Optimizing Physical Layer Parameters for Wireless Sensor Networks

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As wireless sensor networks utilize battery-operated nodes, energy efficiency is of paramount importance at all levels of system design. In order to save energy in the transfer of data from the sensor nodes to one or more sinks, the data may be routed through other nodes rather than transmitting it directly to the sink(s). In this paper, we investigate the 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 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 enable network designers to select the hop distance, transmit power and/or modulation scheme that maximize network lifetime.

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General Terms: Design, Performance, Algorithms

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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, low cost sensor nodes (motes), enabling the deployment of large-scale networks for a variety of sensing applications [Akyildiz et al. 2002]. 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

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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 [Chen et al. 2003; Ammer and Rabaey 2006; Wang et al. 2001]. This paper 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.

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 both an additive white Gaussian noise (AWGN) channel model as well as a block Rayleigh fading channel model. Moreover, we examine the relationship among these physical layer 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 [Heinzelman et al. 2002]. 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 [Wang et al. 2001]. Here we look at the case where the probability of error is a function of the basic modulation scheme in an AWGN channel and a block Rayleigh fading 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 (e.g., models that incorporate channel coding).

To illustrate these physical layer tradeoffs, consider the linear network shown in Fig. 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. 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 transmit energy to get the

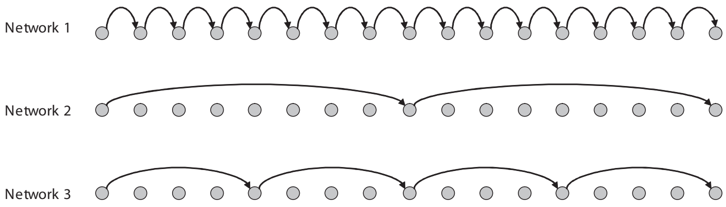


Fig. 1. Three examples of a linear wireless network. Network 1 has a short hop distance, Network 2 has a long hop distance, and Network 3 has the optimal hop distance.

data to the base station will be much less using the multi-hop approach than a direct transmission [Heinzelman et al. 2002]. However, in this network, the main factor in the energy dissipation of the 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.

The contribution of this paper 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, $E_{s,TX}$, and the modulation scheme. In addition, ESB depends on the channel model. 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 network.

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

2. RELATED WORK

Several researchers have examined the problems of minimizing energy to send data and finding optimum energy-efficient transmit distances. In [Ammer and Rabaey 2006], 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. The authors define the energy per useful bit (EPUB) metric as:

$$\begin{aligned} \text{EPUB} &= (\text{Preamble Overhead}) \times (\text{Total Energy}) \qquad (1) \\ &= (\frac{B_D + B_P}{B_D})(P_{TX} + \sigma P_{RX})T \qquad (2) \end{aligned}$$

where B_D is the average number of data bits and B_P is the average number of preamble bits. The terms P_{TX} and P_{RX} are transmit and receive power, respectively. The parameter σ is determined by the MAC protocol and represents the proportion of time spent in receive mode compared to the proportion of time spent in transmit 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 authors claim that a more complex MAC can reduce the total energy, but it requires a longer preamble, and 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 [Cui et al. 2005], the authors provide detailed analysis about the power consumptions of the components at both the transmitter and the receiver ends. Moreover, the authors differentiate the power consumptions of different modulation schemes (linear or nonlinear). Both circuit power consumption and transmit power consumption are considered in [Cui et al. 2005]. A peak-power constrained optimization over the constellation sizes, linear/nonlinear modulations, and coded/uncoded transmission schemes over different transmission distances are provided. The authors concluded that at short transmission distances, bandwidth efficient schemes (uncoded linear modulations with large constellation sizes) are energy efficient; on the other hand, at large transmission distances, energy efficient schemes (coded nonlinear modulations with small constellation sizes) are energy efficient. The authors in [Cui et al. 2005] assume a fixed target bit error probability and no retransmissions. This assumption may not meet some quality of service (QoS) requirements, such as reliable communications.

In [Wang et al. 2001], 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. In [Rodoplu and Meng 1999], the authors propose a distributed position-based network protocol optimized for minimum energy consumption in wireless networks. In this protocol a node determines the potential relay nodes around it based on the optimum energy dissipation of the combined transmit/receive power of the source and relay nodes. Similarly, in [Chen et al. 2002] the optimum one-hop transmission distance that will minimize the total system energy is investigated. The main conclusion of this study is that the optimum one-hop transmission distance depends only on the propagation environment and the transceiver characteristics and is independent of other factors (e.g., physical network topology, the number of transmission sources and the total transmission distance). In [Panichpapiboon et al. 2005] it is shown that given a route bit error rate (BER) and node spatial density, there exists a global optimal data rate at which the transmit power can be globally minimized. The authors also report that there exists a critical node spatial density at which the optimal transmit power is the minimum possible for a given data rate and a given route BER. In this study the optimal common transmit power is defined as the minimum transmit power used by all nodes necessary to guarantee network connectivity.

The authors in [Chen et al. 2003] analytically derive the 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.

$$E_{Total} = \frac{D}{d} E_{Hop} \tag{3}$$

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

$$\begin{aligned} E_{Hop} &= E_{TX} + E_{Hop,Fixed} \\ &= \alpha E_{RX} d^n + E_{TX,Fixed} + E_{RX,Fixed} \\ &\approx \alpha E_{RX} d^n + 2E_{Fixed} \end{aligned} \tag{4}$$

The value E_{Hop} is made up of 2 components, E_{TX} and $E_{Hop,Fixed}$. $E_{Hop,Fixed}$ 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. $E_{Hop,Fixed}$ 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 broken into multiple components. As seen in equation 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.

Combining equations 3 and 4 yields the following result.

$$E_{Total} = D(\alpha E_{RX} d^{n-1} + 2E_{Fixed} d^{-1}) \tag{5}$$

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.

$$E'_{Total} = D(\alpha(n-1)E_{RX}d^{n-2} - 2E_{Fixed}d^{-2}) \tag{6}$$

$$\begin{aligned} \alpha(n-1)E_{RX}d^{*n-2} &= 2E_{Fixed}d^{*-2} \\ d^* &= \sqrt[n]{\frac{2E_{Fixed}}{\alpha(n-1)E_{RX}}} \end{aligned} \tag{7}$$

Equation 7 is the expression for the energy-efficient optimal hop distance.

In [Deng et al. 2004] the authors provide an analytical model for determining the transmission range that achieves the most economical use of energy in wireless networks under the assumption of a homogeneous node distribution. Given node locations, the authors propose a transmission strategy to ensure the progress of data packets toward their final destinations. By using the average packet progress for a single common transmission range metric, they determine the transmission range that optimizes this metric.

Optimizing the packet size in wireless networks has also found considerable attention in the literature [Chien et al. 1999; Modiano 1999; Sankarasubramaniam et al. 2003; Korhonen and Wang 2005; Ci et al. 2005; Hou et al. 2005]. In [Chien et al. 1999] techniques for adapting radio parameters (e.g., frame length, error control, processing gain, and equalization) to channel variations is studied to improve link performance while minimizing battery energy consumption. In [Modiano 1999] an algorithm for estimating the channel BER using the acknowledgement history is presented. Estimated channel BER is used to optimize the packet size. It is reported that this algorithm can achieve close to optimal performance using a history of just 10,000 bits. In [Sankarasubramaniam et al. 2003] the effect of error control on packet size optimization and energy efficiency is examined. It is shown that forward error correction can improve the energy efficiency, while retransmission schemes are found to be energy inefficient. Furthermore, binary BCH codes are found to be more energy efficient than the best performing convolutional codes. In [Korhonen and Wang 2005] an analytical model characterizing the dependency between packet length and delay characteristics observed at the application layer is presented. It is shown that careful design of packetization schemes in the application layer may significantly improve radio link resource utilization in delay sensitive media streaming under harsh propagation environments. In [Ci et al. 2005] link adaption techniques at the MAC layer, which use adaptive frame size, are used to enhance the energy efficiency of wireless sensor nodes. To obtain accurate estimates and to reduce computational complexity, extended Kalman filtering is utilized for predicting the optimal packet size.

These existing techniques all look at the efficiency of the physical layer with some predefined bit error rate. In contrast, in this paper we examine the effects of varying the bit error rate (through changes in transmit power, hop distance and modulation technique for a fixed channel model) to find the physical layer parameters that minimize the energy required to successfully receive the data.

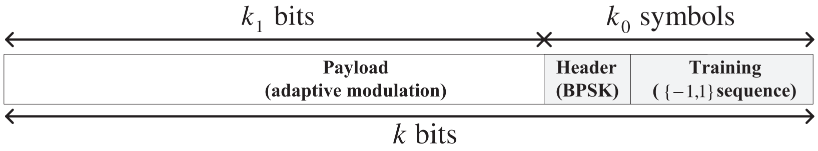


Fig. 2. The packet structure used in AWGN channels.

3. CHANNEL AND PHYSICAL LAYER MODEL

In this section, we derive the model for the energy per successfully received bit (ESB) for a given transmitter/receiver structure and packet structures. The ESB model is established for AWGN channels and for block Rayleigh fading channels.

3.1 ESB over AWGN channels

3.1.1 *Packet structure.* In communications systems, packets must be sent with a training sequence in order to estimate the channel conditions and facilitate the synchronization of the transmitter and receiver. The length of the training sequence depends on the estimation algorithm, synchronization algorithm, RF technology, oversampling rate, and the required system performance [Shin and Schulzrinne 2007]. Usually, the longer the training sequence is, the more accurate the channel estimate and synchronization are. Also, using more robust modulation schemes and operating at high SNRs will shorten the required training sequence length [Chen 2004]. In [Vilaipornsawai and Soleymani 2003], the authors state that in a slowly changing Rayleigh fading channel, a training sequence of 50 symbols can completely remove any phase offset. Thus, we assume a training sequence length of 50 symbols for our work.

Additionally, in adaptive communications systems, a header must be included to inform the receiver of the modulation scheme used for the information bits (packet payload). We assume a header length of 14 symbols. The training sequence and header must be transmitted using a predetermined modulation scheme, which will be fixed regardless of the modulation scheme used for the information bits. The modulation used for the training sequence/header should be robust even though it may be bandwidth inefficient. In this paper, we assume that the training sequence consists of a binary signal ({1, -1}), and the header is always modulated using BPSK, regardless of the modulation scheme used in the packet body.

We assume that a packet of length k contains k_1 information-bearing bits and k_0 bits of training sequence and header. Further, we assume that the training sequence and header bits are always error-free. The packet structure used for AWGN channels is shown in Fig. 2.

3.1.2 *Energy for a single packet transmission..* We use the model from [Chen et al. 2003] for the total energy for a single packet transmission:

$$E_{Consumed} = \alpha E_{RX} d^n + E_{Fixed} \tag{8}$$

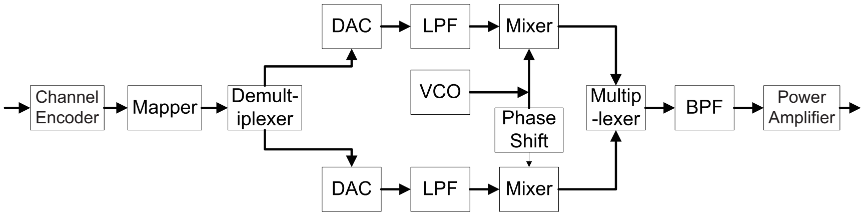


Fig. 3. A typical transmitter structure using linear modulation.

An analysis of this equation is provided in Section 2. Some fixed energy is required both in the transmitter and in the receiver to run the circuitry. E_{Fixed} represents the total fixed energy in both the transmitter and receiver to transmit/receive one packet, and E_{RX} is the received energy per packet.

The relationship between the transmit and circuit power consumption and energy consumption per symbol can also be determined. Assume each symbol contains b bits and the signal bandwidth is B Hz, then the time duration to transmit a packet of k bits (with k_1 information bits and k_0 overhead bits) is

$$T_k = \frac{k_1}{bB} + \frac{k_0}{B}. \tag{9}$$

Also, we assume that the transmit power at the transmitter is P_t and the total circuit power of the transmitter and receiver is P_c. Thus, the energy to transmit and receive a packet of k bits is

$$\begin{aligned} E_{Consumed} &= (P_t + P_c)T_k, \\ &= (P_t + P_c)(\tfrac{k_1}{bB} + \tfrac{k_0}{B}). \end{aligned} \tag{10}$$

Since each packet contains $k_1/b + k_0$ symbols, then the energy consumption per symbol is

$$\begin{aligned} E_s &= \tfrac{E_{Consumed}}{k_1/b+k_0} \\ &= \tfrac{P_t+P_c}{B}, \\ &= E_{s,TX} + E_{s,Fixed}, \end{aligned} \tag{11}$$

where $E_{s,TX} = P_t/B$ is the transmitted energy per symbol and $E_{s,Fixed} = P_c/B$ is the fixed energy consumption per symbol. Therefore, for a fixed bandwidth, $E_{s,TX}$ can be adjusted by changing the transmit power P_t. $E_{s,Fixed}$ is determined by the circuitry power consumption P_c. The circuitry power consumption can be found according to the transceiver structure, modulation schemes, coding techniques, etc. In this paper, we only consider linear modulation schemes (e.g., MQAM), which have typical transmitter and receiver structures as shown in Figs. 3 and 4.

As shown in Fig. 3, the major energy consuming components at the transmitter are the digital-to-analog converter (DAC), the low pass filter (LPF), the bandpass filter (BPF), the mixer, the frequency synthesizer and the power amplifier (PA). In this paper, the power consumption of the LPF, BPF, mixer, and frequency synthesizer are viewed as constants, while the power consumption of the DAC follows the model in [Cui et al. 2005]. Also, the power amplifier does not have perfect efficiency (see Section 4.7). The circuit power consumption here excludes

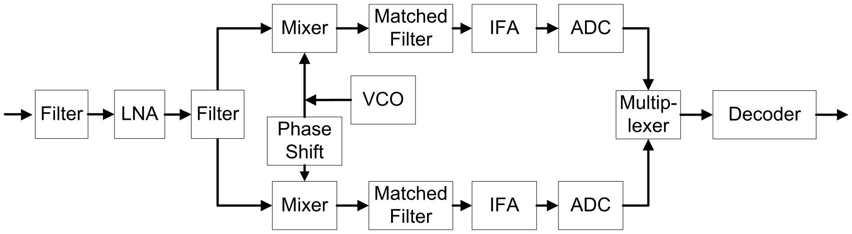


Fig. 4. A typical receiver structure using linear demodulation.

Table I. Power Consumption Values

	P_{filter}	P_{mixer}	P_{LNA}	P_{syn}
Transmitter P_{ct}	2.5 mW	30.3 mW	-	50mW
Receiver P_{cr}	2.5 mW	30.3 mW	20 mW	50mW

the power consumed by the power amplifier. The energy consumption from the power amplifier is considered as a part of $E_{s,TX}$.

Fig. 4 shows the major energy consuming components at the receiver, which are the analog-to-digital converter (ADC), the low pass filter (LPF), the low noise amplifier (LNA), the mixer, the frequency synthesizer, and decoder. In this paper, the power consumption of the LPF, LNA, mixer, and frequency synthesizer are viewed as constants. The power consumptions of the ADC and the Viterbi decoder follow the models in [Cui et al. 2005].

The power consumption of the circuit components of the transmitter (excluding the power amplifier) and the receiver is defined as

$$P_c = 2P_{mixer} + 2P_{syn} + P_{filter} + P_{DAC} + P_{LNA} + P_{ADC} + P_v, \tag{12}$$

where P_{mixer}, P_{syn}, P_{filter} and P_{LNA} are the power consumptions of the mixers, frequency synthesizers, filters, and LNA, respectively. The above power consumptions are assumed to be constant. The values for these parameters are chosen based on typical implementations, as shown in Table I [Cui et al. 2005]. P_{DAC} and P_{ADC} represent the power consumption of the DAC and the ADC, respectively. P_v is the power consumption of the Viterbi decoder. $P_v = 0$ when uncoded modulation schemes are used. These power consumptions can be determined using the formulas in [Cui et al. 2005]. From the value of P_c and the signal bandwidth B, we can calculate $E_{s,Fixed}$. For example, when $P_c = 286$ mW and $B = 100$ kHz, $E_{s,Fixed} = \frac{P_c}{B} = 2.86$ μJ.

3.1.3 *ESB model.* We model the probability of error in data reception using an AWGN channel with noise variance N_0 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.

First, we need to find the relationship between the energy per received symbol

$E_{s,RX}$ and the transmitted energy $E_{s,TX}$.

$$E_{s,RX} = \frac{E_{s,TX}}{\alpha d^n} \tag{13}$$

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

$$\alpha = \frac{1}{\frac{G_T G_R \lambda^2}{(4\pi)^2} L} \tag{14}$$

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:

$$P_{s,p} = (1 - P_{e,s})^{\frac{k_1}{b}} \tag{15}$$

where $P_{e,s}$, the probability of a symbol error, is dependent on the SNR of the signal. Note that the above calculation of the probability assumes that the k_0-bit training sequence bits are error free. The formulas for $P_{e,s}$ are given in Table II for a selection of modulation techniques. The value k_1 is the number of information bits per packet, and $b = log_2(M)$ is the number of bits per symbol. Thus the value $\frac{k_1}{b}$ is the number of symbols needed for a k-bit packet containing k_1 information bits.

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

$$T = k_1 P_{s,p} \tag{16}$$

The ratio of the total energy to send a packet and the expected amount of data per 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.

$$\begin{aligned} ESB &= \frac{(\frac{k_1}{b} + k_0)(E_{s,TX} + E_{s,Fixed})}{T} \\ &= \frac{(\frac{k_1}{b} + k_0)(E_{s,TX} + E_{s,Fixed})}{k_1 (1 - P_{e,s})^{\frac{k_1}{b}}} \end{aligned} \tag{17}$$

So, for BPSK modulation, the equation for ESB (see Table II for $P_{e,s,BPSK}$) is:

$$ESB_{BPSK} = \frac{k(E_{s,TX} + E_{s,Fixed})}{k_1 \left(1 - Q(\sqrt{\frac{2E_{s,TX}}{\alpha d^n N_o}})\right)^{k_1}} \tag{18}$$

Equation 17, the energy per successfully received bit, is the primary metric for determining the energy efficiency values. As shown in Fig. 5, 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.

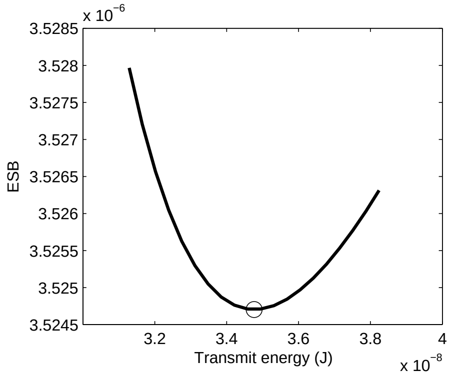


Fig. 5. The energy per successfully received bit (ESB) as a function of the transmit energy $E_{s,TX}$. This plot shows a clear minimum and thus the optimal transmit energy. These results assume a fixed distance $d = 10m$, BPSK modulation and fixed channel noise.

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

Table II. Table of symbol error formulas from [Proakis 2001].

3.2 ESB over block fading channels

3.2.1 *Packet structure.* In narrowband communication networks, the transmitted signal most often encounters block fading. In block fading environments, the training sequence at the beginning of a packet cannot provide an effective estimation of the channel, especially when the packet length is large. Therefore, *interleaved* training sequences can be used to update the channel estimation periodically according to the coherence time of the block fading channel. The packet structure for this case of block fading is shown in Fig. 6.

Assume that there are N_p inserted training sequences, each of length k_0, and the coherence time of the Rayleigh fading channel is τ_c. To have the maximum efficiency and maintain estimation accuracy, we should have

$$\frac{k_1}{bB} + \frac{N_p k_0}{B} \approx N_p \tau_c, \tag{19}$$

where k_1 is the total number of information bits in a packet. Thus, the total number of bits in a packet is $k = k_1 + N_p k_0$.

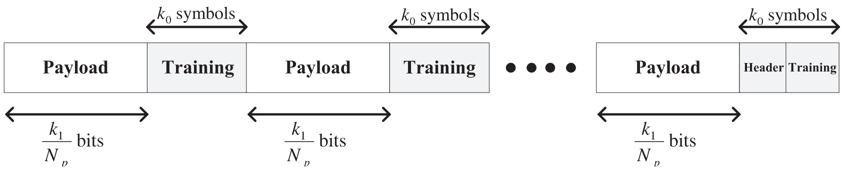


Fig. 6. The packet structure with header and *interleaved* training sequence in block Rayleigh fading channels.

The number of required training sequences is therefore

$$N_p = \frac{k_1}{b(B\tau_c - k_0)}. \tag{20}$$

3.2.2 *Energy for a single packet transmission.* For the sake of conciseness, we assume the same energy model for the transmitter and receiver in block Rayleigh fading channels as for AWGN channels. Although there are additional components in the transceiver when considering block fading channels, such as automatic gain controller (AGC) to fight Rayleigh fading, their power consumptions are constant and can be viewed as a small amount of increment over the circuit power, P_c, in AWGN channels. For example, the AGC will increase P_c by about 7 mW [Cheung et al. 2001].

3.2.3 *ESB model.* From equation 10, we have

$$\begin{aligned} E_{Consumed} &= (P_t + P_c)(\tfrac{k_1}{bB} + N_p\tfrac{k_0}{B}),\\ &= (E_{s,TX} + E_{s,Fixed})(\tfrac{k_1}{b} + N_p k_0),\\ &= (E_{s,TX} + E_{s,Fixed})\tfrac{k_1 B\tau_c}{b(B\tau_c - k_0)}. \end{aligned} \tag{21}$$

Thus, the ESB is now

$$\begin{aligned} ESB &= \tfrac{E_{Consumed}}{T},\\ &= (E_{s,TX} + E_{s,Fixed})\tfrac{k_1 B\tau_c}{b(B\tau_c - k_0)}\tfrac{1}{k_1(1-P_{e,s})^{\frac{k_1}{b}}}.\\ &= (E_{s,TX} + E_{s,Fixed})\tfrac{B\tau_c}{b(B\tau_c - k_0)(1-P_{e,s})^{\frac{k_1}{b}}}. \end{aligned} \tag{22}$$

3.2.4 *ESB model with average system outage probabilities.* In fading channels, the system outage probabilities must be considered in system design. Assume that the SNR threshold is γ_T, then the system outage probability can be defined as

$$Pr(\gamma < \gamma_T) = \int_0^{\gamma_T} \frac{1}{\bar{\gamma}} e^{-\gamma/\bar{\gamma}} d\gamma, \tag{23}$$

where $\bar{\gamma} = \frac{E_{s,RX}}{N_0}$ is the average SNR at a given distance, which is determined by path loss. Then, the ESB considering average system outage probabilities becomes

$$ESB = (E_{s,TX} + E_{s,Fixed})\frac{B\tau_c}{b(B\tau_c - k_0)[(1-P_{e,s})^{\frac{k_1}{b}}(1-Pr(\gamma<\gamma_T))]}. \tag{24}$$

Description	Parameter	Value
Fixed radio cost	$E_{s,Fixed}$	2.86 μJ/symbol
Packet size	k	360 bits
Overhead bits per packet	k_0	64 bits
Path loss exponent	n	3.5
Amplifier efficiency	L	0.02
Carrier frequency	f	2.4 GHz
Signal bandwidth	B	100 kHz
Channel coherence time	τ_c	1 ms
Outage threshold	γ_T	0.1 (-10 dB)

Table III. Default parameters used in the models.

The selection of SNR threshold γ_T is very important, especially considering multi-hop transmission, since γ_T reflects the configuration of the transmission range of a node. A high γ_T will increase the outage-probability-scaled ESB in equation 24 and require the designer to choose more nodes to cover a given distance. On the other hand, a low γ_T will decrease the outage-probability-scaled ESB and make it possible to use fewer nodes to cover a given distance. However, in this paper, we do not focus on the selection of SNR threshold. Instead, we view γ_T as a predetermined system-level parameter.

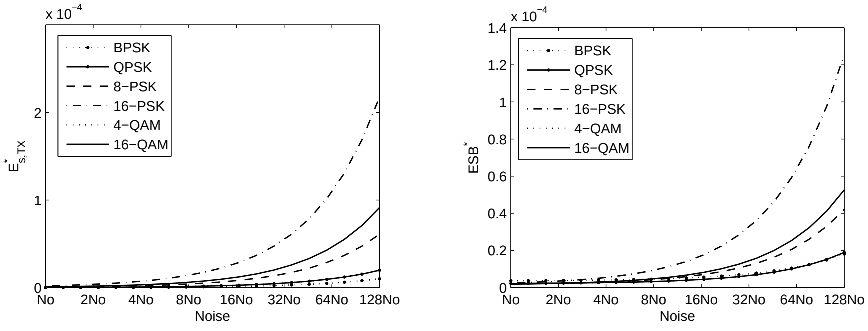
4. OPTIMIZING PHYSICAL LAYER PARAMETERS

We performed several numerical calculations to minimize ESB, the energy per successfully received bit, and hence find the optimum transmit energy and the energy-optimal hop distances for different modulation schemes. There are considerable similarities in the analysis for AWGN and block Rayleigh fading channels. Therefore, for the sake of brevity, we focus on the analysis in AWGN channels (Sections 4.2 - 4.8), with Section 4.9 providing an illustration of the performance in block Rayleigh fading channels.

4.1 Numerical Calculations

All 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. All that is needed to find the minimum 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 is chosen such that the bit error rate (BER) of a BPSK symbol is 10^{-5} for an energy per received bit $E_{b,RX} = 50nJ$. In simulations where a range of noise values are considered, the values are logarithmically spaced from N_0 to $128N_0$. Unless otherwise specified, we used the parameters shown in Table III for determining ESB.



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

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

Fig. 7. $E^*_{s,TX}$ and ESB^* for a fixed distance, $\hat{d} = 15m$ and a range of noise values for different modulations.

4.2 Optimum Transmit Energy in AWGN Channels

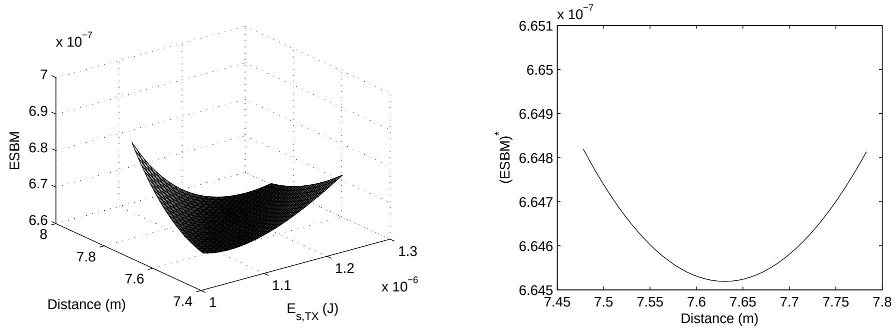
In this section we evaluate the case where hop distance is fixed. Finding the optimum transmit energy is a simple matter of finding the minimum of the ESB function with respect to energy $E_{s,TX}$ for a particular channel (N_0, n) and at a particular hop distance (d) and modulation. It was shown in Fig. 5 that ESB has a minimum with respect to $E_{s,TX}$. This value cannot be solved analytically because of the multiple Q-functions in the derivative of the ESB formula. However, the optimal $E_{s,TX}$ can be solved numerically. Fig. 7 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. The optimal ESB (ESB^*) and the optimal $E_{s,TX}$ $(E^*_{s,TX})$ values were stored and plotted against the noise value in Fig. 7.

Fig. 7(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. Fig. 7(b) shows that as the noise increases, the optimal ESB also increases.

4.3 Optimum Distance in AWGN Channels

In addition to finding the optimum transmit energy, we also want to find the optimal hop distance. In this section we 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 if a packet needs to travel a route of distance D, then $ESBM \times D$ gives the ESB of the entire route. Thus, by minimizing $ESBM$, then ESB is minimized for the entire route.

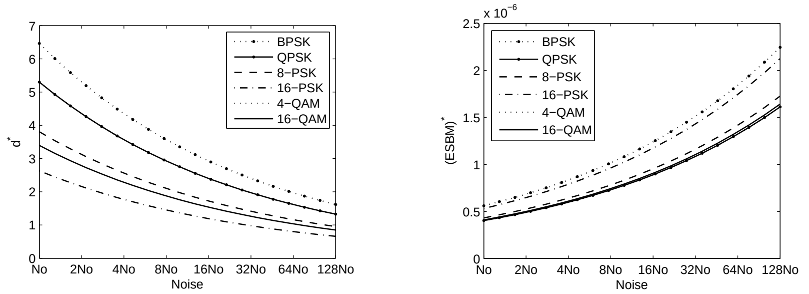
The optimal distance can be seen by looking at a plot of $ESBM$ versus transmit energy and hop distance, shown in Fig. 8(a). The line of minimum values occur at



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

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

Fig. 8. Determining optimal hop distance.



(a) Optimal distance

(b) Optimal $ESBM$

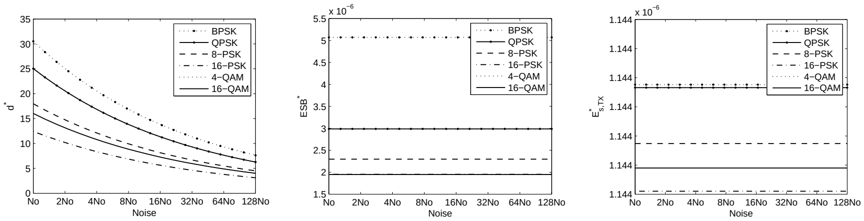
Fig. 9. Energy optimal hop distance as a function of noise. $E_{s,TX} = 5$ nJ.

each distances' optimum transmit energy value. It may appear that $ESBM$ has a range of values that are minimum, but as seen in Fig. 8(b), a plot of the values along the trench, $ESBM$ has a clear minimum value and, thus, an optimum hop distance.

Fig. 9 shows the optimal distance d^* and $ESBM^*$. Both plots were generated with $E_{s,TX} = 5$ nJ. Fig. 9(a) shows that the optimum distance decreases with increasing channel noise. Similarly, Fig. 9(b) shows that as the channel noise increases, $ESBM^*$ increases. This is as expected, since as the channel gets worse, more energy on average to transmit the data is needed due to the increased probability of retransmission.

4.4 ESB at the Optimum Distance and Transmit Energy in AWGN Channels

In Sections 4.2 and 4.3, the metric ESB was evaluated with one degree of freedom, namely, $E_{s,TX}$ or d, respectively. 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



(a) Optimum hop distance (b) Optimum ESB (c) Optimum $E_{s,TX}$

Fig. 10. Parameters calculated using $E^*_{s,TX}$ and d^* at each point considered.

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. Fig. 10 shows the results when both parameters are set to their optimal values. Fig. 10(a) shows the optimal hop distance. As expected the optimal hop distance decreases with an increase in channel noise. Unexpectedly, Figs. 10(b) and 10(c) show that the optimal ESB and $E_{s,TX}$ are independent of channel noise. This means that nodes 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 can be seen by rewriting equation 17 as follows:

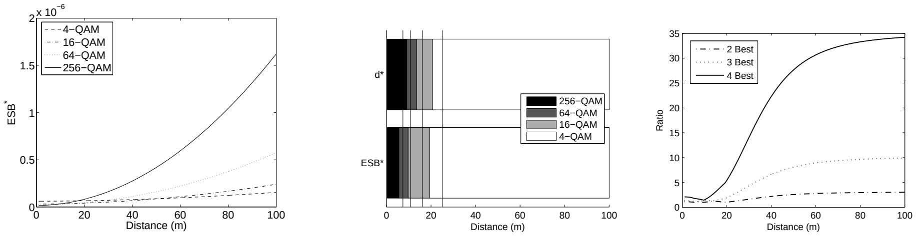
$$ESB = \frac{(\frac{k_1}{b} + k_0)(E_{s,TX} + E_{s,Fixed})}{k_1(1 - P_{e,s}(\frac{E_{s,TX}}{\alpha d^n N_0}))^{\frac{k_1}{b}}}.$$

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 $d \rightarrow \frac{1}{\sqrt[n]{\xi}} d$.

4.5 Selecting the Optimal Modulation Scheme

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 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 Fig. 11(a), for each hop distance, there is an optimal modulation scheme that minimizes energy dissipation.

Fig. 11(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



(a) Optimum ESB vs distance

(b) Optimum ESB vs Optimum distance

(c) Ratio of ESB vs suboptimal ESB

Fig. 11. Selection of the modulation scheme for each (noise, distance) value based on (a) which modulation scheme's optimal is closest to the point and (b) which modulation scheme obtains the optimum ESB at that point. Subfigure (c) shows the ratio of ESB using the nth best modulation and the best modulation scheme.

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.

Fig. 11(c) is an evaluation of the effects of using a suboptimal modulation 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.

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 15. 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 16 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 Fig. 12, 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 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.

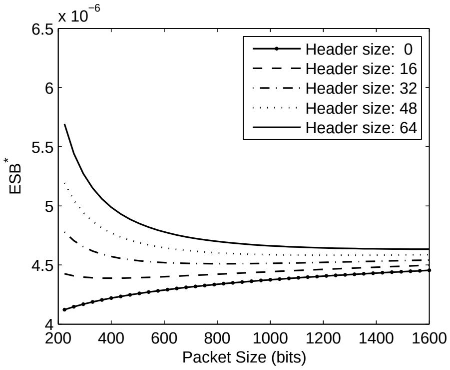


Fig. 12. Effect of packet size on the ESB.

4.7 Amplifier Efficiency

In our model, parameter 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 to the antenna. In a traditional model for a radio, there is some fixed cost for operating the radio. That is, for every 1 mW put into the amplifier, there will be δ mW radiated out of the antenna, where $\delta < 1$.

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 17 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 $E_{b,RX} = 50nJ$. This means that using an α that depends on the amplifier efficiency is equivalent to scaling the noise term, as shown in this equation:

$$ESB = \frac{(\frac{k_1}{b} + k_0)(E_{s,TX} + E_{s,Fixed})}{k_1(1 - P_{e,s}(\frac{E_{s,TX}}{\alpha d^n N_0}))^{\frac{k_1}{b}}}. \tag{25}$$

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 Sentilla Corporation (formerly MoteIV Corporation [MoteIV 2007]) have a table that specifies the current draw of the system, which provides us with the energy values shown in Table IV.

Fig. 13 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. This figure shows a slight change in the shape of the curve as the value of α changes. 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

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 IV. Table of power consumed based on transmit power for the MoteIV Tmote Sky. Based on information from [MoteIV 2007].

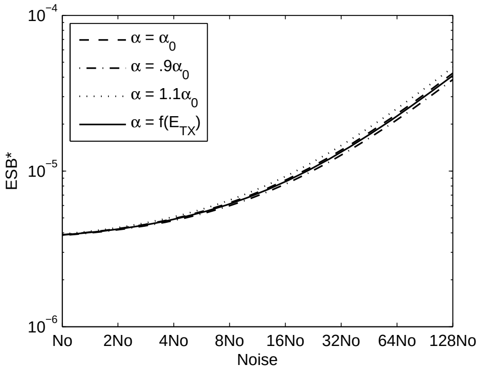


Fig. 13. ESB^* as a function of channel noise N_o for different amplifier efficiency values.

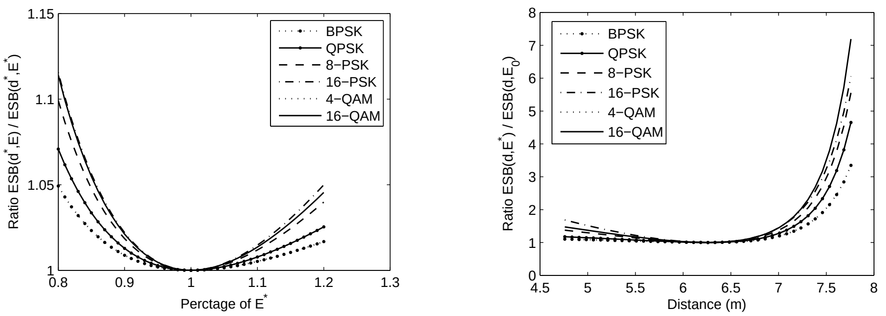
results obtained in the previous sections.

4.8 Gain Achieved By Optimizing Physical Layer Parameters in AWGN Channels

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.

Figs. 14(a) and 14(b) show the impact of deviation from the optimum transmit



(a) Error in energy

(b) Error in distance

Fig. 14. Gain of finding optimal transmit energy and optimal distance.

energy and hop distance values, respectively. Fig. 14(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 20 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.

Fig. 14(b) shows the effect of using hop distances other than the one used to find the optimal transmit power. In this figure, the optimal transmit power was found for a distance of 20 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 Fig. 14 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.

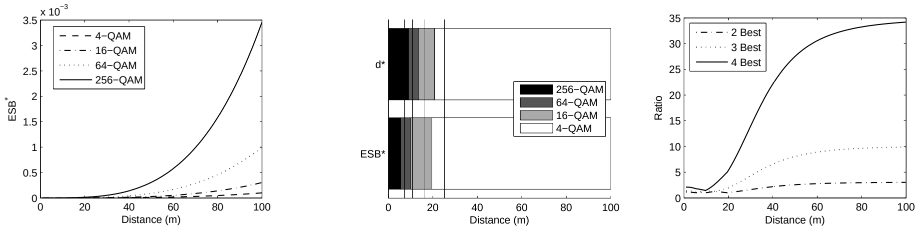
Table V shows the effects on $ESBM$ of using suboptimal modulation schemes. This data tells us that the penalty for using a suboptimal modulation scheme can be quite high, and thus it is important to match the modulation scheme with the expected hop distance and channel model to reduce energy to send data in wireless sensor networks.

4.9 The Performance in Block Rayleigh Fading Channels with Outage Probability

The performance of different modulations is also evaluated in block Rayleigh fading channels. The ESB model in this case is from equation 24. By observing equations 17 and 24, we find that the ESB models in AWGN channels and block Rayleigh fading channels are similar. Compared with the ESB model in AWGN channels, the ESB in block Rayleigh fading channels is scaled by the outage probability and multiple sequences of training symbols. Some illustrative results for block Rayleigh fading channels are shown in Fig.15. Fig. 15(a) shows that, for each hop distance, there is an optimal modulation scheme that minimizes energy dissipation in block

Maximum difference		Optimum Modulation			
		4-QAM	16-QAM	56-QAM	256-QAM
Modulation Used	4-QAM	0%	43%	77%	110%
	16-QAM	203%	0%	17%	37%
	56-QAM	893%	82%	0%	12%
	256-QAM	3323%	393%	41%	0%
Average difference		4-QAM	16-QAM	56-QAM	256-QAM
Modulation Used	4-QAM	0%	24%	63%	100%
	16-QAM	150%	0%	10%	31%
	56-QAM	683%	37%	0%	8%
	256-QAM	2566%	201%	19%	0%

Table V. Percent increase in $ESBM$ by using suboptimal modulation schemes. Data used in figure 11(c).



(a) Optimum ESB vs distance

(b) Optimum ESB vs Optimum distance

(c) Ratio of ESB vs suboptimal ESB

Fig. 15. Selection of the modulation scheme for each (noise, distance) value based on (a) which modulation scheme's optimal is closest to the point and (b) which modulation scheme obtains the optimum ESB at that point. Subfigure (c) shows the ratio of ESB using the nth best modulation and the best modulation scheme.

Rayleigh fading channels. Fig. 15(b) shows that using a particular modulation's optimum hop distance does not guarantee the most energy efficiency. Fig. 15(c) shows the importance of using either the optimal or the next-optimal modulation scheme to save energy. These results are similar to the results for AWGN channels, and similar conclusions about optimal selection of transmit power, hop distance and modulation scheme can be made. The most significant differences in the results using AWGN and block Rayleigh fading channels are due to the increased energy consumption caused by the outage probability and the multiple sequences of training symbols. For example, the optimized ESB for 4-QAM is about 1×10^{-7} J at $d = 50$ m in AWGN channels; while the optimized ESB for 4-QAM increases to 1.1×10^{-5} J at $d = 50$ m in block Rayleigh fading channels.

5. CONCLUSION

In this paper we investigated the impact of physical layer parameter selection on the energy efficiency of wireless sensor networks. The analysis is conducted mostly in

AWGN channels, while we show that a similar procedure can be readily adopted for the analysis in block Rayleigh fading channels. The results presented in this paper can be of great help to network designers. For example, as the simulation results show, 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, as well as the optimum transmit energy. The contributions of this study are itemized as follows:

- The main conclusion of this study is that using optimal transmit energy and optimal relay distance are crucial in achieving energy efficiency for a wireless sensor network.
- Optimizing only the transmit energy without optimizing the relay distance is not enough to achieve the best possible ESB.
- Overestimating the transmit energy is preferable over underestimating the transmit energy.
- 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 requiring a change in the transmit energy.
- It is important to match the modulation scheme with the expected hop distance and channel noise model in order to efficiently use the limited sensor energy. Average increases in ESBM from using a suboptimal modulation scheme range from 8% up to greater than 2500%.
- The results presented for AWGN channels also hold for block Rayleigh fading channels.
- As all networks will not be operating under the same conditions, it is important for future wireless sensor network standards to allow for adaptation in order to achieve long network lifetimes.

There are many ways we can extend this work. We plan to take the information in Section 4.2 about optimum energy for a fixed distance and apply this 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 requirements. If nodes are chosen around the optimum distance with some probability, then the optimum transmit energy would likely change. Another area of our future work is to test this analysis on actual hardware (e.g., motes) and evaluate the results.

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