# Power Efficient Topologies for Wireless Sensor Networks*

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## Abstract

*Wireless sensor networks have become possible because of the on-going improvements in sensor technology and VLSI. One issue in smart sensor networks is achieving efficient operation because of the limited available power. For important classes of sensor networks, such as biomedical sensors, the locations of the sensing nodes are fixed and the placement can be pre-determined. In this paper, we consider the topology that best supports communication among these sensor nodes. We propose a power-aware routing protocol and simulate the performance, showing that our routing protocol adapts routes to the available power. This leads to a reduction in the total power used as well as more even power usage across nodes. We consider different routes and topologies, demonstrating the difference in performance and explaining the underlying causes.*

**Keywords**: Wireless sensor networks, topology, power adaptive routing, simulation, resource aware.

## 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 [6]. While the space station research is concentrating on direct networks, this would be an excellent case were the flexibility of wireless networking could be aptly applied.

There are also countless medical applications, including monitors and implantable devices, such as a retinal prosthesis [9]. 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. Before we can use WSN in these applications, however, we need to overcome several obstacles, including limited energy, computational power, and communication resources available to the sensors in the network [5].

A wireless smart sensor network node can include MEMS components such as sensors, RF components, actuators, or CMOS building blocks such as interface pads, data fusion circuitry, specialized and general purpose signal processing engines or micro-controllers [7]. These individual nodes can be *resource-aware* – expose their system resources to other node over the network and manage to reduce participation in the network, and *resource-adaptive* – can adapt to the environment that they are in and change the way they communicate with other nodes. More important than the individual data in a wireless sensor network is the aggregate data that the network contains, for this gives a clear, multi-dimensional view of the sensing environment.

In this paper, we will examine the relationship between power usage and the system parameters of a wireless sensor network and then present our solution, Directional Source Aware-Protocol (DSAP). In studying the relationship between the power performance and system parameters, we first need to identify some of these system parameters that we encounter in our study of the WSN: (a) Distance between nodes, (b) Network topology, (c) Routing algorithm, (d) Transmitter power, (e) Network capacity, (f) Data encoding, (g) Modulation schemes, (h) Channel RF band-

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width, and (i) Channel access.

We will study the effect of choosing different topologies on the power dissipated in the network with all other parameters fixed. 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, 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.

## 2 Related Work

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 [6]. 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, 11] (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 [7]. 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, 8, 10]. 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.

## 3 Problem Statement

Wireless sensor networks typically have power constraints. The absence of wires implies the lack of an external power supply such as battery packs. Although photovoltaics 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. Moreover, for biomedical sensors, power usage results in heat dissipation that may further require minimizing the total power consumed by the wireless sensor network.

In this paper 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.

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 results 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 paper, we simulate a variety of topologies to examine this trade-off.

In this paper, 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 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 1 and Table 1) [2]. To transmit a $k$-bit message a distance $d$ meters using our 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 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.

We are going to assume that the distance between the wireless nodes is equal to each other and all data packets contain the same number of bits. In this paper we are minimizing the overall power dissipated in the system.

**Table 1. Radio Characteristic [2]**

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

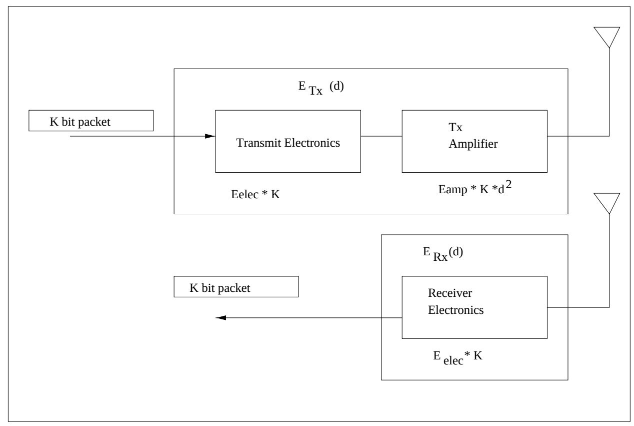


**Figure 1. First Order Radio Model**

We assume the following parameters: the distance $d = 0.5$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 [6]. The topologies that we are going to evaluate are as follows:

- 2D Mesh with maximum of 3 neighbors (Figure 2).
- 2D Mesh with maximum of 4 neighbors (Figure 3).
- 2D Mesh with maximum of 6 neighbors (Figure 4).
- 2D Mesh with maximum of 8 neighbors (Figure 5).
- 3D Mesh with maximum of 6 neighbors (Figure 6).

## 5 The DSAP Protocol

When considering the constraints and requirements, we found that existing routing protocols are either inefficient or inadequate, mainly because there has been little if any research on routing for low-power fixed wireless topologies.

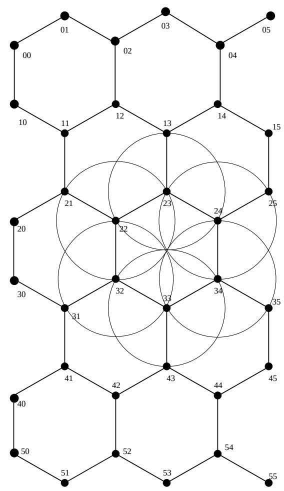

**Figure 2. 2D Topology with up to 3 Neighbors**

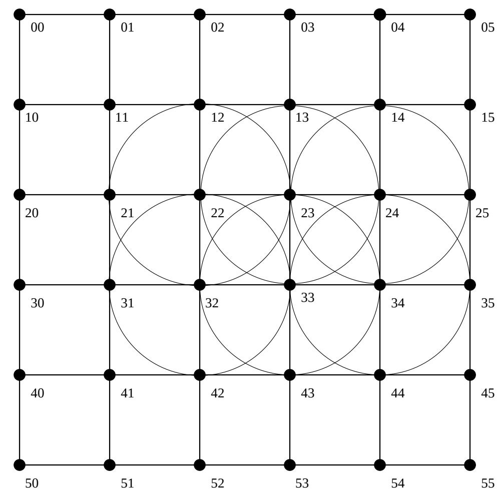


**Figure 3. 2D Topology with up to 4 Neighbors**

This led us to develop the Directional Source-Aware Protocol (DSAP). DSAP has many advantages over other routing protocols, including incorporating power considerations and having no routing table. The routing works by assigning each node an identifier that places that node in the network. Each of the numbers tells how many nodes separate that node from the edge of the network through all possible directions. For instance, in the four-neighbor case of Figure 3, node 31 would have an identifier of $(1, 3, 4, 2)$. This means that there is 1 node to the edge in direction 0 (left), 3 in direction 1 (up), 4 in direction 2 (right), and 2 in direction 3 (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.

When transmitting a message, the destination node identifier is subtracted from the source node identifier. This gives at most two positive numbers (for a 2D topology with 4 neighbors) that describe in which way the message needs to move, one in either north or south, and one in either east or west. Negative numbers are disregarded. The decision to move right/left or up/down is determined by the *directional value* of the nodes in question. Taking each of the neighbor's identifiers and subtracting it from the destination node's identifier computes the directional value (DV). These four 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.

Consider a 2D network with 6 neighbors (Figure 4). Node 51 is the source with an identifier $(1, 5, 4, 4, 0, 0)$ and node 33 is the destination with an identifier $(3, 3, 2, 2, 2, 2)$. According to the DSAP routing, first we subtract the directional values of 33 from 51 resulting $(-2, 2, 2, 2, -2, -2)$. Only the positive directions are considered, which means taking one of the three directions leading to 41, 42, and 52. Node 42 has the lowest DV with respect to the destination. Therefore, DSAP selects 42 as the new source. Since each node is aware of its neighbors, node 42 transmits the message directly to 33 thus completing the transmission.

This is the basic scheme developed for routing the messages. However, the objective was to incorporated energy efficiency as well. This was 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.

## 6 Analysis of Power Usage

In this section, the 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 and show the relative performance of each.

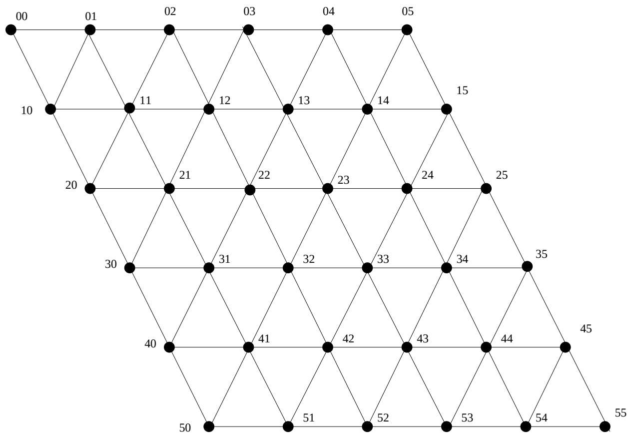


**Figure 4. 2D Topology with up to 6 Neighbors**

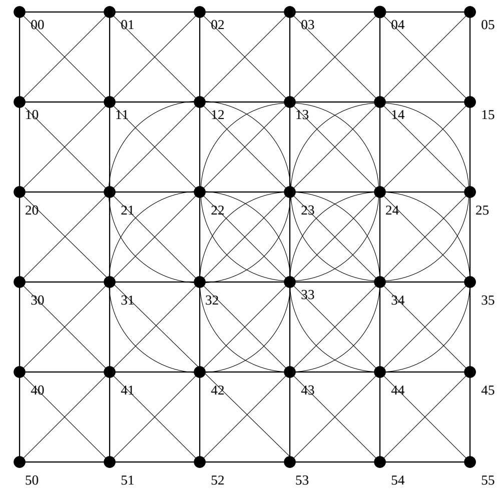


**Figure 5. 2D Topology with up to 8 Neighbors**

**Table 2. Interior Routing, 2D**

| Neighbors | $T_x$ | $R_x$ | Energy Used |
|---|---|---|---|
| 3 | 10 | 27 | $9.473 \times 10^{-4}$ |
| 4 | 10 | 36 | $11.777 \times 10^{-4}$ |
| 6 | 10 | 52 | $15.873 \times 10^{-4}$ |
| 8 | 10 | 69 | $20.225 \times 10^{-4}$ |

## 6.1 Analysis of overall power dissipation

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, six, and eight neighbors. Second, we consider three-dimensional networks with six neighbors. 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. Shortest paths are used in the next set of simulations. For both routes, a message is sent over the diameter of the network.

### 6.1.1 Two Dimensional Analysis

The Degree of Routing Freedom is the number of alternative paths that a routing protocol can select. Figures 2 – 5 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.

From tables 2 and 3, edge routing dissipates less power than interior routing in all cases except for 3 neighbors. This is because the 3 neighbor network makes edge routing difficult. With either routing strategy, as the number of neighbors increases the power dissipated increases for the same number of transmissions.

In Table 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 shown in Figures 2 and 4.

As we can see from Table 4, increasing the number of neighbors decreases the number of transmissions and 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 5.

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 3. Edge Routing, 2D**

| Neighbors | $T_x$ | $R_x$ | Energy Used |
|---|---|---|---|
| 3 | 14 | 33 | $12.034 \times 10^{-4}$ |
| 4 | 10 | 28 | $9.729 \times 10^{-4}$ |
| 6 | 10 | 37 | $12.033 \times 10^{-4}$ |
| 8 | 10 | 46 | $14.337 \times 10^{-4}$ |

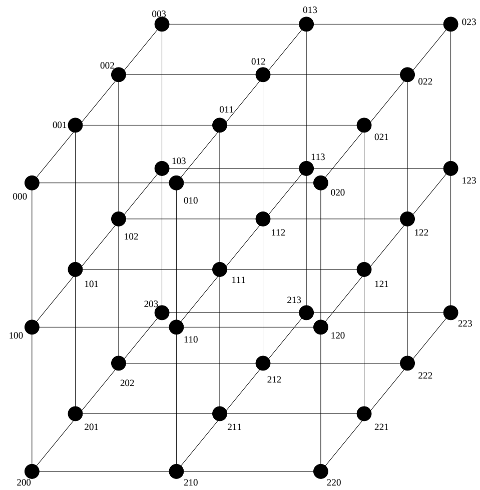


**Figure 6. 3D Topology with up to 6 Neighbors**

**Table 4. Routing Freedom and Power Dissipation; 3 and 6 Neighbors**

| Neighbors | $T_x$ | $R_x$ | Energy Used |
|---|---|---|---|
| 3 | 10 | 27 | $9.473 \times 10{-}4$ |
| 6 | 5 | 27 | $8.193 \times 10{-}4$ |

#### 6.1.2 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 6, 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 6.

**Table 5. Routing Freedom and Power Dissipation; 4 and 8 Neighbors**

| Neighbors | $T_x$ | $R_x$ | Energy Used |
|---|---|---|---|
| 4 | 10 | 36 | $11.777 \times 10^{-4}$ |
| 8 | 5 | 38 | $11.009 \times 10^{-4}$ |

**Table 6. Edge and Interior Routing Power Dissipation**

| Network | Path | $T_x$ | $R_x$ | Energy Used $\times 10^{-4}$ |
|---|---|---|---|---|
| 2D 4 Neighbor | Interior | 10 | 36 | 11.777 |
| | Edge | 10 | 28 | 9.729 |
| 3D 6 Neighbor | Interior | 7 | 27/33 | 8.705 – 10.241 |
| | Edge | 7 | 25 | 8.193 |

From Table 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.

### 6.2 Analysis of DSAP

In order to evaluate the performance of DSAP, several simulations with the various topologies were run. Java simulation program was developed that incorporated the number of nodes, topology, distance, number of bits transmitted, power transmitted / received for each node. These simulations were conducted for 1000, 10,000, and 100,000 messages. The source and destination of each message are chosen randomly. All nodes start with the same initial power level. For each pair simulations we used the same set of nodes both for the power-aware and not power-aware routing. A network size of 36 was chosen, since it fits nicely with all of the topology cases considered. The Java program returned key values, including the total power dissipated in the system to receive and transmit the bits.

In this simulation we have two versions of DSAP. The first one is DSAP routing without power-aware routing and the second is Power-DSAP with power-aware routing. DSAP routing selects the paths according to the minimum directional value whereas Power-DSAP routing selects the paths according to the ratio of the directional value and the power available at the neighboring nodes. Tables 7 – 9 summarize the results of these simulations.

As we increase the load by a factor of 10 we notice that the power dissipation also increases by almost the same factor. From Table 7, we can observe the following:

**Table 7. 1000 Node Pairs**

| | | DSAP routing (Not Power Aware) | | |
|---|---|---|---|---|
| Neighbors | | $T_x$ | $R_x$ | Total Power used |
| 2D | 4 | 3881 | 13649 | 0.4488177 |
| | 6 | 3311 | 17203 | 0.5252008 |
| | 8 | 2712 | 18926 | 0.5539675 |
| 3D | 6 | 3051 | 13228 | 0.4167816 |
| | | Power-DSAP (Power Aware) | | |
| Neighbors | | $T_x$ | $R_x$ | Total Power used |
| 2D | 4 | 3881 | 13235 | 0.4382193 |
| | 6 | 3311 | 16818 | 0.5153448 |
| | 8 | 2712 | 18926 | 0.5539675 |
| 3D | 6 | 3051 | 12573 | 0.400014 |

**Table 8. 10,000 Node Pairs**

| | | DSAP routing (Not Power Aware) | | |
|---|---|---|---|---|
| Neighbors | | $T_x$ | $R_x$ | Total Power used |
| 2D | 4 | 38932 | 137051 | 40505663 |
| | 6 | 33089 | 172018 | 5.211627 |
| | 8 | 27412 | 190813 | 5.5869109 |
| 3D | 6 | 30131 | 131043 | 4.126413 |
| | | Power-DSAP (Power Aware) | | |
| Neighbors | | $T_x$ | $R_x$ | Total Power used |
| 2D | 4 | 38932 | 132163 | 4.38053 |
| | 6 | 33121 | 167551 | 5.137627 |
| | 8 | 27548 | 191085 | 5.597357 |
| 3D | 6 | 30131 | 123656 | 3.937333 |

**Table 9. 100,000 Node Pairs**

| | | DSAP routing (Not Power Aware) | | |
|---|---|---|---|---|
| Neighbors | | $T_x$ | $R_x$ | Total Power used |
| 2D | 4 | 388540 | 1369487 | 45.010465 |
| | 6 | 331801 | 1723883 | 52.629757 |
| | 8 | 274405 | 1908911 | 55.896402 |
| 3D | 6 | 302160 | 1312998 | 41.35415 |
| | | Power-DSAP (Power Aware) | | |
| Neighbors | | $T_x$ | $R_x$ | Total Power used |
| 2D | 4 | 388540 | 1317896 | 43.689735 |
| | 6 | 349314 | 1725563 | 53.121322 |
| | 8 | 287599 | 1918073 | 56.468884 |
| 3D | 6 | 302160 | 1239477 | 39.469775 |

1. The number of transmissions is the same for both DSAP and Power-DSAP, because we are using only a small number of messages (1000) for simulation.

2. Power dissipated is less when Power-DSAP is used for both the 2D as well as the 3D.

3. An increase in the number of neighbors increases the total power used regardless of the type of routing used.

4. The 3D network consumes less power than any of the 2D configurations. This is because more nodes are distributed around the edges rather than the interior.

From Tables 8 and 9 we observe the following: both the 2D-4 neighbor and the 3D-6 neighbor topologies have the same number of transmissions but differ in the number of receptions. This is because the 2D-4 neighbor and the 3D-6 neighbor networks have the same characteristics. On the other hand, for the 2D-6 and 8 neighbors, Power-DSAP has more transmissions than DSAP, because Power-DSAP routes around nodes that are low on power.

In figures 7 and 8 we plot the power distribution among the nodes for DSAP and Power-DSAP. We can see that Power-DSAP distributes the power almost equally among the interior nodes by adopting routes with higher power.

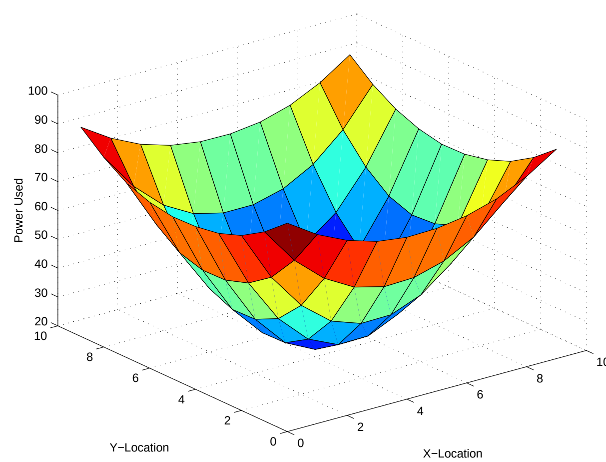


**Figure 7. Remaining Power in each Node using DSAP**

In general, we can conclude that the 3D network dissipates less power than the 2D network for both DSAP routing and Power-DSAP routing. Moreover, Power-DSAP performs better than DSAP for the 3D network. Finally, the 2D network with 4 neighbors consumes less power than 2D networks with 6 and 8 neighbors in all the simulations. This is because of the trade-offs between the number of neighbors and the power dissipated in the system.

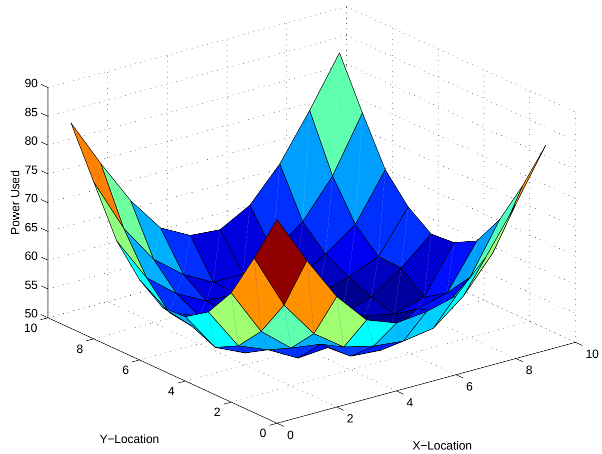


**Figure 8. Remaining Power in each Node using Power-Aware DSAP**

## 7 Conclusions Future Work

In this paper, we considered three major topics: overall power dissipation, DSAP routing, and Power-DSAP routing. The first set of simulations was a proof of concept. From this 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, for since the nodes are 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. The Power-DSAP routing protocol is a promising candidate for addressing this problem.

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

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