Optimizing physical layer parameters for wireless sensor networks

Matthew Holland

Supervised by
Professor Wendi Heinzelman

A thesis
submitted in partial fulfillment
of the
Requirements for the Degree of
Master of Science
in
Electrical and Computer Engineering

University of Rochester
Rochester, New York

2007

Curriculum Vitae

The author was born in Cortland, New York on April 29th, 1984. He attended the University of Rochester from 2002 to 2006, and graduated with a Bachelor of Science in Electrical and Computer Engineering concentrating in waves and devices. He then continued his studies at the University of Rochester in the 3-2 Masters program in Electrical and Computer Engineering, concentrating on communications. With the guidance of Professor Wendi B. Heinzelman, he has researched wireless communications protocols with a focus on sensor networks.

Acknowledgements

I would like to thank Professor Wendi B. Heinzelman for her support throughout my academic career. Her classes, projects, and guidance have had a lasting impression on me, and have shaped my choices in academics and my career. I am profoundly grateful to have had the opportunity to work with her. In addition, would like to thank professors Gaurav Sharma, Zeljko Ignjatovic, and Mark Bocko for their help and support here at Rochester.

I would also like to thank all of my colleges in the Wireless Communications and Networking Group. You have helped me overcome obstacles in my research and provided a wonderful environment to work in. I would especially like to thank Ryan Aures for all the help he has provided me over the years.

Finally, I would like to thank my parents, my friends and my wife, Colleen. You have provided me with an overwhelming amount of support for which I am forever grateful.

Abstract

Wireless sensor networks utilize battery-operated nodes, and thus energy efficiency is of paramount importance at all levels of system design. The main goal of sensor networks is often to transfer large amounts of data from the sensor nodes to one or more sinks or base stations. In order to save energy in this data transfer, it is often more efficient to route the data to the sink(s) through other nodes, instead of transmitting directly to the sink(s). In this thesis, we investigate this problem of energy-efficient transmission of data over a noisy channel, focusing on the setting of physical layer parameters. We derive a metric called the energy per successfully received bit, which specifies the expected energy required (including retransmissions) to transmit a bit successfully over a particular distance given a channel noise model. By minimizing this metric, we can find, for different modulation schemes, the energy-optimal relay distance and the optimal transmit energy as a function of channel noise level and path loss exponent. These results provide network designers with a means to select the best modulation scheme for a given network deployment (node spacing) and for a given channel (channel noise and path loss exponent). Alternatively, for a fixed modulation scheme, these results provide network designers a means to select optimal node density and transmit power in order to maximize network lifetime.

Contents

List of Figures

Chapter 1

Introduction

In the past ten years there has been increasing interest in wireless sensor networks. This interest has been fueled, in part, by the availability of small, cheap sensor nodes (motes), enabling the deployment of large-scale networks for a variety of sensing applications. In many wireless sensor networks, the number and location of nodes make recharging or replacing the batteries infeasible. For this reason, energy consumption is a universal design issue for wireless sensor networks. Much work has been done to minimize energy dissipation at all levels of system design, from the hardware to the protocols to the algorithms. This thesis describes an approach to reducing energy dissipation at the physical layer, by finding the optimal transmit (relay) distance and transmit power for a given modulation scheme and a given channel model, in order to maximize network lifetime.

1.1 Motivation

In the past decade there has been a vast increase in research on wireless sensor networks. This boom mostly comes from the low cost of the sensor nodes and the new vision of the problem. In the past there was an emphasis on only using a few high precision sensors. The recent trend is to use many lower quality sensors and to use redundancy to regain some of the accuracy of the individual measurements. With all the added redundancy, newer sensor systems are also much more fault tolerant than previous systems. The following are just a few examples of applications that can benefit from wireless sensor networks.

- Agricultural monitoring - evaluation of soil nutrients and moisture.
- Home automation - temperature or movement detection.
- Industrial monitoring - sensing any errors in machinery or surveillance of property.
- Wildlife/environmental survey - cataloging animal movements and the status of forested areas.
- Battlefield surveillance - rapidly deployable systems to send data back to a virtual command center.

For a detailed discussion of these and other applications, the reader is referred to [6].

1.2 Problem Description

To make the best use of the limited energy available to the sensor nodes, and hence to the network, it is important to appropriately set parameters of the protocols in the network stack. Here, we specifically look at the physical layer, where the parameters open to the network designer include: modulation scheme, transmit power and hop distance. The optimal values of these parameters will depend on the channel model. In this work, we consider an additive white Gaussian noise (AWGN) channel model, and we examine the relationship among these parameters as the channel model parameters are varied.

When a wireless transmission is received, it can be decoded with a certain probability of error, based on the ratio of the signal power to the noise power of the channel, (i.e., the SNR) . As the energy used in transmission increases, the probability of error goes down, and thus the number of retransmissions goes down. Thus there exists an optimal tradeoff between the expected number of retransmissions and the transmit power to minimize the total energy dissipated to receive the data.

At the physical layer, there are two main components that contribute to energy loss in a wireless transmission, the loss due to the channel and the fixed energy cost to run the transmission and reception circuitry. The loss in the channel increases as a power of the hop distance, while the fixed circuitry energy cost increases linearly with the number of hops. This implies that there is an optimal hop distance where the minimum amount of energy is expended to send a packet across a multi-hop network. Similarly, there is a tradeoff between the transmit power and the probability of error. In this tradeoff, there are two parameters that a network designer can change to optimize the energy consumed, transmit power and hop distance. The third option for physical layer parameter selection is much broader than the other two. The coding/modulation of the system determines the probability of success of the transmission. Changes in the probability of a successful transmission lead to changes in the optimal values for the other physical layer parameters. In this thesis the probability of error is a function of the basic modulation scheme in an AWGN channel, and it depends on the noise level of the channel and the received energy of the signal (i.e., it depends on the SNR). However, this work can be extended to incorporate any packet error or symbol error model.

1.3 Example Scenario

To illustrate the physical layer tradeoffs we consider in this thesis, consider the linear network shown in Figure 1.1. In this network, a node must send data back to the base station. The first physical layer consideration is hop distance.

In the first case (Network 1), the hop distance is very small, which translates to low per-hop energy dissipation. The small hop distance means the energy to transmit the message will also be small. Because the transmit energy must be proportional to d^n where $n \geq 2$ and d is the distance between the transmitter and receiver, the total energy to transmit the data to the base station will be much less using the multi-hop approach than a direct transmission. In this case, the main factor in the energy dissipation of this transmission is the large number of hops. The fixed energy cost to route through each intermediate hop will cause the total energy dissipation to be high.

In the second case (Network 2), the hop distance is very large. With so few hops there is little drain of energy on the network due to the fixed energy cost. However, there is a large energy drain on the nodes due to the high energy cost to transmit data over the long individual hop distances. With a large path loss factor, the total energy in this case will far exceed the total energy in the case of short hops. Thus it is clear that a balance must be struck, as shown in Network 3, so that the total energy consumed in the network is at a minimum.

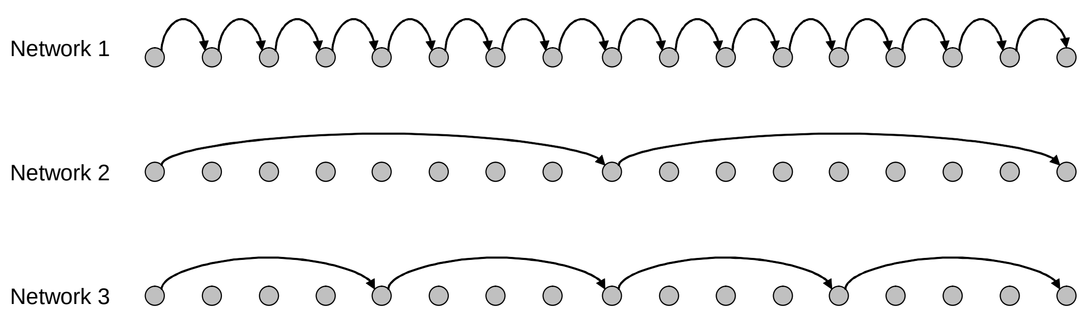


Figure 1.1: Three examples of a linear wireless network. Network 1 has a short hop distance, Network 2 has a long hop distance, and Network 3 has the optimal hop distance.

1.4 Thesis Contributions

The contribution of this thesis is a method of finding the optimum physical layer parameters to minimize energy dissipation in a multi-hop wireless sensor network. To achieve this goal, first we define a metric that specifies the energy per successfully received bit (ESB). This metric is a function of three physical layer parameters: hop distance (d), transmit energy ($E_{b,TX}$) and the modulation scheme. In addition, the ESB depends on the channel noise (N_0) and path loss (n) parameters. Given a specific channel model and a constraint on any two of the three physical layer parameters, this formula allows a network designer to determine the remaining physical layer parameter that will minimize energy dissipation and hence optimize the performance of the system.

1.5 Thesis Organization

This thesis is organized as follows. In Chapter 2 we discuss work that has already been completed in this area of physical layer optimization. In Chapter 3, we explain the channel and physical layer models that are used in this work, and we describe the analytic framework used to optimize the physical layer parameters. In Chapter 4, we show the results of experiments to analyze the relationship between the three physical layer parameters as a function of different channel models. Chapter 5 provides analysis and discussion of the experiments as well as thoughts on future work that can be done in this area.

Chapter 2

Related Work

Several researchers have examined the problems of energy to send data and optimum energy-efficient transmit distances. In this chapter, we discuss some of the work that has been done in this area.

In [8], the concept of an energy per useful bit metric was proposed. This metric sought to define a way of comparing energy consumption, specifically looking at the impact of the preamble on the effectiveness of the system. In this work they defined the metric as:

$$EPUB = (Preamble\ Overhead)(E_{TOT}) \quad (2.1)$$

$$= (\frac{B_D + B_P}{B_D})(P_{TX} + \sigma P_{RX})T \quad (2.2)$$

where B_D is the average number of bits of data and B_P is the average number of bits of preamble. The terms P_{TX} and P_{RX} are transmit and receive power, respectively. The parameter σ represents the proportion of time spent in transmit mode compared to the proportion of time spent in receive mode. Finally, T is the time to transmit a bit. By looking at this metric, we can see that in finding the minimum EPUB, there is a relationship between the complexity of the MAC (i.e., the size of the preamble) and the reduction in total energy. The paper claims that a more complex MAC can reduce the total energy, but they require a longer preamble. The energy consumption of this longer preamble can outweigh the gains of the improved energy from the more complex MAC. The paper compares six physical layers to find the $EPUB$. The conclusion drawn from the analysis is that simpler non-coherent modulations such as OOK and FSK-NC have the lowest $EPUB$.

In [9], the authors show how startup time correlates with the energy efficiency of the system. This paper is based on the idea that the energy consumed in startup is a significant part of the energy consumed in a transmission. For M-ary modulations, as M increases the maximum transmit energy must increase for a fixed BER, but the number of transmissions decreases. With higher order modulations the transmitter is on for a shorter time and so even with the higher maximum cost it is shown that higher order modulation schemes are more energy-efficient. However, this result does not hold when there is a large startup time. This paper demonstrates the importance of evaluating the startup time of a physical layer, and it shows that for certain startup times, certain modulation schemes are preferable to others.

The idea of finding an energy-efficient optimal hop distance has been evaluated in previous work. The authors in [3] analytically derive this optimal hop distance given a particular radio energy dissipation model. The goal of the derivation is to minimize the total energy consumed by the network to transmit data a distance D.

$$E_{Total} = \frac{D}{d} E_{Hop} \quad (2.3)$$

where D is the total distance between the source and the destination, and d is the hop distance. E_{Hop} is the total energy to transmit the data over one hop.

$$\begin{aligned} E_{Hop} &= E_{TX} + E_{Hop-Fixed} \\ &= \alpha E_{RX} d^n + E_{TX,Fixed} + E_{RX,Fixed} \\ &\approx \alpha E_{RX} d^n + 2E_{Fixed} \quad (2.4) \end{aligned}$$

The value E_{Hop} is made up of 2 components E_{TX} and E^*_{Fixed}. E^*_{Fixed} is the fixed energy cost expended during the hop. This energy is based on running the circuits to perform the modulation and any other processing, and it is not dependant on the distance between the nodes or the amount of energy radiated into the channel by the radio. E^*_{Fixed} can be divided into two parts $E_{TX,Fixed}$ and $E_{RX,Fixed}$. These are the fixed energy costs of the transmitter and receiver, respectively. While these two values are not necessarily equal, it is common to set them equal and thus the fixed energy is $2E_{Fixed}$.

The value E_{TX} is the energy consumed to appropriately amplify the signal for transmission. It can also be devolved into multiple components. As seen in equation 2.4, E_{TX} is the product of the received energy, E_{RX}, the hop distance d raised to the path loss factor n, and a scalar α. E_{RX} is the energy accumulated at the receiver, or more specifically, the desired received energy. The constant α is the attenuation of the channel that comes from the wavelength of the signal and antenna gains. This constant also includes the amplifier efficiency. In section 4.7, the case where α is not constant is evaluated.

Combining equations 2.3 and 2.4 yields the following result.

$$E_{Total} = D(\alpha E_{RX} d^{n-1} + 2E_{Fixed} d^{-1}) \tag{2.5}$$

By taking the derivative of the total energy with respect to hop distance and setting this derivative equal to zero, the optimal hop distance, d^*, can be found.

$$E'_{Total} = D(\alpha(n-1)E_{RX} d^{n-2} - 2E_{Fixed} d^{-2}) \tag{2.6}$$

$$\begin{aligned} \alpha(n-1)E_{s,RX} d^{*n-2} &= 2E_{s,Fixed} d^{*-2} \\ d^* &= \sqrt[n]{\frac{2E_{Fixed}}{\alpha(n-1)E_{RX}}} \end{aligned} \tag{2.7}$$

Equation 2.7 is the expression for the energy-efficient optimal hop distance.

Unlike the analysis in this thesis, these systems look at the efficiency of the physical layer with some predefined bit error rate.

Chapter 3

Channel and Physical Layer Model

3.1 Energy in a Transmission

The channel model used in this thesis for the total energy in a transmission is given in the following equation.

$$E_{Consumed} = \alpha E_{RX} d^n + 2E_{Fixed} \tag{3.1}$$

An analysis of this equation is provided in Chapter 2. Figure 3.1 shows the components of this model. The channel is modeled as an additive white Gaussian noise (AWGN) channel with noise variance N_0. Note that we do not consider a fading channel, as this would only alter the probability of error equations and would thus not change the overall results provided here.

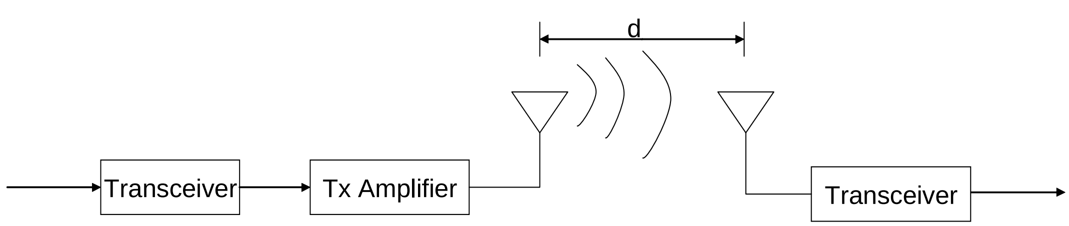


Figure 3.1: Wireless channel system model.

In both the transceiver and the amplifier there is some fixed energy to run the circuitry. Also in the amplifier there is some power loss because every 1 dBm of power input to the system does not equate to 1 dBm power sent to the antenna. The relationship between the power input to the system and the power sent to the antenna is called the amplifier efficiency and will be discussed in detail in Chapter 4.

3.2 Probability of Error Analysis

Here we model the probability of error in data reception to find the energy required to successfully receive a data packet. We assume that an error in the reception of the packet implies that the packet needs to be retransmitted. Thus there is a tradeoff that can be balanced to reduce energy dissipation through appropriate selection of physical layer parameters. A further discussion of these formulas can be found in [1].

First, we need to find the relationship between the energy per received symbol $E_{s,RX}$ and the transmitted energy $E_{s,TX}$.

$$E_{s,RX} = \frac{\alpha E_{s,TX}}{d^n} \quad (3.2)$$

The parameter α is the product of the amplifier efficiency (L) and the loss in the channel. For instance in the free space model:

$$\alpha = \frac{G_T G_R \lambda^2}{(4\pi)^2} * L \quad (3.3)$$

where in general L is a constant. Section 4.7 investigates the case where L is a function of $E_{s,TX}$. The term $E_{s,RX}$ is used to determine the SNR of the received signal, which is important for determining the probability of error.

The probability of a successful packet transmission is as follows:

$$P_{s,p} = (1 - P_{e,s})^{\frac{k}{b}} \quad (3.4)$$

where $P_{e,s}$, the probability of a symbol error, is dependent on the SNR of the signal. The formulas for $P_{e,s}$ are given in Table 3.3 for a selection of modulation techniques. The value k is the number of bits per packet and $b = log_2(M)$ is the number of bits per symbol. The value $\frac{k}{b}$ is the number of symbols needed for a k-bit packet.

The product of the probability of packet success and the number of data bits gives the expected amount of data received per packet.

$$T = (k - k_0)P_{s,p} \tag{3.5}$$

where k_0 is the number of overhead bits in the packet. The ratio of the expected amount of data per packet and the total energy to send a packet gives the metric *energy per successfully received bit* (ESB). This is the value that should be minimized by appropriate setting of the physical layer parameters.

$$\begin{aligned} ESB &= \frac{\frac{k}{b}(E_{s,TX} + 2E_{s,Fixed})}{T} \\ &= \frac{\frac{k}{b}(E_{s,TX} + 2E_{s,Fixed})}{(k - k_0)(1 - P_{e,s})^{\frac{k}{b}}} \end{aligned} \tag{3.6}$$

So, for BPSK the equation for ESB is:

$$ESB_{BPSK} = \frac{k(E_{s,TX} + 2E_{s,Fixed})}{(k - k_0)(1 - Q(\sqrt{\frac{\alpha 2E_{s,TX}}{d^n N_o}}))^k} \tag{3.7}$$

Equation 3.6, the energy per successfully received bit, is the primary metric for determining the energy efficiency values. As shown in Figure 3.2, ESB has a minimum with respect to the transmit energy $E_{s,TX}$.

To find the minimum of ESB, we can take the derivative with respect to $E_{s,TX}$ and set it equal to zero. However, the equation $\frac{d}{dE_{s,TX}}ESB = 0$ has no closed-form solution and thus the values that minimize ESB must be calculated numerically.

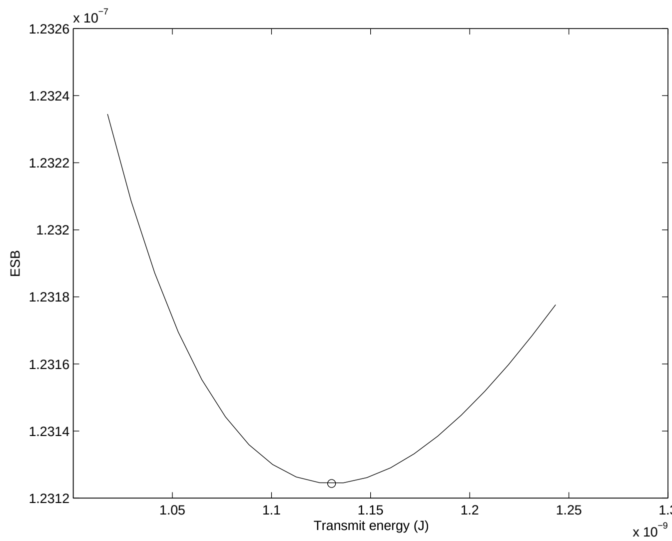


Figure 3.2: The ESB as a function of the transmit energy $E_{s,TX}$. This plot shows a clear minimum and thus the optimal transmit energy. These results assume a fixed distance $d = 10m$, BPSK modulation and fixed channel noise.

Modulation	$P_{e,s}$
BPSK	$Q(\sqrt{\frac{2E_{b,RX}}{N_o}})$
QPSK	$2Q(\sqrt{\frac{2E_{b,RX}}{N_o}})(1 - 0.5Q(\sqrt{\frac{2E_{b,RX}}{N_o}}))$
M-PSK	$2Q(\sqrt{\frac{4\log_2(M)E_{b,RX}}{N_o}} sin(\frac{\pi}{M}))$
M-QAM	$1 - (1 - 2(1 - \frac{1}{\sqrt{M}})Q(\sqrt{\frac{3}{(M-1)}\frac{\log_2(M)E_{b,RX}}{N_o}}))^2$

Figure 3.3: Table of symbol error formulas from [2].

Chapter 4

Optimizing Physical Layer Parameters

Several simulations were performed to show the results of minimizing ESB, the energy per successfully received bit, and hence finding the optimal transmit energy and the energy-optimal hop distances for different modulation schemes.

4.1 Simulation Description

All simulations and numerical optimizations are performed in Matlab. The primary optimization metric is ESB, the energy per successfully received bit. The goal is to minimize this value to reduce the energy required to transmit data successfully in the presence of channel noise. Because there is no closed-form solution, Matlab is used to numerically solve the optimization of ESB with respect to transmit energy. The Matlab function used to find the minima is `fminsearch`. The function `fminsearch` uses the convergence of the Nedler-Mead Simplex [5]. All that is needed to find the minimal transmit energy at an arbitrary distance is to search ESB for a minima through different $E_{s,TX}$ values. Finding optimum distances is more difficult and is described in section 4.3.

As a basis, the reference noise value $N_{0,Ref}$ is chosen such that the bit error rate (BER) of a BPSK symbol is 10^{-5} for a energy per received bit $E_B = 50nJ$. In simulations where a range of noise values are considered, the values are logarithmically spaced from $N_{0,Ref}$ to $128N_{0,Ref}$.

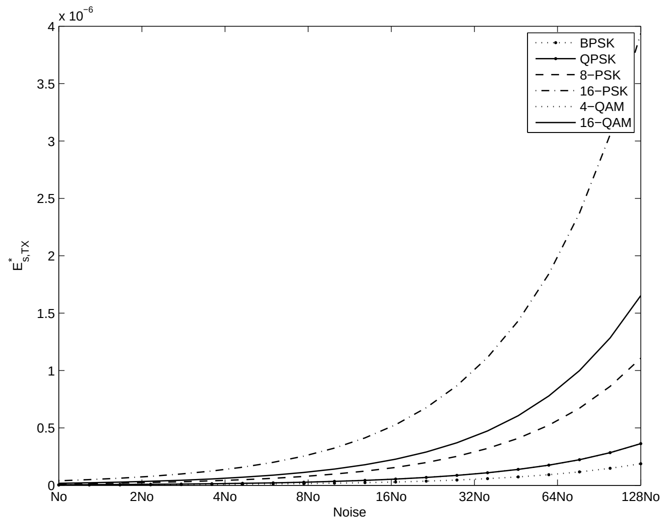
4.2 Finding Optimum Transmit Energy

Using the proper transmit energy is important to the efficiency of the wireless system. In this section we will evaluate the case where hop distance is fixed. Finding the optimum transmit energy is a simple matter of finding the minimum of the ESB function with respect to energy $E_{s,TX}$ for a particular channel (N_0, n) and at a particular hop distance (d) and modulation. It was shown in Figure 3.2 that ESB has a minimum with respect to $E_{s,TX}$. This value cannot be solved for analytically because of the multiple Q functions in the ESB formula. However, the optimal $E_{s,TX}$ can be solved for numerically. Figure 4.1 shows the optimum values of $E_{s,TX}$ and ESB over a range of channel noise values and at different modulations. The figures were created by fixing the hop distance d to 15 m and iteratively changing the noise value N_0 and modulation. For each iteration, the value of $E_{s,TX}$ that minimizes ESB is found using the `fminsearch` function described in section 4.1. The optimal ESB (ESB^*) and the optimal $E_{s,TX}$ $(E^*_{s,TX})$ values were stored and plotted against the noise value in Figure 4.1.

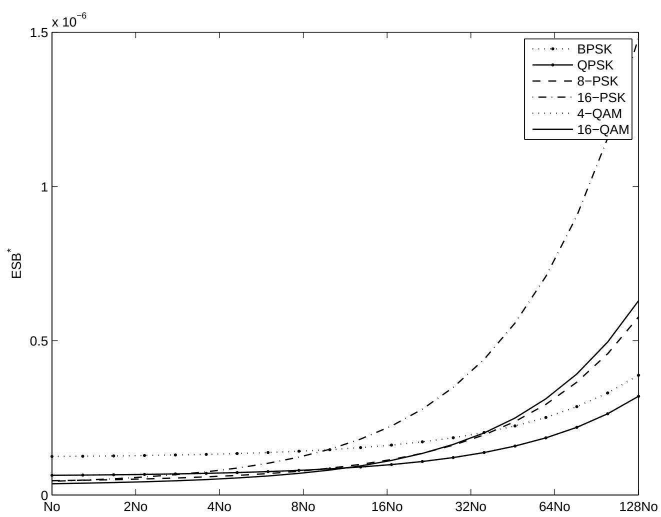
In Figure 4.1, the optimum energy was found for a fixed hop distance of 15 m. Figure 4.1(a) shows that $E^*_{s,TX}$ increases with channel noise. This result is expected to maintain the optimal ESB, as increased channel noise must be offset with increased transmission power to maintain a certain SNR. Figure 4.1(b) shows that as the noise goes up the optimal ESB also increases.

4.3 Finding Optimum Distance

In addition to finding the optimum transmit energy, we also want to find the optimal hop distance. In this section we will evaluate the case where transmit energy and modulation are fixed, and we want to find the optimum relay distance. The optimum energy-efficient hop distance d^* can be found by minimizing the ESB divided by the hop distance d (e.g., ESB/d). This gives the value of energy per successfully received bit per meter, $ESBM$. This metric is important, because



(a) $E^*_{s,TX}$ at fixed distance $\hat{d}$.



(b) ESB^* at fixed distance $\hat{d}$.

Figure 4.1: $E^*_{s,TX}$ and ESB^* for a fixed distance, $\hat{d} = 15m$ at a range of noise values for different modulations.

if a packet needs to travel a route of distance D, then $ESBM * D$ gives the ESB of the entire route. Thus, by minimizing $ESBM$ then ESB is minimized for the entire route.

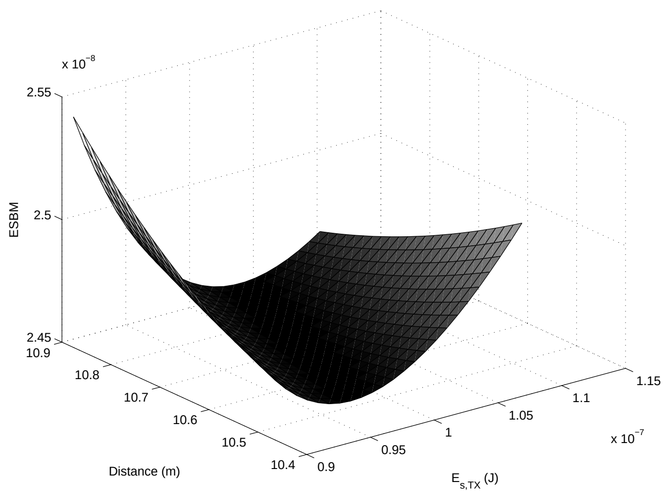
The optimal distance can be seen by looking at a plot of $ESBM$ versus transmit energy and hop distance, shown in Figure 4.2(a). The line of minimum values occur at each distances' optimum transmit energy value. It may appear that $ESBM$ has a range of values that are minimum, but as seen in Figure 4.2(b), a plot of the values along the trench, $ESBM$ has a clear minimum value and thus, an optimum hop distance.

Figure 4.3 shows the optimal distance d^* and $ESBM^*$. Both plots were generated with $E_{s,TX} = 5x10^{-9}J$. Figure 4.3(a) shows the optimum distance, and the optimal distance decreases with increasing channel noise. Similarly, Figure 4.3(b) shows that as the channel noise increases, $ESBM^*$ increases. This is as expected, since as the channel gets worse, we need to spend more energy on average to transmit the data.

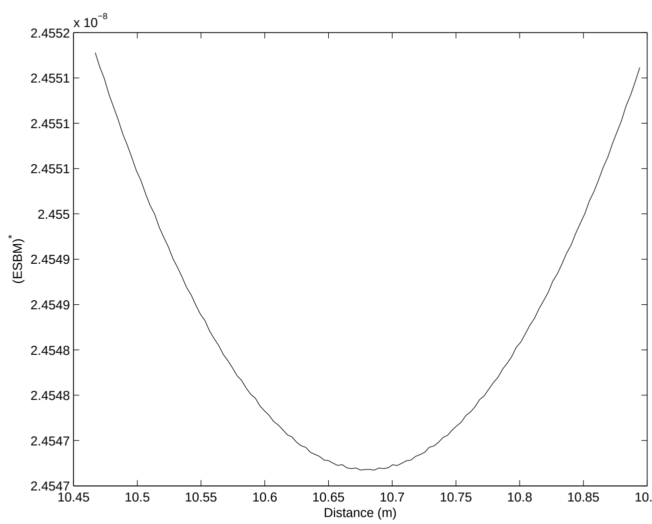
4.4 ESB at the Optimum Distance and Transmit Energy

In sections 4.2 and 4.3, the metric ESB was evaluated with one free parameter, $E_{s,TX}$ and d, respectively. What happens if both of these parameters are free? In this section we look at the case where $E_{s,TX}$ and d are both allowed to be set to their optimum values. For the analysis in this section, all the desired modulations and channel noise values were iteratively evaluated. In each iteration, the optimum hop distance was found, but instead of using one transmit power, the optimal transmit power (as described in section 4.2) was found for each hop distance considered.

The results of this section are very interesting. Figure 4.4 shows the results when both parameters are set to their optimal values. Figure 4.4(a) shows the optimal hop distance. As expected the optimal hop distance decreases with an increase in channel noise. Unexpectedly, Figures 4.4(b) and 4.4(c) show that the optimal ESB and $E_{s,TX}$ are independent of channel noise. This means that nodes

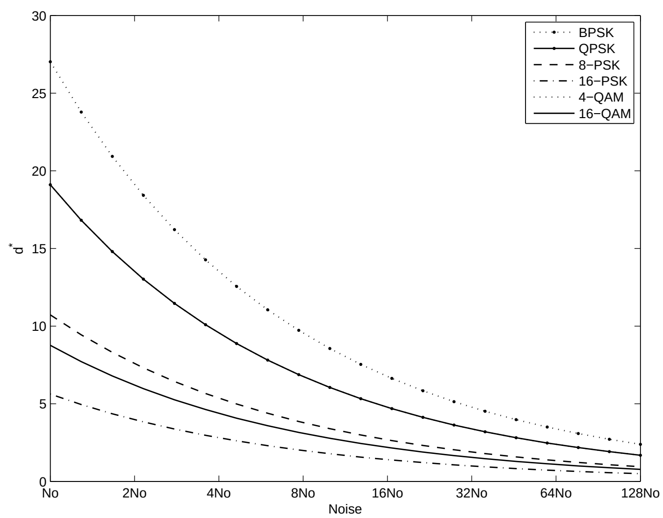


(a) $ESBM$ with respect to d and $E_{s,TX}$

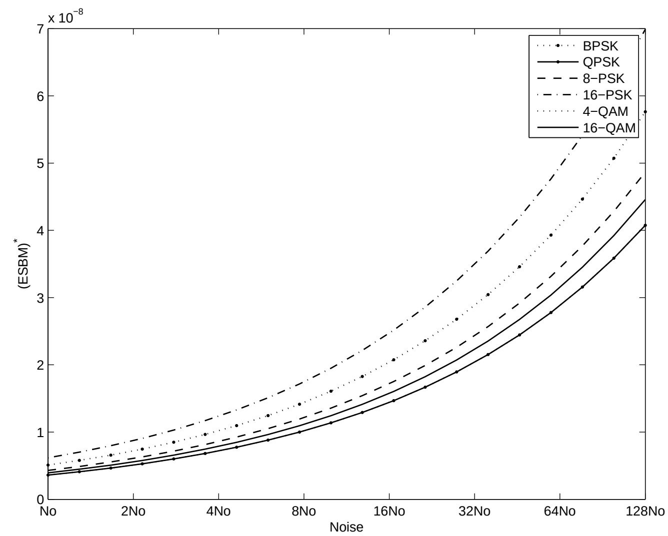


(b) $ESBM$ with respect to d at $E^*_{s,TX}$

Figure 4.2: Demonstrating optimal hop distance.

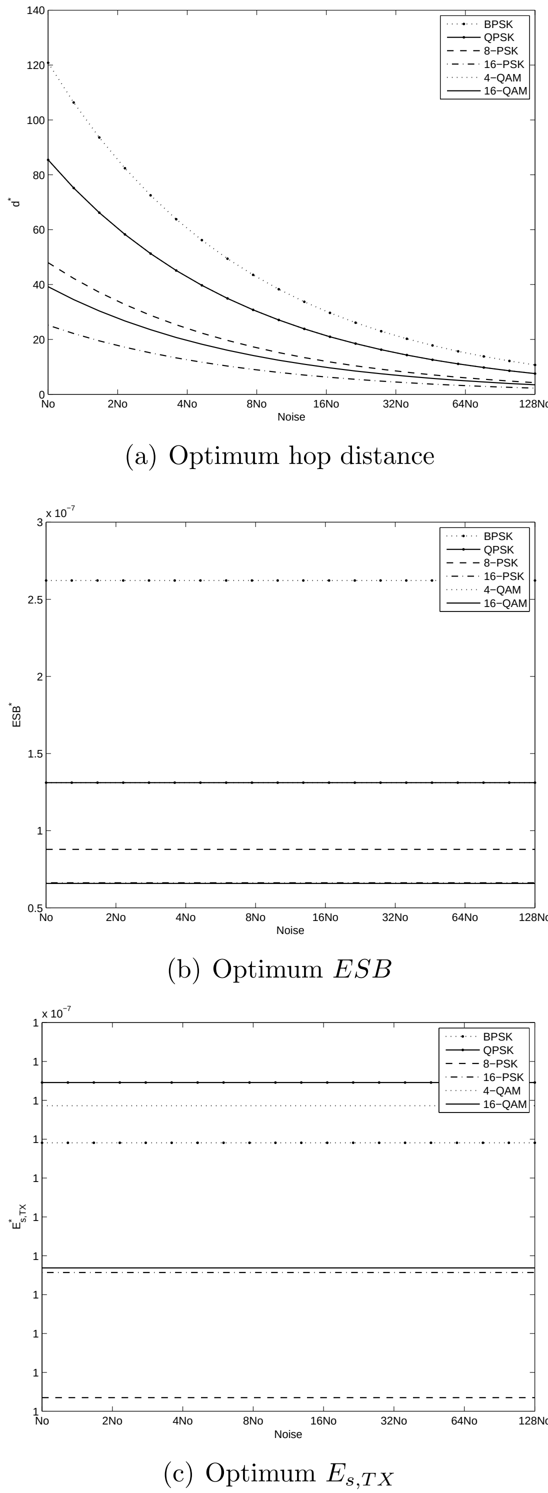


(a) Optimal distance



(b) Optimal $ESBPD$

Figure 4.3: Energy optimal hop distance as a function of noise. $E_{s,TX} = 5x10^{-9}J$.



(a) Optimum hop distance

(b) Optimum ESB

(c) Optimum $E_{s,TX}$

Figure 4.4: Parameters calculated using $E^*_{s,TX}$ and d^* at each point considered.

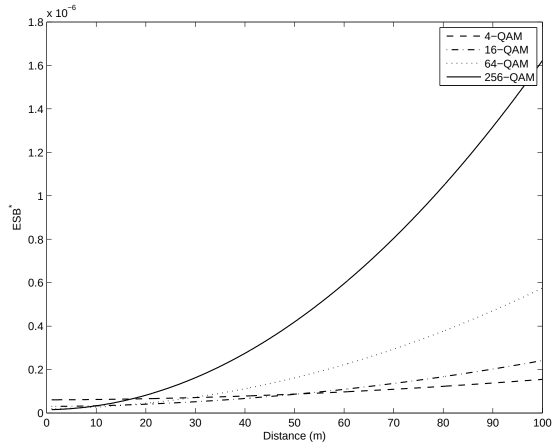
can be set with the predetermined optimal transmit power and that the optimal energy-efficient solution can be obtained by simply changing the hop distance as channel noise varies. This result makes sense because both the hop distance and channel noise scale the SNR of the received signal. Because both of these parameters are just scalars of SNR then they can be viewed as one term. Since N_0 and d only appear in the probability of error formulas within the formula for ESB, once the optimal ESB is found, when one component of the scalar is changed, the optimal solution is to change the other component of the scalar to compensate for the change. Thus, as N_0 changes, d must change accordingly to maintain a constant SNR that minimizes ESB.

4.5 Optimum Distance Not Always Optimal

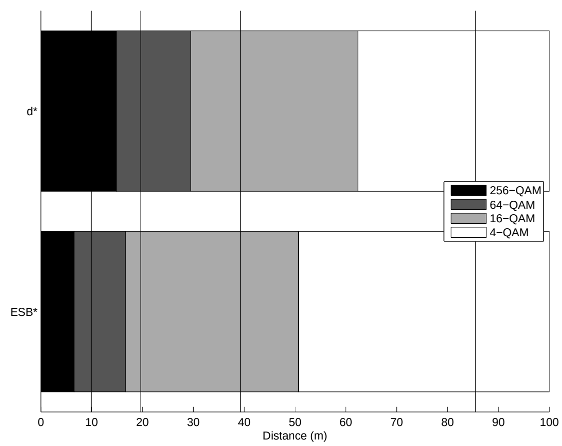
In section 4.2 we showed how to find, for different modulation schemes the optimal transmit energy for a given hop distance, and in section 4.3 we showed how to find the energy optimal hop distance. If these two parameters of hop distance and transmit energy were the constraints on the network and it was up to the network designer to decide what type of modulation and coding to use, then it may seem that the proper solution is to find which coding/modulation scheme has its optimal distance and transmit energy parameters nearest to the desired values provided by the network designer. However, this will not provide the best (minimum total energy) solution. As can be seen in Figure 4.5(a), for each hop distance, there is an optimal modulation scheme that minimizes energy dissipation.

Figure 4.5(b) shows that using a particular modulation's optimum hop distance does not guarantee that it is the most efficient means of modulation. The vertical lines show where the optimal relay distances are for each modulation. The top bar shows which modulation is closest to its optimal for each distance. The lower bar shows which modulation scheme has a minimum ESB for each relay distance. We can see that these two bars are not the same, and thus we need to select the modulation scheme based on which scheme has a minimum ESB for the particular hop distance in order to minimize energy.

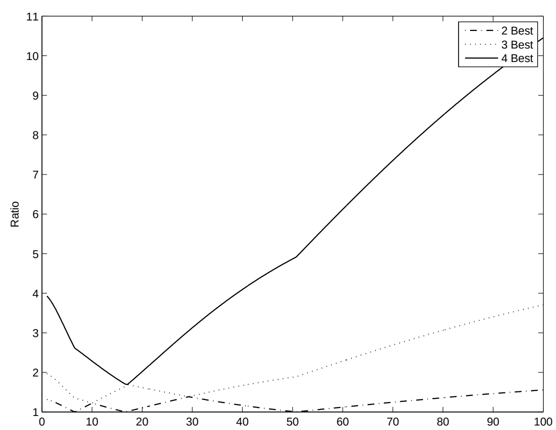
Figure 4.5(c) is an evaluation of the effects using a suboptimal modulation



(a) Optimum ESB vs distance



(b) Optimum ESB vs Optimum distance



(c) Optimum ESB vs distance

Figure 4.5: Optimum ESB vs optimum hop across noise and distance

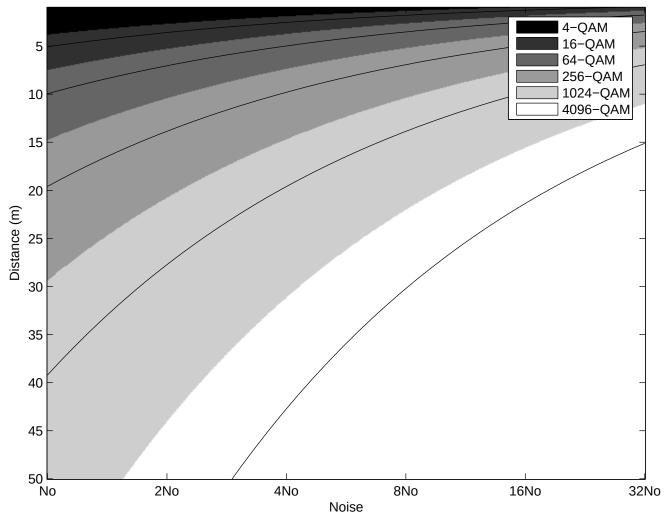
scheme. In this figure, the ratio between the best and the nth best modulation scheme are compared. This figure shows that the penalty for using a modulation that is only one off from the optimal scheme does not have a great impact on ESB, but using a modulation that is much different from the optimal one will perform quite poorly. Thus it is important to use either the optimal or the next-optimal modulation scheme to save energy.

These results can also be seen in Figures 4.6(b) and 4.6(a). In Figure 4.6(b), there is a 2D map of the minimal ESB across changes in channel noise and hop length. Comparing this to Figure 4.6(a), which shows a 2D map of which modulation's optimal distance each (noise, hop length) point is closest to, we see a big difference in the optimal modulation scheme. The black lines are the curves for the optimum hop distance. Similarly to Figure 4.5(b), there is some intersection, but the optimums almost all occur when another modulation has a lower ESB. This means that we need to determine, for each transmit distance, the optimal modulation scheme that leads to the minimum energy, as shown in Figures 4.6(b) and 4.6(a).

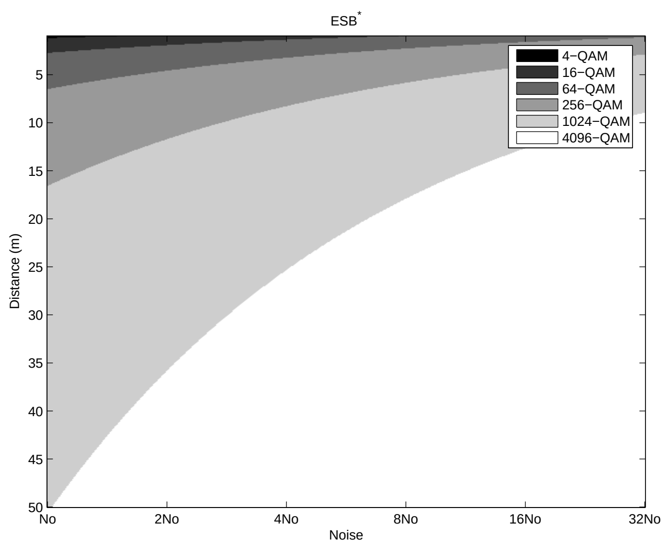
4.6 Effect of Packet Size

Packet size has a significant effect on the efficiency of the system. The model we are using gives the probability of packet success as the product of all symbol successes, as shown in equation 3.4. Then, for a given modulation scheme, the probability of a successfully received packet decreases as the packet size increases. Thus there is an increase in energy efficiency with small packets. However, this is only true if we do not consider the per-packet overhead. Equation 3.5 shows that the throughput of the system approaches zero as the bits per packet, k, approaches the number of overhead bits, k_0. Thus there is some optimal packet size to obtain the highest energy efficiency.

This tradeoff in packet size can be seen in Figure 4.7, which shows the optimal energy per successfully received bit, ESB, as packet size is varied for different amounts of per-packet overhead. The case where packets have zero overhead shows the minimal energy tending to zero. However, when packet overhead is



(a) Closest to d^*



(b) Optimum ESB

Figure 4.6: Optimum ESB vs optimum hop across noise and distance

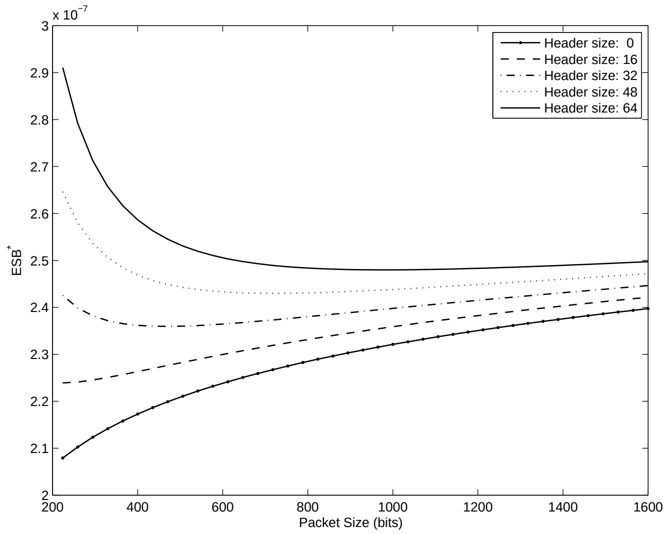


Figure 4.7: Effect of packet size on the ESB

considered, there is a non-zero minimum energy packet size. As expected, as the size of the overhead increases the optimal packet size also increases.

4.7 Amplifier Efficiency

In our model, there is a term α that is used to encapsulate both the loss in the channel and the amplification efficiency. In all the previous experiments, this term was constant. The amplification efficiency term is due to the loss in energy from the loss in amplification of the signal before it is sent over the antenna. In a traditional model for a radio, there is some fixed cost for operating the radio, and for every 1 dBm of power put into the amplifier, there will be δ dBm of energy radiated out of the antenna, where $\delta < 1$. This is an important factor to consider, because δ can be orders of magnitude less than 1.

However, this is not the most important term in the analysis of this work, as this term has only a relational impact on the equations. Rewriting equation 3.6 to be in terms of transmitted energy shows that the only impact of α is as a scalar to the noise, N_0. As described in section 4.1, the reference noise level was defined for a BPSK system to have a BER of 10^{-5} and an $E_B = 50nJ$. This means that using an alpha that depends on the amplifier efficiency is equivalent to scaling the noise term, as shown in this equation:

$$ESB = \frac{\frac{k}{b}(E_{s,TX} + 2E_{s,Fixed})}{(k - k_0)(1 - P_{e,s}(\frac{E_{s,TX}}{\alpha d^n N_0}))^{\frac{k}{b}}} \tag{4.1}$$

Using a constant α is not the most accurate model, because in actual hardware the amplifier is more efficient at higher power levels. For example, the Tmote Sky motes developed by MoteIV Corporation [4] have a table that specifies the current draw of the system, which provides us with the energy values shown in Table 4.1.

Transmitted Power (mW)	Consumed Power (mW)
1	52
0.79	49
0.50	45
0.31	41
0.20	37
0.10	33
0.03	29
0.003	25

Table 4.1: Table of power consumed based on transmit power for the MoteIV Tmote Sky. Based on information from [4].

Figure 4.8 shows the optimal ESB at different noise levels, for various values of α. This plot shows how the optimal ESB changes when α changes. The solid line shows an example of how a non-constant α changes the optimal ESB. Unlike the other curves, there is not a scaling of the channel noise axis in this plot, but a slight change in the shape of the curve. The exact shape and degree of the distortion depend on the range and degree of the nonlinearity in amplifier efficiency as a function of transmit power. As seen in this example, the distortion is not very severe and does not significantly affect the results obtained in the previous sections.

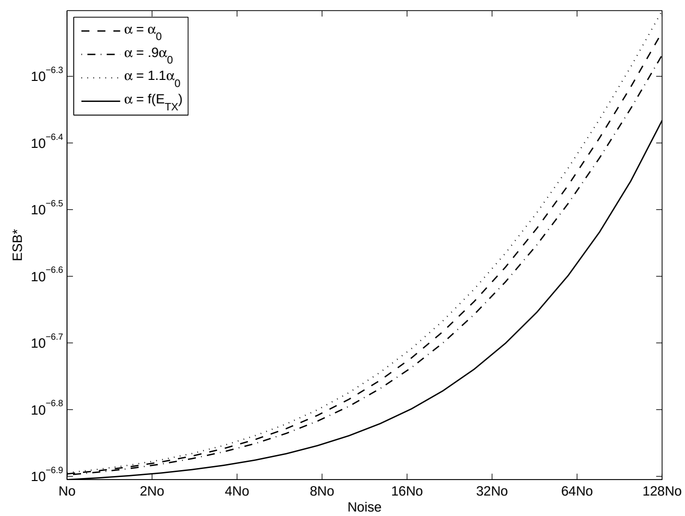


Figure 4.8: ESB as a function of amplifier efficiency

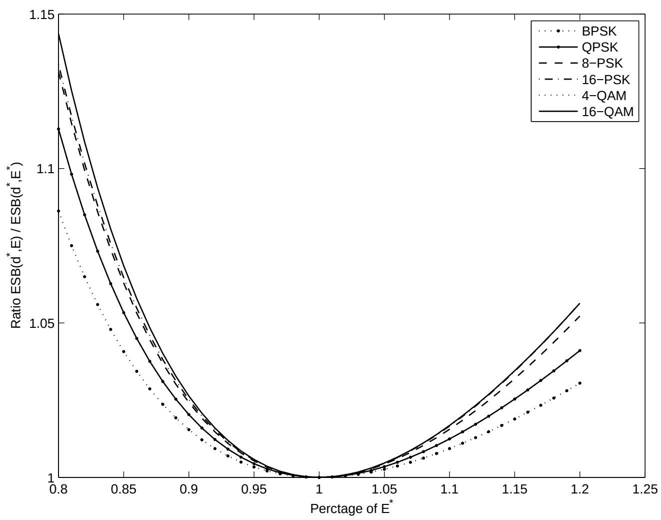
4.8 Gain of Optimizing Physical Layer Parameters

In actual sensor networks it would not be possible to place all nodes in such a way as to guarantee that nodes could always use the optimal hop distance, nor would it be possible to set transmit powers to the exact optimum level. In both cases, the physical constraints of the system in terms of topology of the sensor field and the limitations on the hardware's precision will prevent the system from achieving this theoretical optimum behavior. Thus, the overall benefit of finding an optimum must be considered.

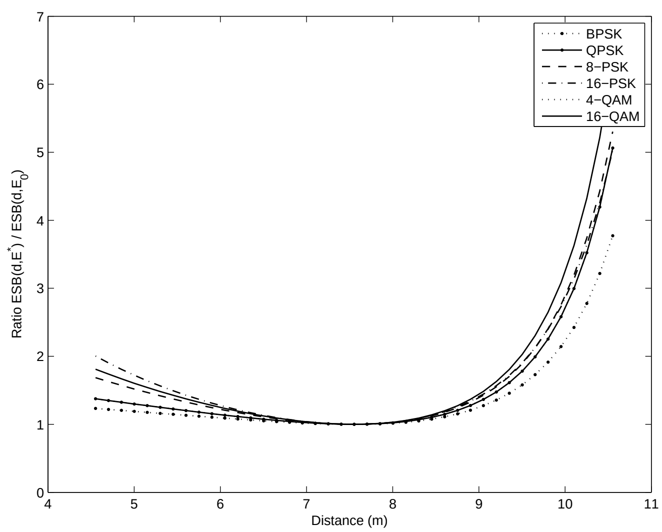
The two ways that a sensor could be used sub-optimally are in its hop distance and in its transmit energy precision. If the nodes' transmit energy is calibrated to transmit a particular distance, and the actual distance covered is different from this calibrated distance, then there will be a waste of energy. If the distance is smaller, the transmitter could have used less power to send the message with a similar probability of success. If the distance is longer, the probability of error will dominate and the number of retransmissions will negatively affect the efficiency. Similarly, if the transmit power is non-optimal, there will be energy waste.

Figures 4.9(a) and 4.9(b) show the impact of deviation from the optimum transmit energy and hop distance values, respectively. Figure 4.9(a) shows how error in $E_{s,TX}$ affects the performance of the system. The figure shows the ratio of ESB^* at an arbitrary distance and ESB with different $E_{s,TX}$ used for that same arbitrary distance of 10 m. The range of $E_{s,TX}$ used are shown in percent of $E^*_{s,TX}$. The figure shows that underestimating $E_{s,TX}$ requires more energy overall than overestimating this parameter.

Figure 4.9(b) shows the affect of using hop distances other than the one used to find the optimal transmit power. In this figure, the transmit power was found for 7.5 m. The ESB was then found for that transmit power over the given range of distances. This was divided by the value of ESB if the optimal transmit power had been recalculated for each distance. This shows that hop distances that are greater than expected will cost much more energy than distances less than expected. Distances greater than expected would be equivalent to underestimating the transmit power, so both figures in Figure 4.9 show that it is better to use more energy in transmission when there is uncertainty or an inability to get exact values of $E_{s,TX}$ and d.



(a) Error in Energy



(b) Error in distance

Figure 4.9: Gain of finding optimal transmit energy and optimal distance.

Chapter 5

Conclusion

5.1 Analysis

There are many interesting conclusions to draw from these simulations. First, graphs like those in Figures 4.6(b) and 4.6(a) can be of great help to network designers, as these show that once the channel and modulation scheme are known, one can easily find the optimum distance that the node should hop to get its data to the destination. Another important observation is that if the system is operating at the optimum distance, then the transmit energy and ESB become independent of channel noise. This means that to maintain the same ESB as the noise floor of the channel increases, the hop distance can be scaled without changing the transmit energy. This can be seen by rewriting equation 3.6 as follows:

$$ESB = \frac{\frac{k}{b}(E_{s,TX} + 2E_{s,Fixed})}{(k - k_0)(1 - P_{e,s}(\frac{E_{s,TX}}{\alpha d^n N_0}))^{\frac{k}{b}}}$$

In this equation we can see that the only places that the hop distance and the noise term appear are as a product of one another. Thus the two can be regarded as one term. Once the desired ESB is found, any change in the environment that causes $N_o \rightarrow \xi N_o$, then the same minimum ESB can be achieved by scaling the hop distance $d \rightarrow \frac{1}{\sqrt[n]{\xi}} d$.

Finally, these results show the importance of system optimization. Figure 4.9(b) shows that a deviation from the targeted value by just 2 meters can cause a system to be half as efficient. Also given that the increase in ESB is higher when the transmit energy is underestimated, it would be better to overestimate the transmit energy required than to underestimate it.

5.2 Future Work

There are many ways to extend this work. One of the most important is an analysis of this system with a non-AWGN model of the channel. Another possible extension of this is to take the information in section 4.2 about optimum energy for a fixed distance and apply that to the case where hop distance has some random distribution. In actual networks nodes will not always be spaced exactly some fixed distance away from each other, and even if they were, some routing schemes will want to choose relay nodes to meet QOS requirement. If nodes are chosen around the optimum distance with some probability, then the optimum transmit energy would likely change. Another area of research is to test this analysis on actual hardware and evaluate the results.

Bibliography

[1] B. Tavli and W. B. Heinzelman. Minimal Energy-Efficient Relaying Distance Over Noisy Channels. Unpublished Manuscript. 2006.

[2] J. Proakis. Digital Communications. McGraw-Hill Book Co. 2001.

[3] Y. Chen and E. Sirer and S. Wicker, On Selection of Optimal Transmission Power for Ad hoc Networks, Proceedings of the Thirty-Sixth Hawaii International Conference on System Sciences (HICSS-36), 2003.

[4] Tmote Sky Data Sheet. www.moteiv.com. 2007.

[5] Definition of the fminsearch. http://www.mathworks.com/access/helpdesk/help/techdoc/index.html?/ access/helpdesk/help/techdoc/ref/fminsearch.html

[6] I. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, A Survey on Sensor Networks, IEEE Communications Magazine, August 2002.

[7] M. Holland, R. Aures and W. Heinzelman, "Experimental Investigation of Radio Performance in Wireless Sensor Networks," IEEE SECON 2006 Poster Session, Sept. 2006.

[8] J. Ammer and J. Rabaey, The Energy-per-Useful-Bit metric for evaluating and optimizing sensor network physical layers, IEEE International Workshop on Wireless Ad-hoc and Sensor Networks, 2006.

[9] A. Y. Wang, S. Chao, C. G. Sodini, and A. P. Chandrakasan, Energy efficient modulation and MAC for asymmetric RF microsensor system, International Symposium on Low Power Electronics and Design, pp 106-111, 2001.