z = \|z_s - z_d\|$

Two nodes are neighbors if:

- $\langle(y, x, z), (y, x+1, z)\rangle$ for $x < n-1$
- $\langle(y, x, z), (y, x-1, z)\rangle$ for $x < n-1$
- $\langle(y, x, z), (y+1, x, z)\rangle$ for $y < m-1$
- $\langle(y, x, z), (y-1, x, z)\rangle$ for $y < m-1$
- $\langle(y, x, z), (y, x, z+1)\rangle$ for $z < k-1$
- $\langle(y, x, z), (y, x, z-1)\rangle$ for $z < k-1$

Optimal Number of hops $(s_{3D}, d_{3D}) = \triangle x + \triangle y + \triangle z$

4.3 Analysis of Power Usage

Various network topologies are studied. First, the routing is considered over the diameter of the network and two possible routes are used - along the edge and through the interior. These results show that different paths consume different amounts of power. Next we consider shortest path routing for the various topologies for a message spanning the diameter of the network. Finally, we simulate DSAP with and without power-aware routing of arbitrary source-destination pairs and show the relative performance of each.

We are going to analyze the power dissipated with respect to the network topology with a variable number of neighbors. We consider first two-dimensional networks with three, four, five, six, seven, and eight neighbors. Second, we consider three-dimensional networks with six neighbors. For each of the topologies we consider two kinds of routing:

1. Edge Routing.

2. Interior Routing.

Edge routing consists of moving messages to the outer edges of the network where there are fewer neighbors. Interior routing keeps the messages in the middle of the network, where there is a consistent number of neighbors for each node. In some cases, longer paths are chosen for some topologies to give a similar number of transmissions. The use of these two methods of routing is only to show the effect of using topologies with different number of neighbors. It also shows how useful it is to increase the number of neighbors. Then we study shortest path routing to see which topology will give the most savings in power. The shortest path will be considered by using the DSAP routing protocol, and also to study the benefit of using a power aware routing metric by using Aware–DSAP.

4.3.1 Two Dimensional Analysis

The Degree of Routing Freedom is the number of alternative paths that a routing protocol can select. Figures 4.2 – 4.7 show that as the number of neighbors increases, the degree of routing freedom increases. For comparison purposes, we fixed the source ($S(0,0)$), destination ($D(5,5)$), and number of nodes to be the same (36 nodes) for all the networks under investigation. An analysis of these networks requires one to classify the routing paths into edge routes and interior routes.

Interior Routing

As defined before, interior routing keeps the messages in the middle of the network, where there is a consistent number of neighbors for each node. From table 4.1 we notice that as the number of neighbors increases the number of transmissions decreases but the number of receptions depends on the topology. This is because as we increase the number of neighbors the routing protocol has more freedom to choose the shortest

Table 4.1: Interior Routing, 2D

Neighbors	T_x	R_x	Energy Used
3	10	27	10.624×10^{-4}
4	10	36	12.928×10^{-4}
5	7	36	11.172×10^{-4}
6	5	27	8.768×10^{-4}
7	5	31	9.792×10^{-4}
8	5	36	10.720×10^{-4}

Table 4.2: Edge Routing, 2D

Neighbors	T_x	R_x	Energy Used
3	14	33	13.645×10^{-4}
4	10	28	10.880×10^{-4}
5	10	37	13.184×10^{-4}
6	10	39	13.696×10^{-4}
7	10	44	14.976×10^{-4}
8	10	46	15.488×10^{-4}

path to the destination and by doing so the protocol will dissipate less power to route a packet from source to destination.

Edge Routing

Using edge routing is to route the packet using only the edge nodes. This strategy of routing is, of course, impossible to use at all times. But here we use it to study the effect of increasing the number of neighbors with respect to the edge nodes. As shown in table 4.2, we see that as the number of neighbors increases the number of neighbors that receive the packet increases, and this will increase the energy used in the network.

Table 4.3: Fixed Number of Hops, 2D

Neighbors	T_x	R_x	Energy Used
3	10	27	10.624×10^{-4}
4	10	36	12.928×10^{-4}
5	10	45	15.232×10^{-4}
6	10	53	17.280×10^{-4}
7	10	61	19.328×10^{-4}
8	10	69	21.376×10^{-4}

Edge Routing vs. Interior Routing

From tables 4.1 and 4.2, edge routing dissipates more power than interior routing in all cases except for 4 neighbors. This is because the path from the source to the destination in a four neighbor topology is the same but the difference is that taking the edge results in fewer neighbors and interior paths have more neighbors. With either routing strategy, as the number of neighbors increases the power dissipated increases for the same number of transmissions.

Fixed Number of Transmissions

In this section we want to study the effect of increasing the number of neighbors. In order to do this we fix the number of transmissions that a certain path can have and also fix certain nodes that a path has to pass through. These fixed nodes are the nodes that fall on the diagonal of the network, like nodes $(1, 1)$, $(2, 2)$, $(3, 3)$, $(4, 4)$, and $(5, 5)$. By using this route we can control the path and study the effect of increasing the number of neighbors. As shown in table 4.3, as the number of neighbors increases the number of receptions also increases. This yields an increase in the energy used in the network.

Table 4.4: Routing Freedom and Power Dissipation; 3 and 6 Neighbors

Neighbors	T_x	R_x	Energy Used
3	10	27	$10.624 \times 10{-}4$
6	5	27	$8.768 \times 10{-}4$

Table 4.5: Routing Freedom and Power Dissipation; 4 and 8 Neighbors

Neighbors	T_x	R_x	Energy Used
4	10	36	12.928×10^{-4}
8	5	36	10.720×10^{-4}

Routing Freedom

We mean by routing freedom that the routing protocol has the freedom to choose an alternative path. In this section we study the effect of doubling the number of neighbors between 3 and 6 neighbors, and between 4 and 8 neighbors to study the effect of increasing the number of neighbors and how it will effect the routing freedom.

In Table 4.4, we consider the power dissipated between the source and destination for a message spanning the diameter of the network for topologies with 3 and 6 neighbors as shown in Figures 4.2 and 4.5.

As we can see from Table 4.4, increasing the number of neighbors decreases the number of transmissions and the total power dissipated in the system. This result can only be attributed to the availability of a shorter path between the source and destination. A similar conclusion can be reached from Table 4.5.

In summary, there is a trade-off between the number of neighbors and the total power dissipated in the system. However, this trade-off breaks in special cases where the availability of alternative shortest paths can be used as an advantage for the power budget calculations.

Table 4.6: Edge and Interior Routing Power Dissipation

Network	Path	T_x	R_x	Energy Used $\times 10^{-4}$
2D 4 Neighbor	Interior	10	36	12.928
	Edge	10	28	10.880
3D 6 Neighbor	Interior	7	33	11.046
	Edge	7	25	8.998

4.3.2 Three Dimensional Analysis

A three-dimensional network can be constructed from a two-dimensional network with four neighbors just by adding another dimension and that will create a 3-dimensional network with six neighbors. The same thing can be done for two-dimensional networks with six neighbors, but implementing such a network with a regular structure is not possible. Figure 4.8 shows a three-dimensional network with six neighbors, which has some advantages due to its inherent symmetry.

In a three dimensional network, the routing paths between any given source and destination without misrouting would always result in the same number of transmissions but a different number of receptions. For example, from source (0,0,0) to destination (2,2,3), the number of transmissions using either interior or edge routing is constant and equals 7 in Figure 4.8.

From table 4.6, we can conclude the following:

1. Edge routing in the case of the 3D network has lower power dissipation than interior routing does.
2. The number of transmissions and receptions, and the total power dissipated in a three dimensional network is less than a two dimensional network for edge routing as well as interior routing.

For table 4.7 we fixed the number of neighbors to study the effect of using two different dimensions on the number of transmissions each path will require using

Table 4.7: Six Neighbors for 2D and 3D Routing Power Dissipation

Network	Path	T$_x$	R$_x$	Energy Used $\times 10^{-4}$
2D 6 Neighbor	Interior	5	27	8.768
	Edge	10	39	13.696
3D 6 Neighbor	Interior	7	33	11.046
	Edge	7	25	8.998

edge routing and interior routing. We notice using interior routing that 2D with six neighbors has fewer transmissions than the 3D with six neighbors. Also from the nature of the 2D topology, using edge routing takes longer paths than 3D and this is because the 3D topology makes the diameter smaller than the 2D case. So, there is a trade-off between using edge routing and using interior routing for the two different dimensions.

4.4 The DSAP Analysis

To study the relationship between the number of neighbors and the power dissipated in the network, we use a controlled environment. This has been done to study the effect of increasing the number of neighbors on the power dissipated in the network. The effect of increasing or decreasing the number of neighbors is studied from two viewpoints. First, study the power usage in the network. Second, by studying which topology or number of neighbors will extend the life of the network, since extending the life of the network is one of the main objectives of designing wireless sensor network protocols.

In the simulation we have used two different methods for routing. First, DSAP without the power aware metric, which is based on the shortest number of hops between a source and a destination. Second, DSAP with a power aware metric, which incorporates the power available at the next neighbor and tries to balance the load among the neighbors of a source.

In the simulation we have two runs. First, a fixed run from $S(0,0)$ to $D(5,5)$. Second, a run where each node sends a message to every other node in the network. Both of these should help in studying the relationship between the power usage in the system and the number of neighbors. In the tables we have used the following abbreviations:

- T R means the total number of packets received by the neighbors of a source.
- T T means the total number of transmissions in the network.
- T P A means the total power available for the network.
- T P R means the total power used receiving these packets by the neighbors of a transmitting source.
- T P T means the total power used for transmitting these packets.
- GeoMean is the Geometric Mean. The idea behind the use of the geometric mean is that it is a measure of central tendency, just like a median. It is different than the traditional mean (which we sometimes call the arithmetic mean) because it uses multiplication rather than addition to summarize dat values. The geometric mean is useful summary when we expect that changes in the data occur in a relative fashion. They are also natural for summering ratios. Geometric mean tends to dampen the effect of very high or low values, which might bias the mean if a straight average (arithmetic mean) were calculated.
- STDEV is the standard deviation.

4.4.1 Two Dimension Analysis

In table 4.8, a message is sent from source $(0,0)$ to destination $(5,5)$ for 10000 times. We note the following:

Table 4.8: Round 10000 from S(0,0) to D(5,5)

		DSAP routing				
Neighbors		T R	T T	T P A (J)	T P R (J)	T P T (J)
2D	4	280000	100000	25.12	7.16	3.71
	5	370000	90000	23.19	9.47	3.34
	6	270000	50000	27.23	6.91	1.86
	7	310000	50000	26.20	7.94	1.86
	8	350000	50000	25.18	8.96	1.86
		Aware–DSAP routing				
Neighbors		T R	T T	T P A (J)	T P R (J)	T P T (J)
2D	4	314787	100000	24.23	8.06	3.71
	5	359428	87861	23.54	9.20	3.26
	6	301852	65926	25.83	7.73	2.45
	7	388748	73624	23.32	9.95	2.73
	8	396424	73212	23.13	10.15	2.72

- Increasing the number of neighbors, for DSAP in general, results in decreasing the number of transmissions that the network does. This is because having more neighbors creates shorter paths or alternative routes that are shorter to the destination. This is also reflected in the total power transmitted (T P T) in the network, which is decreased as we move from a sparse topology to a more dense topology.

- Looking at the power used for both protocols, we notice that DSAP with power aware uses more power, which is reflected throughout table 4.8. But looking at figures 4.9 and 4.10 we notice DSAP with power aware has a better power distribution among the nodes than DSAP without power aware does. This means that we can extend the life of the network using the power aware concept.

In tables 4.9 and 4.10, we studied when the first node dies in the network. We notice the following:

- In table 4.9, more than one node died in the network. This is because using DSAP without power aware uses the concept of shortest path, so every message

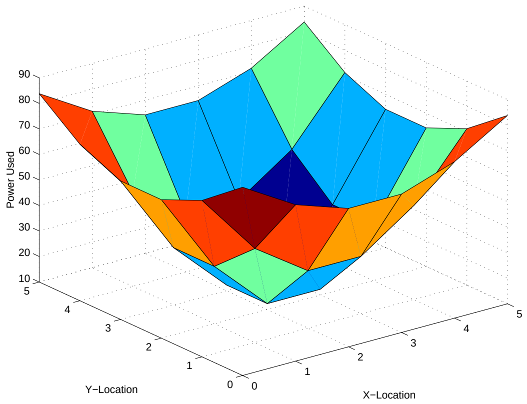


Figure 4.9: Remaining Power in each Node using DSAP

takes the same path, which means these nodes will lose power faster than other nodes.

- In table 4.10, we notice that the first node died at different rounds and even at a higher number of rounds than in table 4.9. This is because in table 4.10, DSAP with power aware was used. This gives the routing protocol more alternative paths to use and also balances the load in the network.

- Also notice that in table 4.10 as we increase the number of neighbors, that the number of rounds when the first node dies decreases. This is because more neighbors are hearing the transmission of each source.

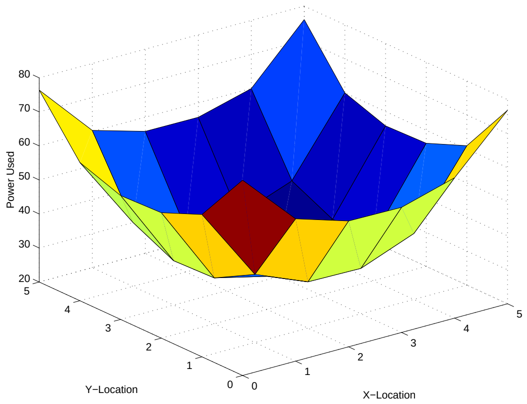


Figure 4.10: Remaining Power in each Node using Aware–DSAP

In tables 4.11, 4.12, and 4.13 each node sends a message to every other node in the network. This will be considered as one complete run and is repeated until a fixed round or until the death of the first node. In these tables we ran the simulation for DSAP without power aware and also for the power aware protocol.

In table 4.11, we observe the following:

- As we increase the number of neighbors, the first node dies at a lower number of rounds in both protocols. This is because more nodes will be reached during each transmission, so more nodes will lose power.

- We notice that the number of rounds in the DSAP with power aware is higher than the DSAP without power aware. This is because alternative paths have

Table 4.9: First Node Dead For DSAP at Round 10191 from S(0,0) to D(5,5)

Neighbors		Dead Nodes	GeoMean
2D	4	8	51.89
	5	7	48.20
	6	3	64.55
	7	3	62.42
	8	3	60.36

Table 4.10: First Node Dead Aware–DSAP from S(0,0) to D(5,5)

Neighbors		Round	GeoMean
2D	4	14350	49.58
	5	13563	47.76
	6	14350	52.71
	7	13060	48.52
	8	11456	54.82

been used, resulting in a better load balance than the DSAP without power aware.

- Notice that the standard deviation for the DSAP with power aware is less than the DSAP without power aware. This is because in DSAP with power aware we have a better distribution of power usage than the DSAP without power aware.
- Also the geometric mean is less in the DSAP with power aware than the DSAP without power aware. This is because DSAP with power aware balances the load among all the nodes.

In tables 4.12 and 4.13 we compare the two protocols at round 28512 (at this round none of the nodes are dead) to study the geometric mean, the standard deviation, and different power parameters. We observe the following:

- In table 4.12, notice that Aware DSAP has a lower standard deviation than DSAP, but has in some cases higher geometric mean.

Table 4.11: First Node Dead For Fixed All Routing

		DSAP routing		
Neighbors		GeoMean	STDEV	Number of Rounds
2D	4	39.69	21.33	39605
	5	39.99	21.82	34001
	6	44.33	22.04	31715
	7	42.09	21.34	29485
	8	45.07	22.94	29120
		Aware–DSAP		
Neighbors		T_x	R_x	Total Power used
2D	4	20.75	15.24	56084
	5	31.04	18.66	30934
	6	27.50	14.31	39512
	7	28.76	15.71	29485
	8	24.48	18.17	37915

Table 4.12: Topology At Round 28512 for Fixed All Routing

		DSAP routing		Aware–DSAP routing	
Neighbors		GeoMean	STDEV	GeoMean	STDEV
2D	4	58.79	15.42	61.34	7.81
	5	51.75	18.38	44.66	15.40
	6	51.31	19.84	51.96	11.60
	7	44.67	20.59	43.98	13.98
	8	46.74	22.45	47.11	15.61

- In table 4.12, notice that the topology with four neighbors has a lower standard deviation in both protocols.

- In table 4.13, notice that as we increase the number of neighbors, the number of transmissions decreases as we have noted for table 4.8.

In general, we conclude that for the 2D topologies there is a trade-off between increasing the number of neighbors and the power dissipated in the networks. As we increase the number of neighbors, the protocol will have alternative routes but more power will be dissipated in the network. Also, using a power aware routing protocol will help in extending the life of the network.

Table 4.13: Power Values at Round 28512 for Fixed All Routing

		DSAP routing				
Neighbors		T R	T T	T P A (J)	T P R (J)	T P T (J)
2D	4	390720	110880	21.88	10.0	4.12
	5	478522	105292	19.84	12.25	3.91
	6	490776	94556	19.93	12.56	3.51
	7	570768	91718	17.98	14.61	3.4
	8	544456	78232	19.16	13.94	2.90
		Aware–DSAP routing				
Neighbors		T R	T T	T P A (J)	T P R (J)	T P T (J)
2D	4	376541	110880	22.24	9.64	4.12
	5	558634	127596	16.96	14.30	4.74
	6	507003	104465	19.14	12.98	3.88
	7	608627	103897	16.56	15.58	3.86
	8	578045	90638	17.83	14.79	3.36

Table 4.14: Power Assessment for 3D Topology

Protocol	DSAP routing			Aware–DSAP routing		
Number of Rounds	1000	10000	100000	1000	10000	100000
Total Power Used (J)	0.416	4.126	41.354	0.4	3.937	39.469
Total Transmissions	3051	30131	302160	3051	30131	302160
Total Reception	13228	131043	1312998	12573	123656	1239477

4.4.2 Three Dimension Analysis

In table 4.14, different runs were done for the 3D topology to try to see how the power dissipated in the network will be effected by using the two different protocols that we have. We notice that for the first 1000 rounds there is only a difference in the number of receptions in the network. This is because as the network is used more, the DSAP with power aware tries to find alternative paths with more power. If we look at round 10000 and round 100000 we notice that the power used is less in the DSAP with power aware than the DSAP without power aware. This is for the same reasons that were mentioned above.

4.5 Summary

In WSNs we have to look at the network topology from a different perspective, from a neighborhood point of view. In these topologies, the number of neighboring nodes determines the number of receivers and hence may result in more overall power usage, even though the number of transmissions decreases. Thus, there is a fundamental trade-off between decreasing the number of transmissions and increasing the number of receptions. In this chapter, we have presented a variety of topologies and examined this trade-off.

Because the number of neighbors differs with different topologies, one expects different topologies to have different power usage rates. Even our simulations of the contention-free case show that different topologies have different levels of power efficiency. The results show that the total power consumption is reduced for topologies with fewer neighbors; although the topologies with more neighbors require fewer hops, the power expended by many nodes to receive these messages increases the power usage. Among the 2D topologies, the best power efficiency is achieved with four neighbors. The 3D topology performs even better, although a 3D topology may not be feasible for some applications.

Chapter 5

Power Aware Metrics for WSN

5.1 Issues of Power Metrics

Wireless devices must operate for a long period of time, relying on only their battery power. While many developers have looked at extending the life of a wireless system from a hardware point of view, such as directional antennas and improving battery life, power based routing is a relatively new concept in wireless networking. Until recently most routing protocols in wireless networks have concentrated mainly on establishing routes, and maintaining these routes under frequent and unpredictable changes in network topology. The concept of using routing to minimize power usage has only recently been looked at and it has been shown to be moderately successful. It has been proposed that routing packets in a power aware method will complement hardware based methods of extending the network's life. The metrics that have so far been devised to minimize power can be grouped into two main groups: power-aware and cost-aware metrics. Power-aware metrics aim to minimize the total power needed to route a message between two different locations, while cost-aware metrics look at the methods that extend each nodes' battery lifetime. The main objective is to further develop power-aware and cost-aware metrics, which have been devised to minimize power loss and maximize battery life of wireless units.

In most routing protocols the paths are computed based on minimizing hop count or delay. When the transmission power of nodes is adjustable, hop count may be replaced by a power consumption metric. Some nodes participate in routing packets for many source-destination pairs, and the increased energy consumption may result in their failure. A longer path passing through nodes that have plenty of energy may be a better solution (Singh, Woo, and Raghavendra 1998).

Singh et al. (Singh, Woo, and Raghavendra 1998) propose several algorithms for power-aware routing in mobile ad hoc networks. The algorithms in (Singh, Woo, and Raghavendra 1998) propose to use a function, *f(A)*, to denote node A's reluctance to forward packets, and to choose a path that minimizes the sum of *f(A)* for nodes on this path. This routing protocol (Singh, Woo, and Raghavendra 1998) addresses the issue of energy critical nodes. As a particular choice for *f*, (Singh, Woo, and Raghavendra 1998) propose $f(A)=1/g(A)$, where $g(A)$ denotes the remaining lifetime of the node. The other metrics used in (Singh, Woo, and Raghavendra 1998) are aimed at minimizing the total energy consumed per packet. However, (Singh, Woo, and Raghavendra 1998) merely observe that the routes selected when using this metric will be identical to routes selected by shortest hop count routing, since the energy consumed in transmitting (and receiving) one packet over one hop is considered constant.

In (Stojmenovic and Lin 2001) and (Stojmenovic and Datta 2002) the authors describe several localized routing algorithms that try to minimize the total energy per packet and/or lifetime of each node. The proposed routing algorithms are all demand-based. These methods use control messages to update positions of all nodes to maintain the efficiency of the routing algorithms.

We are using similar ideas that use power-aware routing but from a local view of the network without sending control messages to request information. Each neighbor will gather local information about each neighbor whenever there is a communication with this neighbor and use this information to calculate or to choose among the possible routes. By doing so the protocol limits the energy consumption, because energy consumption occurs in three domains: sensing, data processing, and communication. In a WSN, communication is the major consumer of energy. Pottie and Kaiser (Pottie and Kaiser 2000) showed that communication costs significantly more than processing. So, it can be beneficial to make trade-offs between data processing and wireless communication. Hence, local data processing is crucial in minimizing power consumption in a multihop sensor network (Sohrabi, Gao, Ailawadhi, and Pottie 2000).

By choosing the minimum directional value, the message is forwarded in direction D-5, which is obvious from figure 5.1. The protocol repeats until reaching the final destination, which will have a DV of 0. In the next section we will explore different power metrics that can be used to enhance the routing mechanism of DSAP.

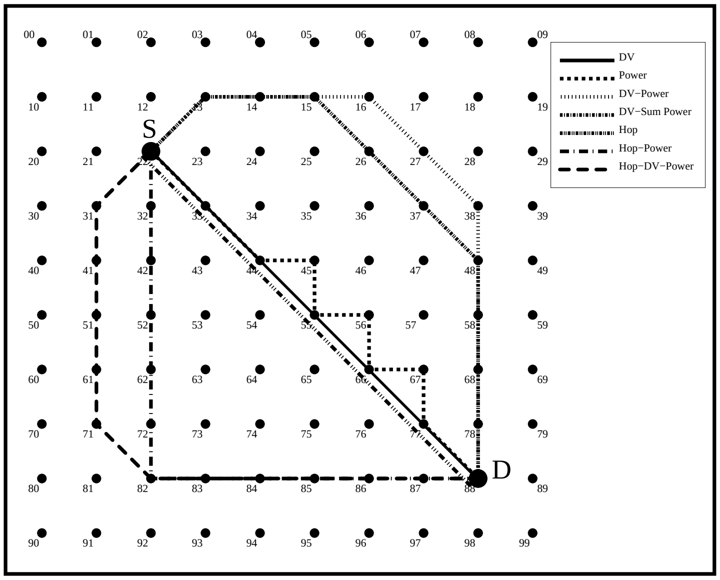


Figure 5.1: Routing Using Different Metrics at Round 4000

5.2 DSAP and Power Metrics

Using local information that is available to each node limits the resources that are available for the routing protocol. Each node knows its neighbors and their DVs. Each node knows the power available at their neighbors and it can calculate the direction of the final destination from the DV. Nodes can calculate the sum of powers from their neighbors and also approximate the number of hops to the destination from the DV.

Considering the above information, we notice that the routing protocol is limited by the choices that are available to decide the next hop to advance the packet. From this local information that is available, we can use power only, directional value, directional value and power, the sum of power and directional value only, the cost of routing and the number of hops, and number of hops, power sum, and DV combined.

We shall now describe the paths chosen by the corresponding localized routing algorithms. For illustration purposes a sample has been taken at round 4000 as shown in figure 5.1 to compare the different routes each method chose. The idea here is to localize everything in the protocol. We mean that each algorithm is applied locally on a hop-by-hop basis from the source to the destination.

5.2.1 Power Only

In figure 5.1, DSAP first calculates the directional value to determine the positive directions and then the packet is forwarded to the node with the maximum power available at that node. As shown in the figure, this routing method may take longer paths because of the power available at each node and may even loop in the network without reaching the final destination. To avoid looping, the algorithm requires each node to keep track of the neighbor that forwarded the packet to it and try to avoid that node.

Table 5.1: Routing Using Power only

Dead	1	5	10	20	25
Power	18.68	17.46	16.26	13.53	12.67
Mean %	74.72	69.83	65.03	54.12	50.07
Trans.	28053	33965	40142	54762	59597
Recv.	218816	260673	301255	393283	422063
STD	22.20	25.56	28.04	31.39	31.53
Rounds	4675	5546	6281	7796	8234
Drop	0	50	177	727	1059

Table 5.2: Routing Using DV only

Dead	1	5	10	20	25
Power	13.97	12.95	12.66	10.99	10.58
Mean %	55.89	51.49	50.62	43.94	42.33
Trans.	50557	55405	56877	65634	67911
Recv.	380131	415083	424983	481768	495196
STD	23.43	25.31	25.85	27.32	27.54
Rounds	10804	11537	11721	12663	12867
Drop	0	59	86	472	627

5.2.2 Directional Value Only

In this approach, the algorithm considers only the DV of its neighbors with respect to the final destination. The only information that is available to the source is the IDs of its neighbors. From these IDs the source can calculate the DV of its neighbors with respect to the final destination. The message will be forwarded to the node with the minimum value. As shown in figure 5.1, node $(2, 2)$ takes the direct path to node $(8, 8)$ without considering the power available at those neighbors. So it may take the shortest path but it may be a costly path that is taken.

5.2.3 Directional Value and Power

In this approach, the algorithm incorporates energy efficiency. This is achieved by considering the maximum available power and minimum directional value when picking which node route to take. Instead of picking the node with the lowest directional

Table 5.3: Routing Using DV and Power

Dead	1	5	10	20	25
Power	8.11	7.80	7.57	7.16	6.82
Mean %	32.45	31.10	29.98	28.58	27.28
Trans.	83160	84825	86150	88795	91261
Recv.	576461	586990	594737	607999	618842
STD	19.53	19.69	19.63	19.42	18.9
Rounds	15078	15284	15409	15599	15753
Drop	0	10	28	115	242

Table 5.4: Routing Using DV and Power Sum

Dead	1	5	10	20	25
Power	7.51	7.32	7.20	6.88	6.59
Mean %	30.06	29.27	28.78	27.52	26.35
Trans.	86166	87236	87952	90009	92031
Recv.	596802	603401	607498	617793	627136
STD	19.30	19.34	19.30	18.87	18.39
Rounds	15720	15852	15919	16072	16203
Drop	0	5	16	82	176

value or the maximum power, the directional value is divided by the power available at that node. The smallest value of this power-constrained directional value is the path that is chosen. This allows for a least-transmission path that is also cognizant of power resources, although in some cases a longer path may be chosen if the available power dictates that choice. As shown in figure 5.1, the path from source $(2, 2)$ to destination $(8, 8)$ is longer than the path taken by using the DV metric only.

5.2.4 Directional Value and Sum of Power

In this approach the algorithm incorporates energy efficiency from a different point of view; it uses the directional value and the power available at the surrounding neighbors. Instead of looking at the power at the neighbors of the source it looks one hop beyond these neighbors. This is accomplished by getting the sum of power at a node's neighbors from each neighbor. By doing so, the protocol can have a better

Table 5.5: Routing Using Number of Hops Only

Dead	1	5	10	20	25
Power	13.23	12.68	11.94	11.06	10.15
Mean %	52.90	50.72	47.78	44.24	40.62
Trans.	54462	57105	60900	65753	70923
Recv.	405459	424099	449042	478724	508945
STD	23.33	24.35	25.57	26.59	26.83
Rounds	11643	12163	12806	13489	14191
Drop	0	30	143	443	967

choice in picking the next route. Compared to the previous algorithms, the choice of the route may be different as shown in figure 5.1.

5.2.5 Number of Hops Only

This algorithm uses only the number of hops, which can be calculated from the directional value. The number of hops for each direction will give a minimum and maximum number of hops. The algorithm will use the average of those two numbers to make a choice on routing the packet. The packet will be forwarded to the neighbor with the minimum number of hops. From figure 5.1, we see that for this sample the result it is the same as the DV metric.

5.2.6 Hop and Cost

In this approach, the algorithm uses the number of hops, which can be calculated from the directional value, and estimates the cost of routing in each direction. The number of hops for each direction will give a minimum and maximum number of hops. The algorithm will use the average of these two numbers and then take the first hop and multiply it by the number of neighbors for the power received. For the rest of the path we estimate the maximum number of neighbors for this topology, which is eight neighbors. For each of these hops, a power transmission is added, because one node will transmit. This will give an estimate of the total power needed to transmit

Table 5.6: Routing Using Hop and Cost

Dead	1	5	10	20	25
Power	12.25	11.58	10.83	9.97	9.65
Mean %	48.99	46.32	43.30	39.87	38.60
Trans.	58353	61374	64852	68941	70542
Recv.	439782	462771	488786	518249	529081
STD	23.35	24.41	25.20	25.42	25.32
Rounds	5342	5608	5908	6240	6364
Drop	0	14	61	201	293

Table 5.7: Routing Using Hops, Cost, DV and Sum of Power

Dead	1	5	10	20	25
Power	8.97	8.56	8.19	7.47	7.16
Mean %	35.90	34.23	32.78	29.89	28.63
Trans.	80195	82326	84196	88131	90078
Recv.	545746	559967	572210	596444	606889
STD	17.52	18.03	18.49	19.25	19.40
Rounds	13159	13436	13651	14038	14172
Drop	0	19	54	203	319

the message from the source to the destination. In figure 5.1, we see that the protocol takes a different route as shown.

5.2.7 Hops, Cost, DV, and Sum of Power

This algorithm takes into consideration all the information that is available to the source and tries to make the decision according to that information. First, calculate the number of hops and estimate the power needed to deliver the packet. Then, calculate the DV and the sum of power at the neighbors. Finally, take the ratio between those two values and pick the one with the minimum value. The packet will be forwarded to that neighbor. As shown in figure 5.1, this approach takes the longest path to try to conserve energy.

5.3 Performance Evaluation

In order to evaluate the performance of DSAP with different metrics, several simulations were run with the various metrics. For each metric that has been tested, we use the same ten randomly generated files that have the same sequence of transmissions from source to destination to guarantee the same requests for each different metric. Then, the average of those ten runs has been taken to create the tables. For each table we calculate the total power level remaining for the network, the mean percentage of the power remaining, the total number of transmissions and receptions, the standard deviation of the power, the number of rounds after which a certain number of nodes died, and the total number of requests that have been dropped because of dead nodes. This compares the status of the network using different routing methods. Finally, we look at the condition of the network at a fixed round to evaluate the performance of each method.

In tables 5.1 - 5.7 we have gathered several values. Each of these values represent the following:

1. Power: represents the total remaining power when 1, 5, 10, 20, and 25 nodes are dead in the network.
2. Mean %: represents the arithmetic mean of the remaining power when 1, 5, 10, 20, and 25 nodes are dead in the network.
3. Trans.: represents the total number of transmitted packets when 1, 5, 10, 20, and 25 nodes are dead in the network.
4. Recv.: represents the total number of received packets when 1, 5, 10, 20, and 25 nodes are dead in the network.
5. STD: represents the standard deviation of the remaining power when 1, 5, 10, 20, and 25 nodes are dead in the network.

6. Rounds: represents the number of rounds that the simulation was stopped when 1, 5, 10, 20, and 25 nodes are dead in the network.

7. Drop: represents the number of messages that was dropped in the network when 1, 5, 10, 20, and 25 nodes are dead in the network. These messages were dropped because the source or the destination is one of the dead nodes.

From tables 5.1 - 5.7 we observe the following:

1. From tables 5.1 (using the Power Only metric) and 5.6 (using the Hops and Cost) we observe that the first node died in round 4675 and 5342, and the power remaining in the network is higher than any other metric. But the standard deviation of the remaining power is also higher than the other metrics.

2. In tables 5.2, 5.3, 5.4, 5.5, and 5.7 the first node died after round number 10000 and in table 5.2 (using DV only) and table 5.3 (using DV and Power) metrics have more than 25 nodes dead. That means that using power or cost only as a metric for routing exhausts the power available at some nodes without trying to distribute the power usage evenly among the rest of the nodes in the network.

3. From these tables notice the amount of energy lost when the first node dies and the 25th node dies. We see that when using the power only metric that the total power lost is higher than with the other metrics. This is because in using power the routing protocol looks for nodes with higher power and tries to exhaust them until they die.

4. From table 5.4 (using DV and Power of Sum) observe that the number of dropped simulation messages using the DV and sum of power metrics is less than the other metrics that have been used. This is because this method uses the sum of power at the neighbors, which gives the method a broader perspec-

Table 5.8: Routing Using All Method at 14000 Rounds

Routing Method	Power Level	Mean %	SD	Dead Nodes	Dropped Packets
Power	8.91	35.64	27.74	40	3693
DV	8.39	33.54	25.70	37	2271
DV P	9.44	37.76	18.45	0	0
DV P Sum	9.64	38.55	18.09	0	0
Hop	10.40	41.59	26.80	24	808
Hop Cost	6.99	27.95	21.47	40	1988
Hop P DV	7.54	30.18	19.15	18	192

tive of the power distribution on future paths. This will conserve the power at the nodes with lower power.

In table 5.8 we want to compare the behavior of the network at a fixed round to see the number of dead nodes and the amount of power remaining in the network. We observe the following:

1. DV with power and DV with sum of power have no nodes dead for that round. This is because the power is distributed almost evenly among all nodes using these methods. We can see this from the standard deviation of the power.
2. We observe that the number of dead nodes in power only, cost only, and DV is much higher than the other methods and the standard deviation is also high.
3. We observe that the amount of power remaining in the network for all the methods is close to each other but they differ in the number of dead nodes and the number of dropped messages.

5.4 Summary

In this chapter we discussed the need to make the routing protocols power-aware from a local point of view. Thus, the routing protocol tries to make its decision using information available from its neighbors only. Basing the decision on the power remaining is not enough by itself. Using the directional value and the sum of power remaining at the next neighbors will give the routing protocol a broader perspective about the condition of the network from a local point of view. Our simulations show that using the DV and the sum of power, and also using DV with power extends the lifetime of the network.

Chapter 6

Evaluation of Cartesian Based Routing Metrics for WSN

6.1 Introduction

Routing packets within a large scale wireless sensor network without storage overhead and routing table updates is a challenging problem. With a large number of sensors, however, overhead would play a significant role in the scalability of the routing protocol. In order to constrain this communication overhead, sensor network routing demands new and efficient methods for routing packets. In order to remove or reduce this overhead, the routing protocol needs some way of implicitly, rather than explicitly, defining paths.

In this chapter, we use the idea of directional routing, which requires only that each sensor know its location within the network relative to the sending node and the destination. This allows the use of simple directional routing based on local information only. However, sensors are energy-constrained devices, so selecting paths within this network could benefit from an energy-aware routing process.

When considering routing metrics for sensor networks, we need to see what kind of information is available for routing. If we consider only the local point of view then there is limited information that each node can get from its neighbors. These items are listed below:

- Cost of communication and distance between a source and its neighbors.
- Cost of communication and distance between a node and the base station.
- Number of neighbors.
- Power remaining at the neighbors.

Basing a routing protocol on these items alone is not enough. Routing paths must be defined. Producing a routing table involves many control messages and also involves route discovery. But with the kind of information that is available and the limited resources that we have, we cannot have control messages to perform route discovery and continually update the routing table. Instead we base the routing protocol on the local information only without using a routing table. In order to achieve this goal we introduced the idea of Directional Value (DV) (Salhieh, Weinmann, Kochhal, and Schwiebert 2001). Each node knows from the request which direction to send the packet. So the node just computes which neighbor is the most suitable to forward the message to and the neighbors on their own will determine the rest of the route. This idea requires the node to contact its neighbors only and saves many control messages throughout the whole network. This provides a routing protocol that will scale with a large number of nodes.

This protocol needs to be power aware, so we base most of the metrics on the power available at the source and its neighbors. In (Salhieh, Weinmann, Kochhal, and Schwiebert 2001) the authors have shown that using a power aware protocol distributes the power usage evenly among the nodes of the network. And in (Salhieh and Schwiebert 2002) the authors compared different power aware metrics and provide the basis for this work.

The use of local information for making routing decisions may not lead to an ideal path. The lack of global knowledge could result in the choice of less efficient paths or even paths that require significant backtracking to reach the destination.

Global knowledge of the nodes and their properties, such as available power, along with knowledge of the current traffic in the network, could allow for optimal path selection for whatever goals we are attempting to achieve. However, the overhead and delay of accumulating and using global information is prohibitively expensive especially for sensor networks. Because network conditions, including each sensor node's power and availability, are dynamic properties, this global information is likely to be obsolete before it is accumulated, so the advantages of using global information are reduced or lost. Despite the fact that routing based on global information is not practical, it provides a good basis for determining how efficient routing based on only local information performs. In this chapter, we evaluate several global metrics and compare these with the corresponding local metrics, showing that the local routing metrics perform reasonably well with limited overhead.

Several criteria will be considered to compare the global methods and the local methods. Some of these criteria that will be used throughout this chapter are:

1. The average number of hops.
2. The number of nodes that die after a fixed number of rounds.
3. The number of rounds when the first node dies and 5, 10, and 20 percent of the nodes die.

6.2 Model

We consider a system of wireless nodes that are homogeneous and highly energy-constrained. Each node produces some information as it monitors (senses) its vicinity. The basic operation in such a system is the systematic gathering of sensed data from one or more points of interest to be eventually transmitted to a base station for further processing. The key challenge in such information gathering is conserving the sensor energy, thereby maximizing the lifetime and hence the utility of the system.

Each sensor in the network knows its position with respect to the network. The location of each node will be determined by using the directional value system. The base station can find its position by finding the directional value of the nodes that it contacted, but nodes don't need to know the global topology. The Base Station (BS) will broadcast to the network and the nodes that can hear the BS will be called base enabled nodes. These nodes will choose coordinators that will manage those nodes and determine who should contact the base station as explained in section 6.4.

6.3 Simulation Setup

In this chapter we define a controlled environment so we can study the performance of local routing versus global routing. We have the following assumptions:

1. The only nodes that can collect data and forward data toward a base enabled node are the nonbase enabled nodes, which in our experiment are nodes from node (90) to node (49) as shown in figure 6.1.
2. The base enabled nodes will be determined from the transmission range of the Base Station as shown in figure 6.1.
3. The same base enabled nodes will be used for the local and global cases.
4. We will compare the number of rounds until $1, 5, 10, 15,$ and 20 nodes die.
5. Study the average number of hops a certain method will take to transmit to the Base Station.
6. Study the different route each method will follow at round 4000.
7. Study how fast the nodes die.

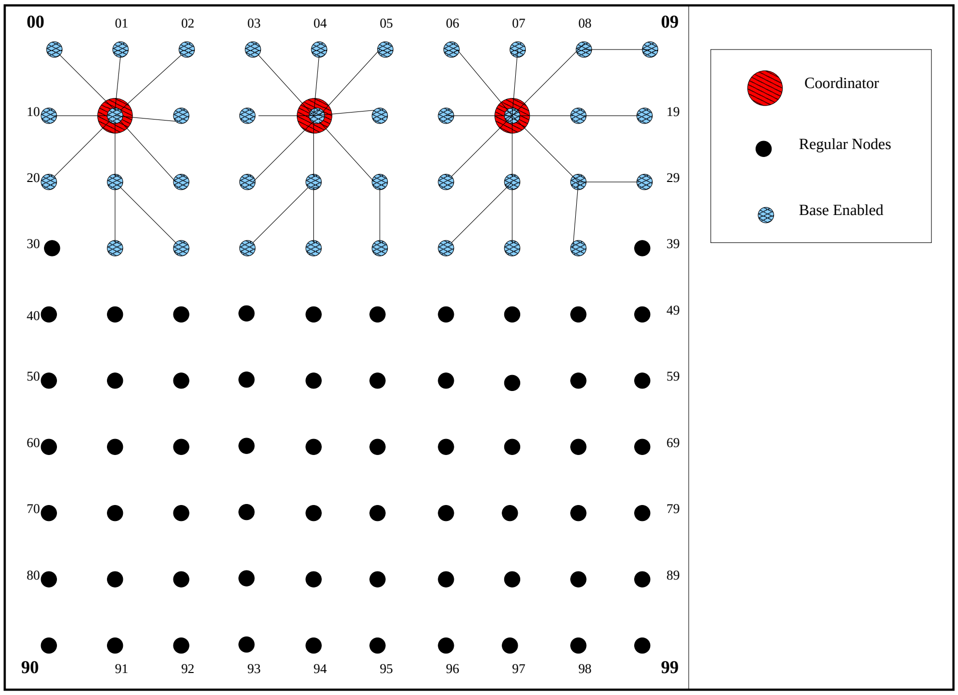


Figure 6.1: Base Enabled Nodes and Coordinator Nodes

6.4 Coordinators

Here we describe the algorithm for choosing the coordinators. These coordinators will be in charge of the nodes which are base enabled and select the most eligible node to send to the Base Station. The algorithm follows a set of rules to elect these coordinators. These rules are listed below:

1. Only nodes that are base enabled can become coordinators.
2. No coordinators are neighbors of each other.
3. The coordinator with the least number of neighbors among all coordinators can be a fixed coordinator.
4. If a coordinator is a fixed coordinator it cannot be eliminated.

5. Each base enabled node can join only one coordinator.
6. Each base enabled node chooses the coordinator that is closest to it by using the DV measure. This means it will compare the directional value of each coordinator that it received and choose the one with the smallest value.
7. If a node joins a fixed coordinator it will eliminate other coordinators that it was connected to.

6.5 Global vs. Localized Approaches

Due to the large number of sensors, network-scale interaction is indeed too expensive. Moreover, a centralized algorithm would result in a single point of failure, which is unacceptable in most applications and severely limits the advantages of using a wireless sensor network.

Comparing local routing with respect to global routing gives a sense of the performance of local routing. Routing using global knowledge has a huge amount of overhead and if we apply this approach to the sensor network will not be practical. Assuming that the base station knows everything about the topology, and the network involves a periodic updates to the base station, this uses power and also creates contention in the network. So we are using global metrics as a benchmark to measure the performance of the local methods that we used in this chapter.

6.5.1 Global Routing

In this section we describe the methods that were used for computing the cost of routing using global information.

1. Power:

   In this method, the power available at each node is used as the weight of each edge. Dijkstra's algorithm is used to pick the route with the maximum power available from source to destination.

2. Directional Value (DV):

   In this method we use the directional value and power as the weight between the nodes. We divide the DV between each node and the destination, and divide this result by the power available at each node.

3. Sum of Power (Sum):

   In this method we use the sum of power at the neighbors of the source, and use that value as the weight between the nodes. This will give a focused perspective of the power available at the neighbors.

4. Hop:

   In this method we use the number of hops between the source and destination, divide that by the power available, and use the result as the weight between the nodes.

5. Power Difference (P Diff):

   In this method we use the difference of available power between the source and the neighbors as shown in equation 6.1. The idea behind this equation is to balance the power usage among the neighbors. Since in the ideal case we would have P_{TNi} negligible, then the value of the equation would be between $0 - 1$. To ensure power usage balance, the routing protocol will pick the node with the highest value.

$$PowerDiff = (P_{aNT} - P_{TNi})/P_{aveNi} \tag{6.1}$$

where:

- P_{aNT} is the power available at the node that is transmitting the packet.
- P_{TNi} is the power needed to transmit to the next hop.
- P_{aveNi} is the average power of all the neighbors of the node that is transmitting the packet.

6.5.2 Local Routing

In this section we describe methods for routing packets that depend on local information only. When we look at the local information that is available to the node and its neighbors we find the following:

- Remaining power at the node and at the neighbors.
- The number of hops between the source and the destination.
- The sum of the remaining power at the neighbors.
- The sum of the remaining power at the neighbors' neighbors of the current node.
- The cost of transmitting to the next hop.

All of the above can be used as the local metrics for routing between a source and a destination. We have developed several methods that can take advantage of this information to try to create a metric that can be used for routing. In the next section, we will describe each of these metrics and how they route, and what are the factors that these metrics use to route the packets.

1. Directional Value only:

   In this approach, the algorithm considers only the DV of its neighbors with respect to the final destination. The only information that is available to the source is the IDs of its neighbors. From this information the source can calculate the DV of its neighbors with respect to the final destination. The message will be forwarded to the node with the minimum value.

2. Directional Value and Power (DV/P):

   In this approach, the algorithm incorporates energy efficiency by considering the maximum available power and minimum directional value when picking which neighbor to use. Instead of picking the node with the lowest directional value or the maximum power, the directional value is divided by the power available at that node. The smallest value of this power-constrained directional value is the path that is chosen. This allows for a least-transmission path that is also cognizant of power resources, although in some cases a longer path may be chosen if the available power dictates that choice.

3. Sum of Power at the next Neighbor:

   In this approach the algorithm incorporates energy efficiency from a different point of view; it uses the directional value and the power available at the surrounding neighbors in the forwarding direction only. Instead of looking at the power at the neighbors of the source, it looks one hop beyond these neighbors. This is accomplished by getting the sum of power at a node's neighbors from each neighbor. By doing so, the protocol may have a better choice in picking the next hop on the route.

4. Restricted Power and Directional Value:

   In this approach the algorithm takes the power available at the neighbors as a metric for forwarding the packet. Note that the algorithm is not inherently loop free and will take longer paths. To insure that the algorithm is loop free, we limit the choice to the nodes that will forward the packet toward the destination.

Table 6.1: Global Power Metrics and Number of Rounds

dead/method	Power	DV/P	Sum	Hop	P Diff
Dead-1	4068	3903	4134	3938	2545
Dead-5	4474	4326	4295	4243	3047
Dead-10	4814	4651	4731	4700	3505
Dead-15	4998	4876	4958	4972	3830
Dead-20	5186	5057	5005	5166	4145

5. Sum of Power at the Neighbor:

   In this approach the algorithm incorporates energy efficiency by considering the sum of power at neighbors of the node that is transmitting the packet. Consider only the nodes that are in the forwarding directions. This will provide a limited perspective of the power unlike the sum of power at the next neighbors.

6.6 Simulation Results

This section is divided into three parts. First, we will discuss the performance of the global methods and discuss the significant differences among those methods, explaining why one method is better than another method. Second, we will do the same for the local methods as we did for the global. Finally, we discuss the differences between the global and local methods for the number of rounds, average number of hops, and percentage of increase in the number of dead nodes at a fixed round.

6.6.1 Global

In table 6.1 we notice that the global method with power as its metric has the highest number of rounds achieved before 20 nodes are dead. But as a tradeoff, we notice that it has a higher average number of hops as shown in table 6.2. This is because the algorithm picks the path with the minimum cost. We notice the same for the metric that depends on the number of hops as its cost between the nodes.

Also notice that using power difference as a power metric yields the lowest number

Table 6.2: Global Power Metrics and Average Number of Hops

dead/method	Power	DV/P	Sum	Hop	P Diff
Dead-1	8.63	8.62	8.64	9.17	8.65
Dead-5	8.62	8.63	8.63	9.15	8.60
Dead-10	8.65	8.69	8.66	9.24	8.58
Dead-15	8.71	8.79	8.80	9.40	8.57
Dead-20	8.86	8.92	8.84	9.28	8.58

Table 6.3: Increase in Number of Rounds for Global Routing

dead/method	Power	DV/P	Sum	Hop	P Diff
Dead$(1-5)$	406	423	161	305	502
Dead$(5-10)$	340	325	436	457	458
Dead$(10-15)$	184	225	227	272	325
Dead$(15-20)$	188	181	47	194	315

of rounds as shown in table 6.1. But, in table 6.2 we see that the average number of hops decreases instead of increasing like the other methods. This is due to the fact that this method depends on the ratio between the power remaining at the source and the average power remaining at the neighbors of that source as shown in equation 6.1. This will create a balance in the power dissipated in the network over the long run and yield an even distribution of power between the source and the forwarding neighbors.

In table 6.3, we compare the increase in number of rounds when the number of dead nodes increases from one stage to the next. We notice that the increase in the number of rounds decreases as the number of dead nodes increases in some methods. When using the Power, DV/P, and P Diff, we see a decrease in the number of increased rounds, but in the sum and hop methods we see that the second stage has more increase than the first stage. This is because those two methods in the second stage are taking more longer hops than the other methods as shown in table 6.2.

Table 6.4 shows the performance of different methods at a fixed round. At round 1500, we notice that the metric that depends on the number of hops has the highest average with respect to the rest. This is because this method depends on the number

Table 6.4: Global Routing and Number of Hops and Dead Nodes

Round	method	Power	DV/P	Sum	Hop	P Diff
1500	*AveHop*	8.67	8.65	8.7	9.55	8.57
	Dead	0	0	0	0	0
3900	*AveHop*	8.64	8.62	8.65	9.17	8.57
	Dead	0	0	0	0	16
5000	*AveHop*	8.71	8.87	8.83	9.42	8.75
	Dead	15	18	19	15	38

of hops and the power level at the next node. So the protocol tries to find the path that can minimize the relationship between the hops and the power. From table 6.4 we see that basing the cost function on a combination of ratios will effect the number of hops for each path.

Figure 6.2 shows that each method takes a different path according to its cost function. Some take longer paths and some take shorter paths.

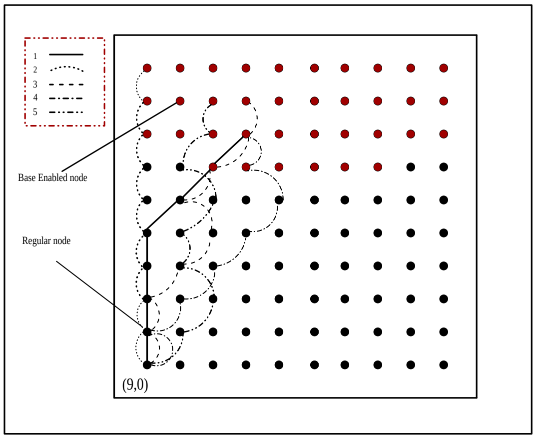


Figure 6.2: Global Routing Using Different Metrics at Round 4000

6.6.2 Local

In studying the efficiency of local routing, we use two different metrics, one for routing within the network and the other for choosing the base enabled node that will transmit to the base station. By doing this we choose the method that will give

Table 6.5: Local Power Metrics and Number of Rounds

dead/method	Sum-N	DV/P	DV	Sum
Dead-1	3204	2555	2489	2549
Dead-5	4236	3956	3851	4163
Dead-10	4661	4652	4563	4520
Dead-15	4772	4852	4777	4672
Dead-20	4882	5017	4934	4795

fairness among the enabled nodes to take turns in transmitting to the base station. In the previous chapter, we have shown that using the sum of power at the next neighbors gives a broader perspective of the network from a local point of view. Since all the base enabled nodes are connected to the coordinator, the coordinator can use this metric to pick which node is most suitable to contact the base station.

In local routing, the algorithm routes in two stages. First, route toward one of the coordinators. Then when the packet reaches the border of the base enabled nodes, route toward the most suitable node to send directly to the base station.

In table 6.5, observe that local methods with the directional value and the power extend the network lifetime better than the rest of the methods. Also notice that with this method (the directional value and the power) when the first node died that it did not have the highest number of rounds, because the directional value influenced the decision of picking the next hop. But after the network was in use, the power has more influence in deciding the next hop. Similarly for the sum of power at the next neighbor, the directional value has more influence at the beginning and then the power has more influence later.

In table 6.7, we compare the increase in number of rounds when the number of dead nodes increases from one stage to the other. We notice that the increase in the number of rounds decreases as the number of dead nodes increase, which is typical, but we also notice from table 6.6 that there is an increase in the average number of hops. Even if we compare the increase in the first stage with the increase in the

Table 6.6: Local Power Metrics and Average Number of Hops

dead/method	Sum-N	DV/P	DV	Sum
Dead-1	6.70	6.83	6.63	6.65
Dead-5	7.49	7.63	7.13	7.53
Dead-10	7.90	7.93	7.38	7.85
Dead-15	8.08	8.08	7.44	8.02
Dead-20	8.17	8.16	7.47	8.10

Table 6.7: Increase in Number of Rounds for Local Routing

dead/method	Sum-N	DV/P	DV	Sum
Dead$(1-5)$	1032	1401	1362	1614
Dead$(5-10)$	425	696	712	357
Dead$(10-15)$	111	200	214	152
Dead$(15-20)$	110	165	157	123

average number of hops we see that there is, on average, an increase of about one hop for the all the methods.

Figure 6.3 shows that each method takes a different path according to its cost function. Some take longer paths and some take shorter paths.

6.6.3 Global vs. Local

In this section we compare global routing with local routing by using three methods for comparison. First, using shortest hops by using the number of hops for global and using the DV from the local, which is equivalent to the shortest hop but from a

Table 6.8: Local Routing and Number of Hops and Dead Nodes

Round	method	Sum-N	DV/P	DV	Sum
1500	Ave Hop	6.39	6.42	6.39	6.39
	Dead	0	0	0	0
3900	Ave Hop	7.45	7.57	7.14	7.4
	Dead	4	4	5	4
5000	Ave Hop	8.16	8.21	7.48	8.22
	Dead	19	23	22	25

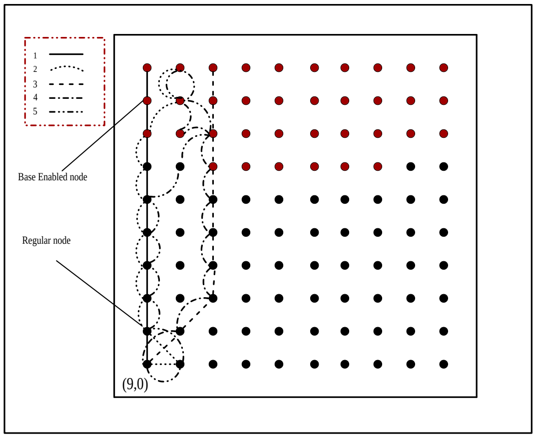


Figure 6.3: Local Routing Using Different Metrics at Round 4000

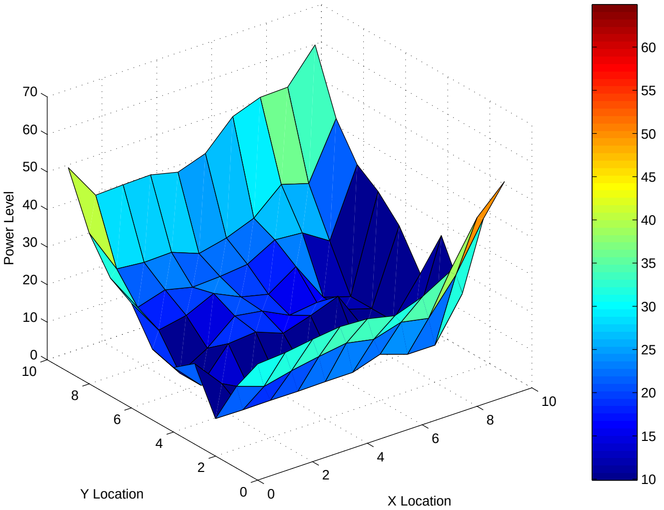


Figure 6.4: Power Distribution for Sum of Power Using Global Metric

local point of view. Second, using a ratio by using the DV/P for both the global and the local. Finally, using the sum of power for both the global and local.

Comparing tables 6.1 – 6.4 with tables 6.5 – 6.8 notice that global routing performs better than local routing in all these cases.There is one case where local is better than global. The reason is the global routing is greedy approach, so it doesn't necessarily pick the total optimal value. Whether from the number of rounds, the average number of hops, in the increase of number of rounds, increase in number of dead nodes, and also in the distribution of power as shown in figures 6.4 and 6.5. The idea here was

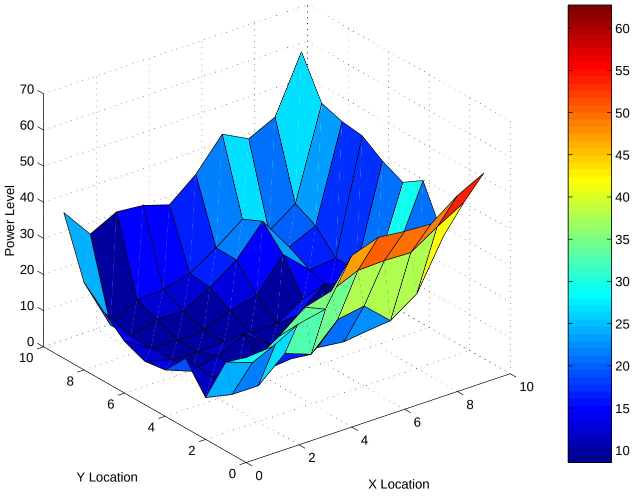


Figure 6.5: Power Distribution for Sum of Power Using Local Metric

to show that local routing performs close to global routing without the overhead.

6.7 Conclusion

The question that we try to answer is do we have to know the global state in order to make the protocol perform well? The answer in no, since the results are close and the difference is not that high between the global and the local routing. In this chapter we used directional routing, where the node needs to know the direction of the final destination to forward the packet to the next hop in that direction. Using the ratio of DV/P and the sum of power at the next neighbor performs better than other methods in local routing. These results have performance comparable to the global routing metrics.

Chapter 7

Implementation of DSAP on TinyOS Motes

Although experiments that characterize our methods are important, we also think it is important to implement an actual application using these methods as a proof-of-concept. Therefore, the final portion of our planned work is the implementation of a testbed that demonstrates the efficiency of our protocols in the context of a sensing application.

In this we want to test our protocol on the so called MIca Mote's. They are wireless sensors that have the capability of sensing different things and also transmitting the results. These sensors run TinyOS (Hill, Szewczyk, Woo, Hollar, Culler, and Pister 2000), which is an event-driven operating system for tiny networked sensors. TinyOS currently runs on the Berkeley MICA platform. Programming applications for TinyOS is done in a C-like environment with the flexibility to interface with any of the mote's hardware components.

TinyOS is an operating system specifically designed for wireless sensor networks. It has a component-based programming model, provided by the nesC language (Gay, Levis, von Behren, Welsh, Brewer, and Culler 2003), a dialect of C. TinyOS is not an OS in the traditional sense. It is a framework for embedded systems and a set of components that enable building an application-specific OS into each application. The three computational abstractions of TinyOS (*i.e.,*, commands, events, and tasks) should be as small as possible, so that high concurrency can be achieved at a fine granularity. At the same time, other system constraints exist on the hardware side.

The sensors are built on (based on) of a 4 MHz ATMEL ATMEGA processor (technology). The processor has 128 Kbits of flash memory and 4 Kb of SRAM. In a given network, thousands of sensors could be continuously reporting data, creating a heavy data flow. Thus, the overall system is memory constrained, but this characteristic is a common design challenge in any wireless sensor network.

Dealing with the tight memory constraint is given special consideration in the development of a software framework or operating system for MICA's modules. The processor has three sleep modes: idle, which just shuts the processor off; power down, which shuts everything off except the watch-dog; and power save, which is similar to power-down, but leaves an asynchronous timer running. Power is provided by an 3 volts power source, typically two AA batteries.

7.1 Introduction To TinyOS mote SIMulator (TOSSIM)

TOSSIM is a discrete event simulator for TinyOS sensor networks. Instead of compiling a TinyOS application for amote, users can compile it into the TOSSIM framework, which runs on a PC. This allows users to debug, test, and analyze algorithms in a controlled and repeatable environment. As TOSSIM runs on a PC, users can examine their TinyOS code using debuggers and other development tools.

TOSSIM's primary goal is to provide a high fidelity simulation of TinyOS applications. For this reason, it focuses on simulating TinyOS and its execution, rather than simulating the real world. TOSSIM captures TinyOS' behavior at a very low level. It simulates the network at the bit level, simulates each individual ADC capture, and every interrupt in the system. While TOSSIM precisely times interrupts (allowing things like bit-level radio simulation), it does not model execution time. From TOSSIM's perspective, a piece of code runs instantaneously. Time is kept at a granularity of 4MHz granularity.

TOSSIM does not model power draw or energy consumption. However, it is very simple to add annotations to components that consume power to provide information on when their power status changes. After a simulation is run, a user can apply a energy or power model to these transitions, approximating overall energy consumption. Because TOSSIM does not model CPU execution time, it cannot easily provide accurate information for calculating CPU energy Consumption.

7.1.1 Radio Models

TOSSIM does not model radio propagation; instead, it provides a radio abstraction of directed independent bit errors between two nodes. TOSSIM simulates the TinyOS network at the bit level, using TinyOS component implementation almost identical to the Mica 40Kbit RFM-based stack. TOSSIM provides two radio models: simple and lossy.

In TOSSIM, a network signal is either a one or zero. All signals are of equal strength, and collision is modeled as a logical or; there is no cancellation. This means that distance does not affect signal strength.

The "simple" radio model places all nodes in a single cell. Every bit transmitted is received without error. Although no bits are corrupted due to error, two motes can transmit at the same time; every mote in the cell will hear the overlap of the signals, which will almost certainly be a corrupted packet. However, because of the perfect bit transmission in a single cell, the probability of two motes transmitting at the same time is very, very low, due to the TinyOS CSMA protocol.

The "lossy" radio model places the nodes in a directed graph. Each edge (a, b) in the graph means a's signal can be heard by b. Every edge has a value in the range $(0, 1)$, representing the probability a bit sent by a will be corrupted (flipped) when b hears it.

By specifying errors at the bit level, TOSSIM can capture many causes of packet loss and noise in a TinyOS network, including missed start symbols, data corruption, and acknowledgment errors.

7.1.2 TinyViz

TinyViz is a Java visualization and actuation environment for TOSSIM. TinyViz can be attached to a running simulation. Also, TOSSIM can be made to wait for TinyViz to connect before it starts up, with the `-gui` flag. This allows users to be sure that TinyViz captures all of the events in a given simulation.

TinyViz is not actually a visualizer; instead, it is a framework in which plugins can provide desired functionality. By itself, TinyViz does little besides draw motes and their LEDs.

7.1.3 TinyOS Networking: AM

The TinyOS packet abstraction is an Active Message (von Eicken, Culler, Goldstein, and Schauser 1992). AM packets assume an unreliable data link protocol, and the TinyOS network stack handles media access control and single hop packet transmission. Active Messages provide precise timestamps as well as synchronous data-link acknowledgments. TinyOS provides a namespace of up to 256 AM message type, each of which can be associated with a separate software handler.

7.1.4 TinyOS Packet Format

TinyOS packets are currently at most 36 bytes long and have the format shown in table 7.1.

Notes: Destination ID is the node ID of the next hop. The final destination is implied to be the base station. The Group ID is used to prevent interference between different sensor networks or to create multiple groups within a single sensor network. Data payload can be from 0 to 29 bytes, and its length is indicated in the data length

Table 7.1: TinyOS packet format

Field	Length
Destination ID	2 bytes
Active message handler	1 byte
Group ID	1 byte
Data length	1 byte
Data	29 bytes (max)
CRC	2 bytes

field. If the CRC passes, a 1 byte acknowledgment is immediately sent to the sender. This acknowledgment currently contains no useful information.

7.1.5 Power Consumption Model for TinyOS

In order to evaluate the power-DSAP on the TOSSIM we have to use power measurements to calculate the power consumption for transmitting and receiving packets. In (Zheng) the author presented power measurements for TinyOS. The overall power consumption is roughly 1.3mJ per packet for transmitting (by averaging over 500 consecutive packets) and 1.2mJ for receiving.

7.2 DSAP on TOSSIM

In running DSAP on TOSSIM we have used the above power measurements and have also used the TinyViz to show the routing of DSAP and how DSAP chooses among different routes. In the TOSSIM simulation we have two types of packets that were used by TinyOS on TOSSIM; the first one is of type 250 which is broadcast to all the neighbors so they can receive that packet. The other one is of type 17 which transmits specifically to a certain node either destined for that node or to be forwarded to the final destination.

In this simulation we have fixed the final destination so we can show as a proof of concept that the DSAP and DSAP-Power actually perform the routing as described by the algorithms of DSAP.

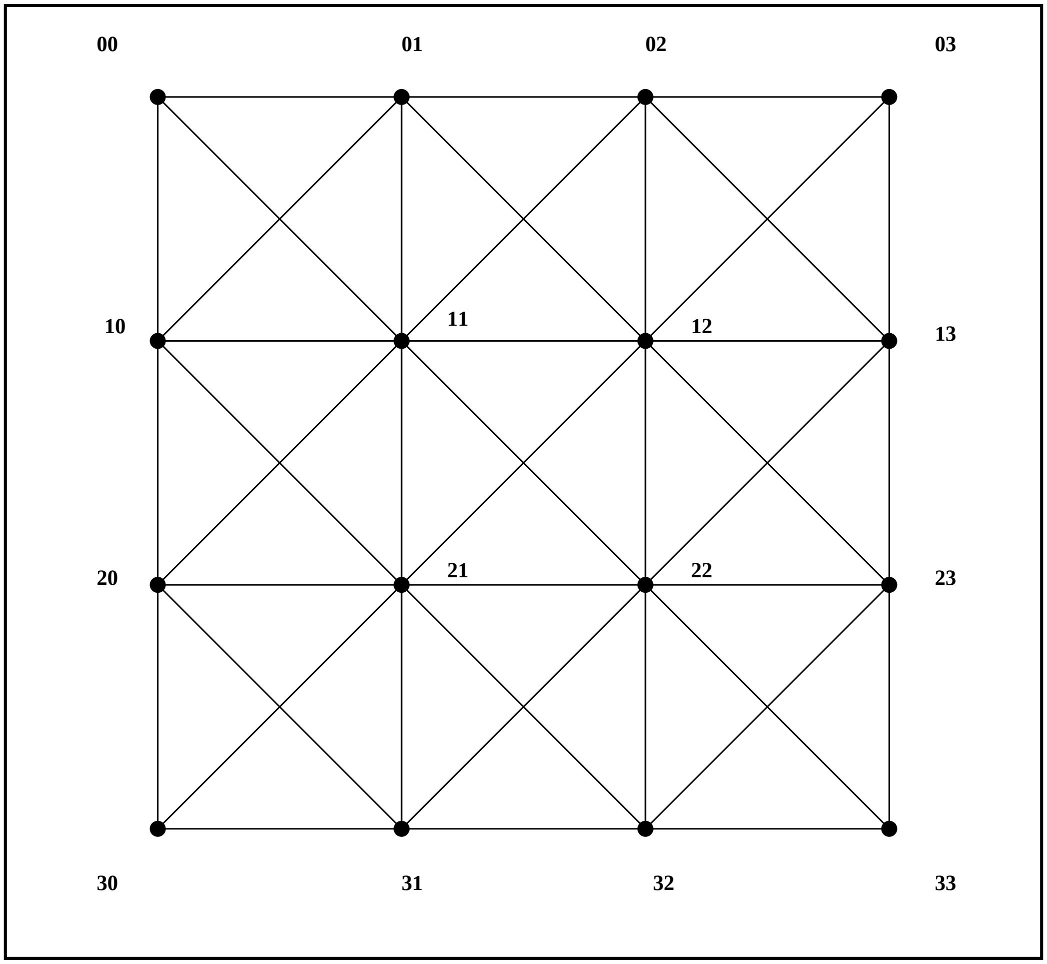


Figure 7.1: 2D Topology with up to 8 Neighbors

In TOSSIM we have used the topology shown in figure 7.1 with 8 neighbors and also hardcoded the directional values of each node and its neighbors as shown in table 7.2. Hardcoding the directional value is reasonable for a small network, or some setup phase could be used to initialize the network.

Figure 7.2 shows the possible routes that a message could take in order to reach the final destination, node 2. For example, if we want to trace the route from node 15 to node 2, the message will take the following path: 15 – 10 – 6 – 2. This will be the case if we have done the theoretical calculation according to algorithm 3.5 in chapter 3.

Figure 7.3 shows TinyViz connecting to TOSSIM running DSAP. The right panel

Table 7.2: Directional Values of 4 × 4 Topology in Figure 7.1

Node	(X,Y)	Dir 0	Dir 1	Dir 2	Dir 3	Dir 4	Dir 5	Dir 6	Dir 7
0	(0,0)	0	0	0	0	3	3	3	0
1	(0,1)	1	0	0	0	2	2	3	1
2	(0,2)	2	0	0	0	1	1	3	2
3	(0,3)	3	0	0	0	0	0	3	3
4	(1,0)	0	0	1	1	3	2	2	0
5	(1,1)	1	1	1	1	2	2	2	1
6	(1,2)	2	1	1	1	1	1	2	2
7	(1,3)	3	1	1	0	0	0	2	2
8	(2,0)	0	0	2	2	3	1	1	0
9	(2,1)	1	1	2	2	2	1	1	1
10	(2,2)	2	2	2	1	1	1	1	1
11	(2,3)	3	2	2	0	0	0	1	1
12	(3,0)	0	0	3	3	3	0	0	0
13	(3,1)	1	1	3	2	2	0	0	0
14	(3,2)	2	2	3	1	1	0	0	0
15	(3,3)	3	3	3	0	0	0	0	0

shows the plugins in TinyViz, while the left panel exhibits radio connectivity for some motes and network traffic. The arrows represent direct connections between two nodes based on hop-by-hop communication according to DSAP. Comparing figure 7.2 and figure 7.3 we see that on both figures the messages take the same paths according to the algorithm for DSAP.

7.3 DSAP–Power on TOSSIM

In running DSAP-Power on the TOSSIM we have used the above power consumption model and also used TinyViz to show the routing for DSAP-Power and how DSAP-Power chooses the different routes. Since TOSSIM has two types of AM messages, we used a type 250 AM message to include the power remaining at that node to be broadcast to its neighbor when that type of message is transmitted. We assume that every node starts with 1J of power and every time a packet is transmitted or received we subtracted the amount of power consumed for that operation.

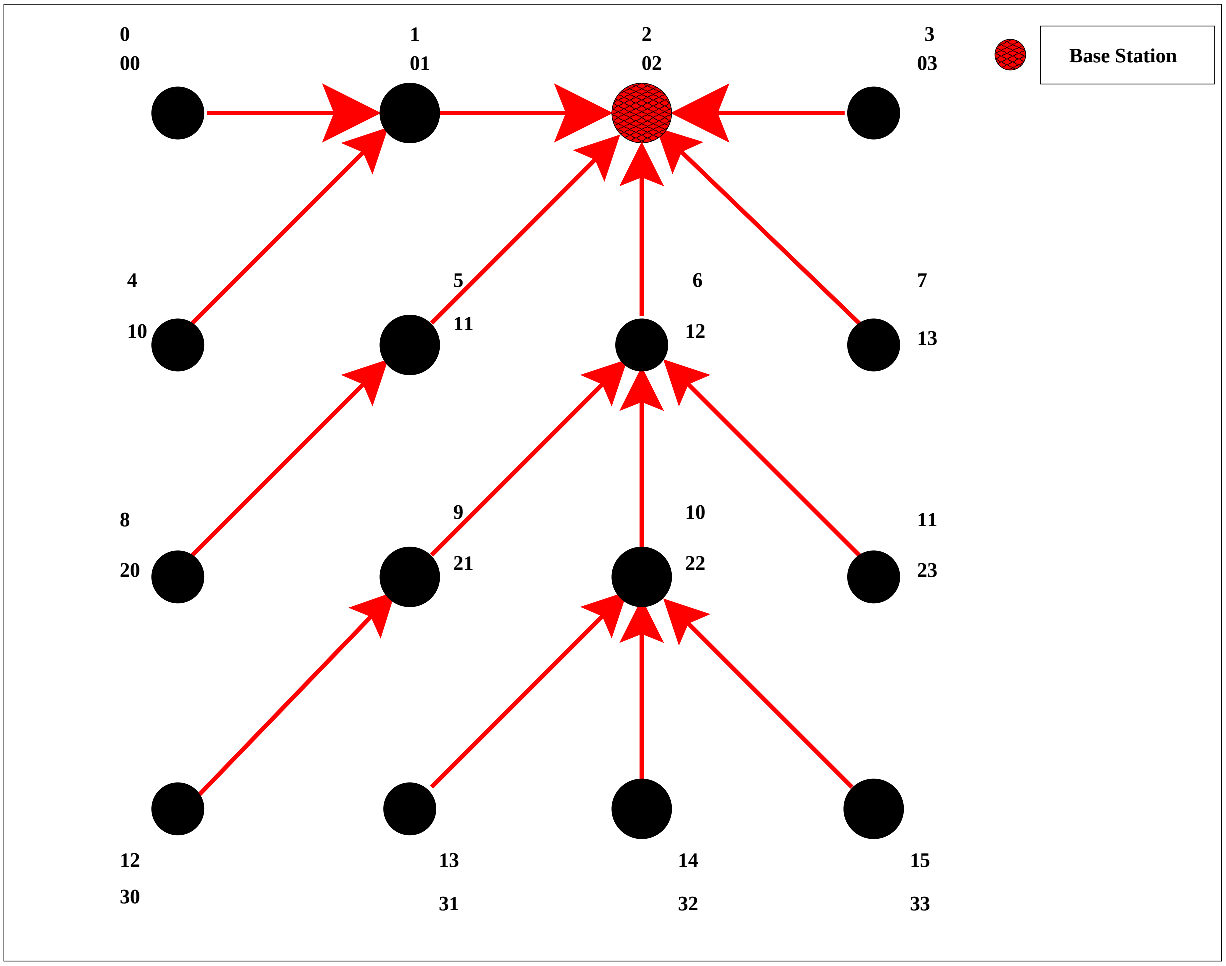
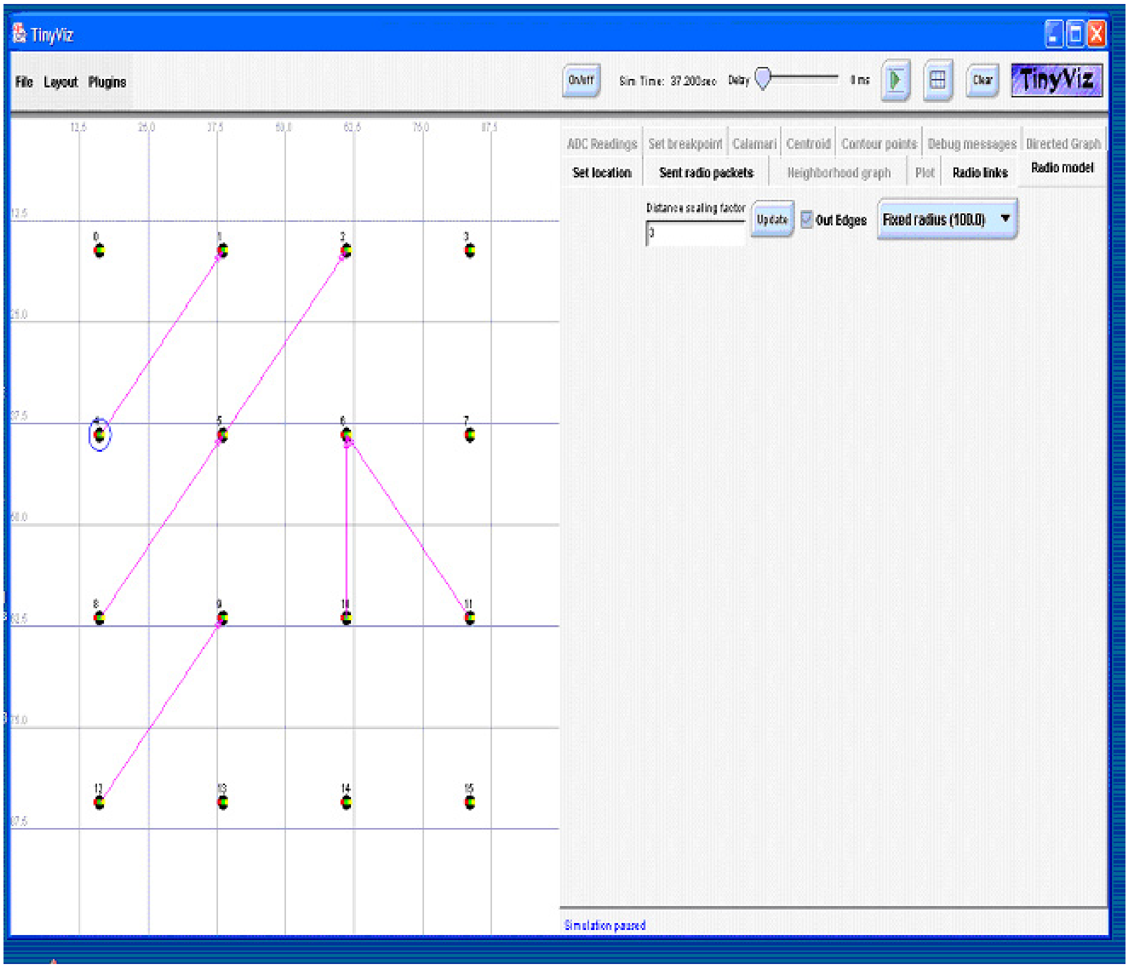


Figure 7.2: Direction of Routing to Final Destination Node 2

We want to show that when there is a power difference between the neighbors, the routing algorithm will choose the node with the maximum ratio of the Directional Value divided by the remaining power at that neighbor.

Figure 7.4 shows how node 15 takes a different route to send to its neighbors than the usual route according to the DSAP without power. In DSAP without power, node 15 takes node 10 as the next hop as shown in figure 7.2, but with the power aware in some cases it takes node 11 as an alternate path to transmit to the Base Station as shown in figure 7.4.

Figure 7.5 shows how node 14 takes a different route to send to its neighbors than



Sim Time: 37.200sec

0 ms

Distance scaling factor: 1

☑ Out Edges

Fixed radius (100.0)

Simulation paused

Figure 7.3: TinyViz connect to TOSSIM running DSAP

the usal route according to the DSAP without power. In DSAP without power node 14 takes node 10 as the next hop as shown in figure 7.2, but with the power aware it takes node 9 as another alternative path to transmit to the Base Station as shown in figure 7.4.

7.4 Summary

In this chapter we implemented DSAP without power and DSAP-Power on TinyOS using TOSSIM and also used TinyViz to show the routing of the messages. Here we wanted to show as a proof of concept that the DSAP with the power aware works when there is a power difference between the neighbor, and that the transmitting node will choose an alternative node to transmit to instead of sending to the same node until that node die.

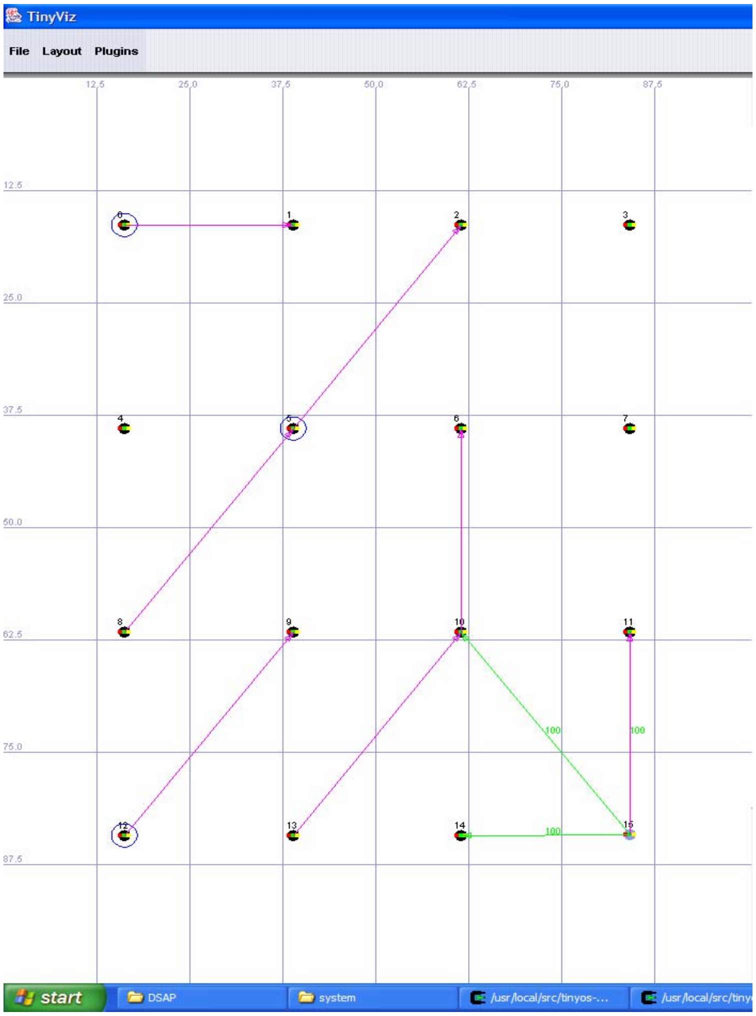


Figure 7.4: TinyViz connect to TOSSIM running DSAP-Power node 15

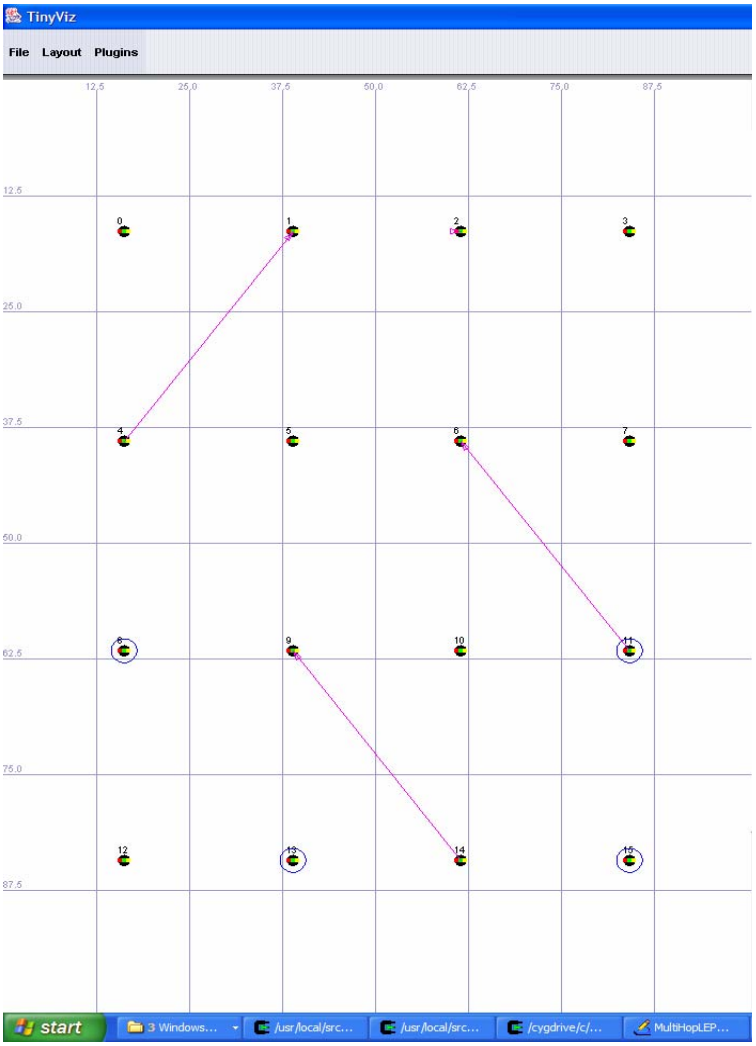


Figure 7.5: TinyViz connect to TOSSIM running DSAP-Power node 14

Chapter 8

Conclusion and Future Work

8.1 Conclusion

Wireless sensor networks have become possible because of the on-going improvements in sensor technology and VLSI. An Important issue in smart sensor networks is achieving efficient operation because of the limited available power. Energy conservation is a critical issue in wireless sensor networks for nodes and network life, as the nodes are powered by batteries only. In order to maximize the lifetime of the nodes and the network, the traffic should be routed such that the energy consumption is balanced among the nodes in proportion to their energy reserves, instead of routing to minimize the absolute consumed power for each message.

In this dissertation we focus on three major points toward an efficient communication for stationary sensor networks. First, we study the relationship between the choice of topology and the power dissipated in the network. Second, we evaluate the effect of power metrics on the choice of routing and the power dissipated in the network. Finally, we determine the effect of using local information instead of using global information on extending the lifetime of the network.

We introduce first the idea of directional routing, which requires only that each sensor know its location within the network relative to the sending node and the destination. This allows the use of simple directional routing based on local information only. For dense networks, sensors near a trajectory from the source to the destination can be found. However, sensors are energy-constrained devices, so selecting paths within this network could benefit from an energy-aware routing process.

In order to develop the idea of directional routing we have developed a Directional Source Aware routing Protocol (DSAP). DSAP is power aware routing protocol that we can implement using different power aware metrics.

From the set of simulations we conclude that it is clear that path selection affects the amount of power used in the network. It is not practical to use edge routing as the mechanism of choice, as it does not scale well. As the number of nodes increases, the number of edge nodes increases at a much smaller rate. This points to a variation of interior routing as the favored choice. DSAP routing was then tested. These simulations show that the new routing scheme does indeed provide a good mechanism for routing the messages. When the power considerations are added to the protocol, we find that the overall power consumption is much more balanced than without taking power into account. This is a very promising result. Since wireless sensor nodes placed in the body can be rechargeable, it is best that they all consume power at the same rate. This allows for more efficient node recharging and even heat dissipation. As interest in wireless sensor networks grows, efficient topologies for stationary wireless networks become more important.

In WSNs we have to look at the network topology from a different perspective, from a neighborhood point of view. In these topologies, the number of neighboring nodes determines the number of receivers and hence may result in more overall power usage, even though the number of transmissions decreases. Thus, there is a fundamental trade-off between decreasing the number of transmissions and increasing the number of receptions. In chapter 4, we have presented a variety of topologies and examined this trade-off.

Because the number of neighbors differs with different topologies, one expects different topologies to have different power usage rates. Even our simulations of the contention-free case show that different topologies have different levels of power efficiency. The results show that the total power consumption is reduced for topologies with fewer neighbors; even though the topologies with more neighbors require fewer hops, the power expended by many nodes to receive these messages increases the power usage. Among the 2D topologies, the best power efficiency is achieved with four neighbors. The 3D topology performs even better, although a 3D topology may not be feasible for some applications.

DSAP was evaluated using different power aware metrics based on only the local information. The simulations show that basing the routing decision on the remaining power of neighboring nodes is not enough by itself. Instead, using the directional value and the sum of power remaining at the next neighbors gives the routing protocol a broader perspective about the condition of the network from a local point of view and enhances the decision process.

Routing packets within a large-scale wireless sensor network without storage overhead and routing table updates is a challenging problem. With a large number of sensors the overhead plays a significant role in the scalability of the routing protocol. In order to avoid this communication overhead, sensor network routing demands new and efficient methods for routing packets. In order to remove or reduce this overhead, the routing protocol needs some way of implicitly, rather than explicitly, defining paths.

The question that we sought to answer is whether we have to know the global state in order to make the protocol perform well. The answer is no, since the results are close, and the difference is not that great between global and local routing. In this paper we used directional routing, where the node needs to know the direction of the final destination in order to forward the packet to the next hop in that direction. Using the ratio of DV/P and the sum of power at the one hop neighbors performs better than other methods in local routing. These results are close to the performance of global routing.

8.2 Future Work

There are still many areas to explore within this research topic. This initial set of experiments serves to demonstrate the marked difference between basic and power-aware DSAP routing. These differences are significant enough to warrant further research. One option would be to rerun the large simulations with each node beginning with a randomly chosen power amount. This would allow for a simulation of a network that has been in use for some time. DSAP can also be extended to include a more efficient power management scheme. Since the message knows in which direction to head, there is no need to broadcast to all neighbors. Rather, the nodes in the wrong direction can be put to sleep. This will reduce the power used, as it takes more power to transmit large message than to poll the neighboring nodes. Contention is also an issue that needs to be addressed in future studies, as it is not realistic to have a system that sends but one message at a time. Although previous work has also ignored this issue to date (Patel, Chai, Yalamanchili, and Schimmel 1997), it is important to find a solution to give a more accurate comparison of the relative performance of the networks.

Fault tolerance is an issue to be considered in the improvement of designing an improved version of DSAP. Since, fault tolerance is the ability of the network to function in the presence of component failures, we want to see how DSAP will function in the presence of more than 20 percent of the nodes are dead. In this case we plane to introduce the idea of backtracking. We mean that, when the direction of routing encounter a dead area that have most of its neighbors are dead. We need to backtrack and try to find another direction. In (Duato, Yalamanchili, and Ni 2003), the authors introduce some models that can be used in DSAP to overcome the failure of nodes and how to route around them.

In studying the topologies we would like to examine the effect of using directional routing on random network? Weneed to determine how to establish the position of each node locally with respect to the other nodes in a random network and how to develop the directional values for that network.

Also we want to introduce a scheduling technique based on local information. It is called **Local Scheduling Multiple Access** (LSMA). The idea of LSMA is that each node coordinates with a local coordinator to issue a schedule. Each node will transmit to its coordinator that it has a packet to transmit. Each node has to join with a local coordinator to synchronize schedules.

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ABSTRACT

EFFICIENT COMMUNICATION IN STATIONARY WIRELESS SENSOR NETWORKS

by

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May 2004

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Wireless sensor networks have become possible because of the on-going improvements in sensor technology and VLSI. An important issue in smart sensor networks is achieving efficient operation because of the limited available power. Energy conservation is a critical issue in wireless sensor networks for nodes and network life, as the nodes are powered by batteries only. In order to maximize the lifetime of the nodes and the network, the traffic should be routed such that the energy consumption is balanced among the nodes in proportion to their energy reserves, instead of routing to minimize the absolute consumed power for each message.

In this dissertation we focus on three major points toward an efficient communication for stationary sensor networks. First, we study the relationship between the choice of topology and the power dissipated in the network. Second, we evaluate the effect of power metrics on the choice of routing and the power dissipated in the network. Finally,we determine the effect of using local information instead of using global information on extending the lifetime of the network.

Routing packets within a large-scale wireless sensor network without storage overhead and routing table updates is a challenging problem. With a large number of

sensors the overhead plays a significant role in the scalability of the routing protocol. In order to avoid this communication overhead, sensor network routing demands new and efficient methods for routing packets. In order to remove or reduce this overhead, the routing protocol needs some way of implicitly, rather than explicitly, defining paths.

We introduce first the idea of directional routing, which requires only that each sensor know its location within the network relative to the sending node and the destination. This allows the use of simple directional routing based on local information only. For dense networks, sensors near a trajectory from the source to the destination can be found. However, sensors are energy-constrained devices, so selecting paths within this network could benefit from an energy-aware routing process.

Secondly, the problem of selecting paths leads us to examine the relationship between power usage and the number of neighbors in a wireless sensor network. Selecting the number of neighbors controls the type of topology to be used. The question that we are seeking to answer is what is the best topology for a wireless network of sensors, assuming we can control the placement of these sensors and the sensor locations are fixed relative to each other. Because the number of neighbors differs with different topologies, one expects different topologies to have different power usage rates. Even our simulations of the contention-free case show that different topologies have different levels of power efficiency. The results show that the total power consumption is reduced for topologies with fewer neighbors even though topologies with more neighbors require fewer hops.

Third, a routing protocol for wireless sensor networks need to be power aware. In order to be power aware we evaluate a number of power-aware routing protocols based on local information only. The simulations show that basing the routing decision on the remaining power of neighboring nodes is not enough by itself. Instead, using the directional value and the sum of power remaining at the next neighbors gives the routing protocol a broader perspective about the condition of the network from a local point of view and enhances the routing decision process.

Finally, in order to gain some understanding of the quality of these local metrics, we also compare the energy usage and path length of these local methods with respect to some routing techniques based on global information. This evaluation demonstrates that changing the routing metric can dramatically affect the performance of the sensor network. These results also shows trade-off between extending the lifetime of the sensor network and reducing the average number of hops a message travels to the base station.

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PUBLICATIONS

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FIELD OF STUDY

Major Field: Computer Engineering