Power Efficient Topologies for Wireless Sensor Networks*

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1 Motivation

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 that can be installed in a building to monitor the building or in an assembly. 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 . Also the use of regular topology or mesh topologies, a node also function as a router and can relay messages for its neighbors. Those networks offers multiple redundant communications paths throughout the network. If one node die or fail other nodes can be use to reroute the message. Also 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.

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2 Background

Much of the related research addresses WSN that are mobile and 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 [7]. 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, as discussed below.

LEACH [2, 13] (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 clusterhead 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.

SPIN [3, 5] (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.

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 [8]. 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 [1]. 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.

Limited research has been conducted on the effect that topology has on wireless networking [4, 9, 12]. 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.

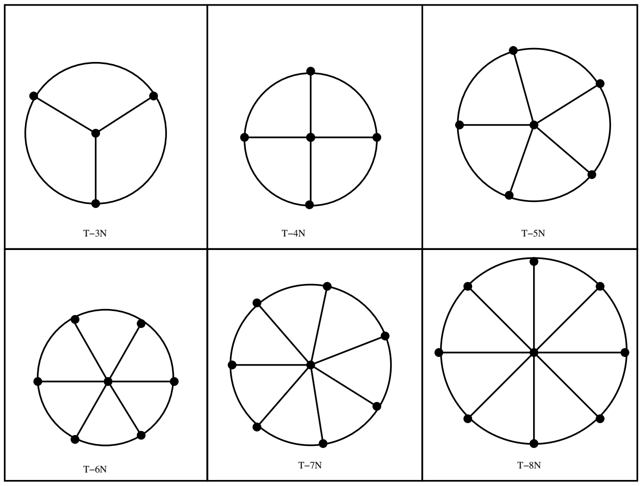

Figure 1. Possible number of Neighbors

3 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, which 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 on 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 transmission. 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) , 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 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 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.

3.1 Three Neighbors WSN

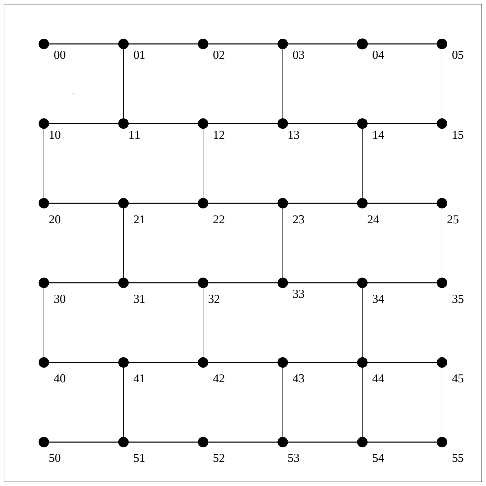

Figure 2. 2D Topology with up to 3 Neighbors

According to figure 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) = $\begin{cases} \triangle x + \triangle y & \text{if } \triangle x \geqslant \triangle y \\ 2\triangle y \pm 1 & \text{if } \triangle x < \triangle y \end{cases}$

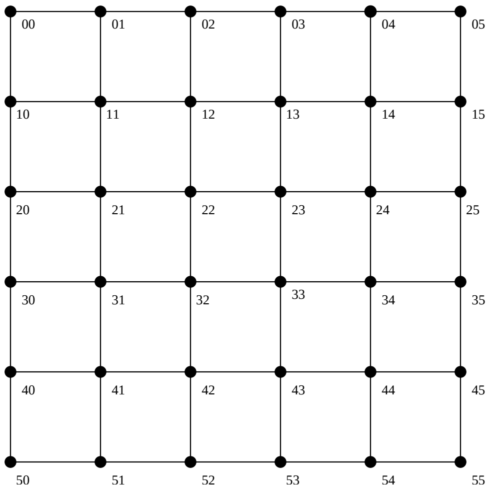

Figure 3. 2D Topology with up to 4 Neighbors

3.2 Four Neighbors WSN

According to figure 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) = $\triangle x + \triangle y$

3.3 Five Neighbors WSN

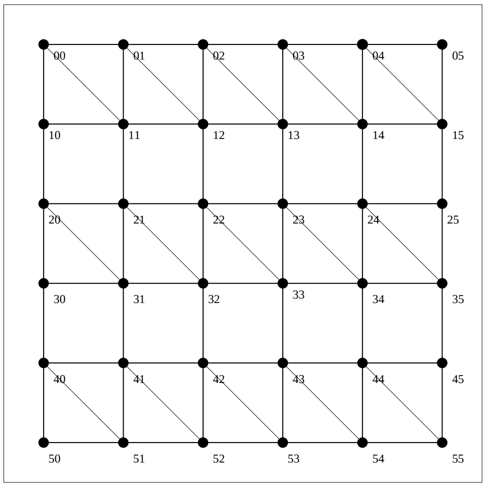

Figure 4. 2D Topology with up to 5 Neighbors

According to figure 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 $y < m-1$
    - $\langle (y,x),(y+1,x+1)\rangle$ for even x.
    - $\langle (y,x),(y-1,x-1)\rangle$ for odd x.
2. Optimal Number of hops (s, d) = $\begin{cases} \triangle x + 2 & \text{if } x_s \geqslant x_d \text{ and } y_s > y_d \\ & \text{or } x_s \leqslant x_d \text{ and } y_s < y_d \\ \triangle x + \triangle y & \text{Otherwise} \end{cases}$

3.4 Six Neighbors WSN

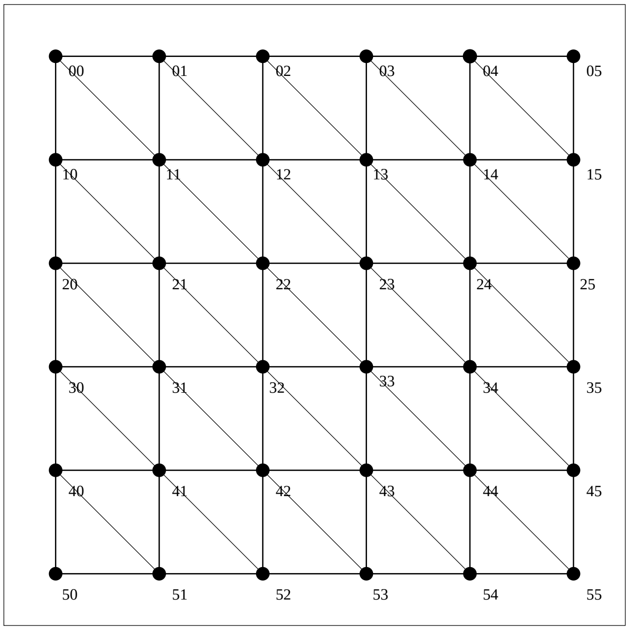

Figure 5. 2D Topology with up to 6 Neighbors

According to figure 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. Two nodes are not neighbors if

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

3.5 Seven Neighbors WSN

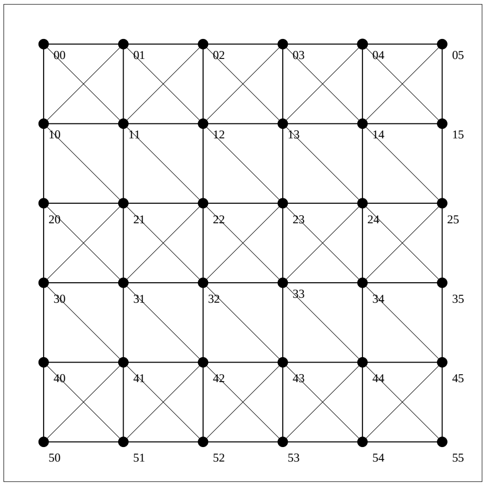

Figure 6. 2D Topology with up to 7 Neighbors

According to figure 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) = $\begin{cases} \triangle x + 2 & \text{if } x_s > x_d \text{ and } y_s < y_d \\ & \text{or } x_s < x_d \text{ and } y_s > y_d \\ \max(\triangle x, \triangle y) & \text{Otherwise} \end{cases}$

3.6 Eight Neighbors WSN

According to figure 7 note the following:

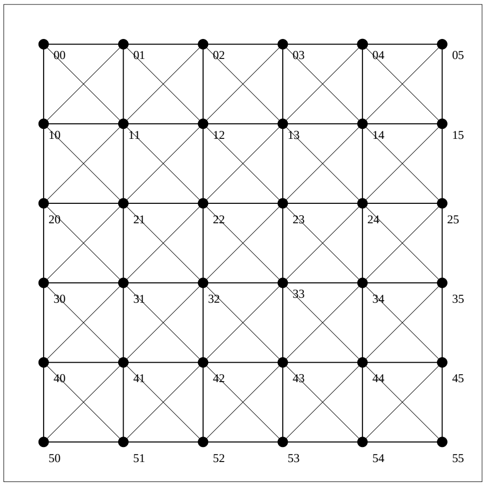

Figure 7. 2D Topology with up to 8 Neighbors

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) = $\max(\triangle x, \triangle y)$

3.7 Six Neighbors for 3D

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:

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

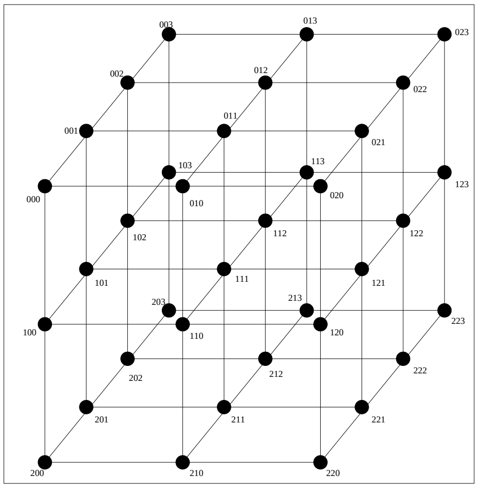

Figure 8. 3D Topology with up to 6 Neighbors

Two nodes are neighbors if:

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

Optimal Number of Hops (S_{3D}, D_{3D}) = $\triangle x + \triangle y + \triangle z$

4 Assumptions

In our work, we assume a simple model where the radio dissipates E$_{elec}$ = 50 nJ/bit to run the transmitter or receiver circuitry and E$_{amp}$ = 100 $pJ/bit/m^2$ for the transmit amplifier to achieve an acceptable E$_b/N_0$ (see Figure 9 and Table 1) [2]. To transmit a k-bit message a distance d meters using this radio model, the radio expends:

$$\begin{aligned} E_{Tx}(k,d) &= E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \\ &= E_{elec} * k + E_{amp} * k * d^2 \end{aligned} \quad (1)$$

To receive this message, the radio expends:

$$\begin{aligned} E_{Rx}(k) &= E_{Rx-elec}(k) \\ &= E_{elec} * k \end{aligned} \quad (2)$$

For simplicity of calculation we will assume that the transmission range of each node is equal to each other on one condition that the value of this transmission range should reach the number of neighbors that is allowed for each network

Table 1. Radio Characteristic [2]

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 $pJ/bit/m^2$

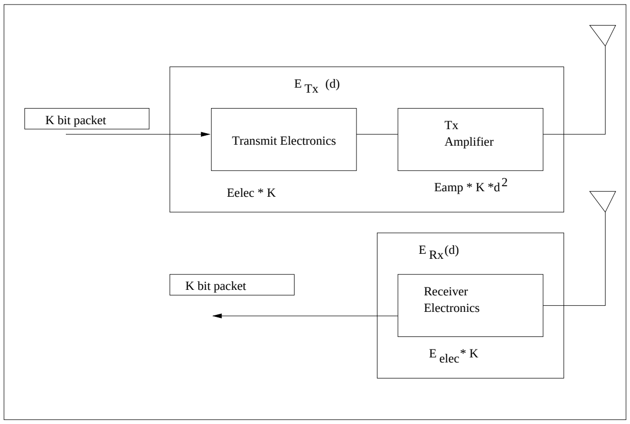

Figure 9. First Order Radio Model

(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, and number of bits transmitted $k = 512$ bits. The number of nodes N was chosen to be 36 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 [7].

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.

4.1 Calculation of the Power Usage for each path

In order to derive the general equations for transmitting a message from a source S to a destination D, we have to consider two things for each path:

- Number of Transmissions.
- Number of Receptions.

Number of transmissions can be measured as the number of hops a packet will travel through a certain path. Number of receptions is the total number of neighbors of each hop that is taken.Minimizing the number of transmission and number of receptions will be the mission any protocol that will be designed. In general, the total power dissipated in the network for one packet to travel from a source to a destination is the sum of total power used for transmission plus the total power used for receiving of the packet at each neighbor of each transmitting source.

In the next equation we will present an estimate for the total power used to transmit a packet over a number of hops from a source S to a destination D.

$$TotalPowerUsed = TotalPowerTransmitted + TotalPowerReceived \tag{3}$$

Equation 3 can be written as:

$$\begin{aligned} TotalPowerTransmitted &= NumberofHops \times PowerTransmitted \\ &= NumberofHops \times E_{Tx}(k, d) \end{aligned} \tag{4}$$

$$\begin{aligned} TotalPowerReceived &= NumberofHops \times NumberofNeighbors \times PowerReceived \\ &= Numberofhops \times NumberfoNeighbors \times E_{Rx}(k) \end{aligned} \tag{5}$$

Substitute equation 4 and equation 5 in eqaution 3 we get the following:

$$TotalPowerUsed = NumberofHops \times (E_{Tx}(k, d) + NumberfoNeighbors \times E_{Rx}(k)) \tag{6}$$

These equations only estimate the power that will be used for a certain number of hops with a fixed number of neighbors. the idea here is to try to minimize equation 3 either by minimizing the total power transmitted and this can be done by minimizing the number of hops by finding the shortest path. Also equation 3 can be minimized by minimizing the total power received and this can be done by taking the paths that have the least number of neighbors. In the next section we will present and analyze the effect of choosing different paths on equation 3.

5 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:

Table 2. 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}

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 were 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.

5.1 Two Dimensional Analysis

The Degree of Routing Freedom is the number of alternative paths that a routing protocol can select. Figures 2 – 7 show that as the number of neighbors increases, the degree of routing freedom increases. For comparison purposes, we fixed the source, destination, 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.

5.1.1 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 2 we notice that as the number of neighbors increases the number of transmissions decrease but the number of receptions depend on the topology. This is because as we increase the number of neighbors the routing protocol has more freedom to choose the shortest path to the destination and by doing so the protocol will dissipate less power to route a packet from source to destination.

Table 3. 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}

5.1.2 Edge Routing

Using edge routing is to route the packet using only the edge nodes. This strategy of routing of course is 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 3, we see that as the number of neighbors increase the number of neighbors that receive the packet increases, and this will increase the energy used in the network.

5.1.3 Edge Routing vs. Interior Routing

From tables 2 and 3, 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 is the same but the difference is that taking the edge results in less number of neighbors and interior paths have more number of neighbors. With either routing strategy, as the number of neighbors increases the power dissipated increases for the same number of transmissions.

5.1.4 Fixed Number of Transmissions

In this section we want to study the effect of increasing the number of neighbors. In order to do that we fixed the number of transmissions that a certain path can have and also fixed a 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 $(1, 1)$, $(2, 2)$, $(3, 3)$, $(4, 4)$, $(5, 5)$, $(6, 6)$, $(7, 7)$, and $(8, 8)$. By using this path we can control the path and study the effect of increasing the number of neighbors. As shown in table 4, as the number of neighbors increases the number receptions increases also. This yields to an increase in the energy used in the network.

5.1.5 Routing Freedom

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

Table 4. 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}

Table 5. 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	$8.768 \times 10-4$

In Table 5, 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 2 and 5.

As we can see from Table 5, 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 6.

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.

5.2 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 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 8.

Table 6. 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}

Table 7. 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

Table 8. 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

From table 7, 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 8 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 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 edges closer than the 2D . So there is a trade-off between using edge routing and using interior routing for the two different dimensions.

6 Directional Source Aware routing Protocol (DSAP)

In order to resolve the problems of power efficiency, 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 that will help in the routing of the packets. The system has the following properties:

- Each node has unique ID.
- Each value represents how far the node is from a certain direction.
- Each ID gives how far the node is from the nodes in each direction.
- Each node can compute the direction of other nodes from its ID.

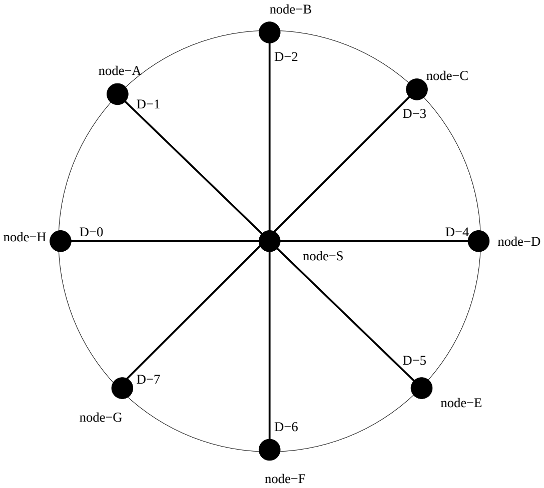

Figure 10. Directional 8 Neighbor node

To help in studying the effect of using different number of neighbors, we have developed a routing scheme based on the identification system that we have. This identification system we refer to as the **directional value (DV)**. To construct the directional value, each node in each topology that has been used has fixed number of neighbors. Each neighbor represents a direction that the node can route through it, as shown if figure 10. 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 purpose of routing.

Each topology was constructed from figure 10 by eliminating the directions that will make 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.

From this directional value we have developed a Directional Source-Aware routing Protocol (DSAP) [11]. DSAP [11] incorporates the directional value and power into routing protocols. For instance, in the four-neighbor case of Figure 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.

In figure 10, 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. When transmitting a message, the destination node identifier is subtracted from the source node identifier. This yields at most five positive 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 numbers are added together and the one with the smaller number is chosen. If both nodes have the same DV, then one is randomly picked. This is the basic scheme developed for routing the messages.

For example, in figure 7 consider the source node $S_{1,1}$ with $DV_{1,1}$=$(1, 1, 1, 1, 4, 4, 4, 1)$ and destination node $D_{4,4}$ with $DV_{4,4}$=$(4, 4, 4, 1, 1, 1, 1, 1)$. According to the algorithm of DSAP [11], 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 positive directions that the message can be forwarded to, then computes the directional value of each positive 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 7. 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 incorporated 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 smaller 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 [10] the authors presented several power aware metrics that can be incorporated with DSAP. The idea here is to show that using a power aware methods will extend the life of the network and have a fair load balance between the nodes. So here used one method only to show the effect of using power aware rather than using shortest path metrics.

7 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 that will extend the life of the network, since extending the life of the network is one of the main objectives of designing wireless sensor networks.

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

In the simulation we have two runs. First, fixed run from $S(0, 0)$ to $D(5, 5)$. Second , a run that each node sends a message to every 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 networks.
- T P A means the total power available for the network.

Table 9. 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

- T P R means the total power received by the neighbors of a transmitting source.
- T P T means the total power used for transmitting these packets.
- GeoMean is the Geometric Mean.
- STDEV is the standard deviation.

7.1 Two Dimension Analysis

In table 9, a message is sent from source $(0, 0)$ to destination $(5, 5)$ for 10000 times. We note the following:

- 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 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 9, but looking figure 11 and 12 we notice DSAP with power aware has a better power distribution than DSAP without power aware. This means that we can extend the life of the network using the power aware concept.

In table 10 and 11, we studied when the first node die in the network. We notice th following:

- In table 10, that 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 takes the same path, which means these nodes will lose power faster than other nodes.
- In table 11, we notice that the first node died at different rounds and even at a higher number of rounds than in table 10. This is because in table 11 DSAP with power aware was used. This gives the routing protocol more alternative paths to

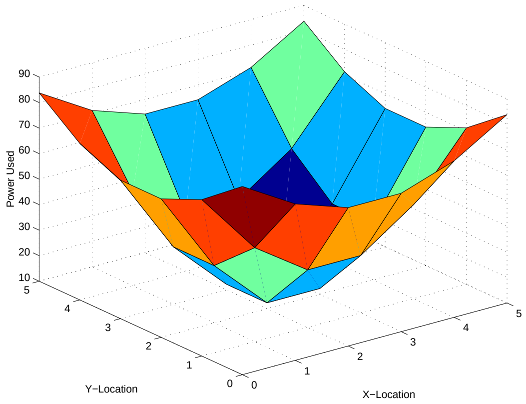

Figure 11. Remaining Power in each Node using DSAP

use and also balances the load in the network.

- Also notice that in table 11 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.

In table 12, 13, and 14, 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 the DSAP without power aware and also for the power aware protocol.

In table 12, we observe the following:

Table 10. 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

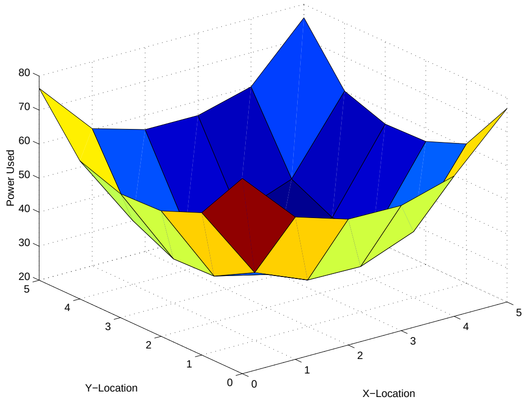

Figure 12. Remaining Power in each Node using Aware–DSAP

- 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 in higher than the DSAP without power aware. This is because alternative paths have been used, resulting in a better load balance than the DSAP without the 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

Table 11. 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

Table 12. 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 13. 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

DSAP with power aware balances the load among all the nodes.

In table 13 and 14, we compare the two protocols at round 28512 to study the geometric mean, the standard deviation and different power parameters. We onserve the following:

- In table 13, notice that DSAP aware has a lower standard deviation than the DSAP, but has in some cases higher geometric mean.
- In table 13, we notice that the topology with four neighbors has a lower standard deviation in both protocols.
- In table 14, we notice that as we increase the number of neighbors, the number fo transmissions decreases as we have noted in table 9.

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 14. 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 15. 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

7.2 Three Dimension Analysis

In table 15, different run 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 that their is only a difference in the number of reception in the network. This is because when the network is used more the Dsap with power aware tries to find alternative paths with more power. If we look at 10000 and 100000 we notice that the power used is lees in the DSAP with power aware than the DSAP without power aware and this is for the same reasons that was mentioned before.

8 Summery

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 the 2D with four neighbors. The 3D topology performs even better, although a 3D topology may not be feasible for some applications.

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 the 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 [7], it is important to find a solution to give a more accurate comparison of the relative performance of the networks.

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