Minimization of Transceiver Energy Consumption in Wireless Sensor Networks with AWGN Channels

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***Abstract*—In this paper, we determine how to minimize energy consumption per information bit in a single link, with the consideration of packet retransmission and overhead. This is achieved by deriving expressions for the optimum target bit error probability and packet length at different transmission distances. Furthermore, the energy consumptions of different modulation schemes are compared over an additive white gaussian noise (AWGN) channel. Finally, it is shown that the optimum target bit error probability and packet length converge to a constant value for long distances. Numerical results show that at short distances, it is optimum to use bandwidth efficient modulation with large packets and low target BER, and at long distances, it is optimum to use energy efficient modulation with short packets and high target BER.**

I. INTRODUCTION

In the conventional design of communication systems, the goal is often to minimize the transmit power. This is represented through considering the performance of the system in terms of the bit or packet error probability versus the signal to noise ratio [1][2]. This focus on the transmit power (and not on the overall consumed energy) is due to two major factors. First, traditional communication links are often designed for long ranges. Consequently, the transmitted energy is the dominant portion of the overall energy consumed. Second, most of the links are designed for mains powered base stations communicating with rechargeable mobile devices. Hence, less attention is paid to energy consumption, compared to other important constraints such as regulatory and practical limitations on transmit power. In recent years, with the advent of wireless sensor networks (WSN) [3], much more attention is being paid to the overall energy consumed because of the particularly restricted resources of sensor nodes. A considerable amount of research has been conducted on prolonging the lifetime of wireless sensor networks from the perspective of higher communication layers (*e.g.,* [4][5][6]). In this paper, we focus on reducing energy dissipation at the physical (PHY) layer.

Due to the ad hoc nature of WSNs, the conditions governing the link performance (such as link distance) are variable. Adaptive modulation techniques can be used to optimize the energy consumption caused by communicating under different conditions. In [7], the authors provide an energy consumption model for the PHY layer and minimize the energy consumption per information bit under AWGN channels. In this work, however, a fixed target bit error probability is assumed. Furthermore, the effect of packet length and retransmissions are not considered. These two parameters are inter-related and have a direct effect on the overall consumed energy. In this paper we extend the work in [7] to minimize the energy consumption per information bit while including the effects of retransmissions and packet overhead. We minimize the energy consumption over both bit error probability as well as the packet length.

The remainder of this paper is organized as follows. Section II introduces the packet structure and transceiver model used in this paper. In Section III we minimize the energy consumption per information bit over target bit error probability and packet length. Numerical results are presented in Section IV. Section V concludes this paper.

II. SYSTEM AND SIGNAL MODEL

A. Packet Structure

The packet structure considered in this paper is shown in Figure 1. It consists of four components: payload, upper layer header, PHY/MAC-header, and preamble. We assume that there are L_L bits in the payload of each packet. The upper layer header contains the control information added by the upper layers, such as routing information, packet ID, etc. We assume there are L_{UH} bits in the upper layer header. From the view of the PHY and MAC layers, the payload and the upper layer header are indistinguishable. Therefore, the payload and the upper layer header are modulated and coded similarly.

Conversely, PHY and MAC headers are modulated using a predefined modulation scheme, such as BPSK for an uncoded system and coded BPSK for a coded system. This is because the PHY and MAC headers carry important control information, such as information regarding modulation and coding for the payload and the upper layer header. Therefore, the modulation scheme of the PHY/MAC-header has to be robust and known to the receiver a priori, so that the receiver can always demodulate the received PHY/MAC-header, no matter what modulation scheme the payload and upper layer header use. Finally, the preamble is a certain predefined sequence that serves the purpose of synchronization, configuration of the automatic gain controller (AGC), etc. Moreover, we assume that the transmission power is constant during the entire packet. A summary of the length and duration parameters for these components are listed in Table I.

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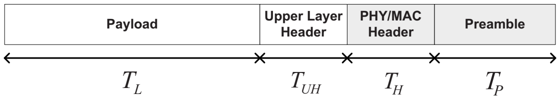

Fig. 1. Packet structure.

TABLE I
PACKET STRUCTURE PARAMETERS

Component	Length (bits)	Duration (s)	Modulation
Payload	L_L	T_L	Adaptive
Upper layer header	L_{UH}	T_{UH}	Adaptive
PHY/MAC header	L_H	T_H	BPSK/coded BPSK
Preamble	-	T_P	-

B. Transceiver Model

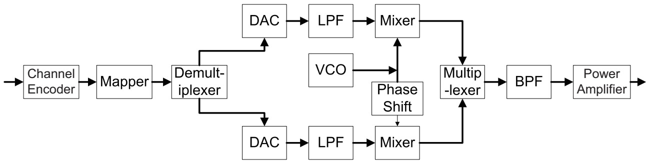

Fig. 2. A typical transmitter structure using linear modulation.

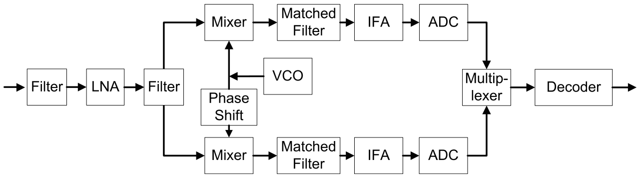

Fig. 3. A typical receiver structure using linear demodulation.

In a sensor node, energy is consumed for sensing, data processing and communications [8][9]. In this paper, only the energy consumption involved in the communications is considered, since the energy consumption of sensing and data processing does not affect our optimization scheme and is usually negligible. At the transmitter end, energy consumption comes from the transmitted energy and the energy consumed in the circuits. At the receiver end, the only energy consumption is that of the circuitry. To facilitate the analysis of the energy consumption, we assume generic transmitter and receiver models as shown in Figures 2 and 3.

1) Transmitter: As shown in Figure 2, the major energy consuming components at the transmitter are the digital-to-analog converter (DAC), low pass filter (LPF), bandpass filter (BPF), mixer, frequency synthesizer and 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 [7].

The power consumption of the power amplifier can be expressed as

$$P_{amp} = \beta P_t, \tag{1}$$

where P_t is the transmission power and $\beta = \frac{\varepsilon}{\rho} - 1$, ε is the peak-to-average ratio, and ρ and the drain efficiency. Note that ε and ρ are both determined by the modulation scheme.

2) Receiver: As shown in Figure 3, the major energy consuming components at the receiver are the analog-to-digital converter (ADC), low pass filter (LPF), low noise amplifier (LNA), mixer, frequency synthesizer, intermediate frequency amplifier (LFA) 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 Viterbi decoder follow the models in [7].

III. MINIMIZATION OF ENERGY CONSUMPTION OVER TARGET BIT ERROR PROBABILITY AND PACKET LENGTH

A. Energy Consumption per Packet

We assume that the transmitter and receiver will stay in the on state for T_{on} seconds, where $T_{on} = (T_L + T_{UH} + T_H)/R_c + T_p$, where R_c is the channel code rate and is set to 1 for the uncoded case.

Therefore, the total energy consumption required to transmit or receive L_L information bits is

$$E = (P_t/G_c + P_{amp} + P_c)T_{on}, \tag{2}$$

where P_t is the transmit power used in an uncoded system, G_c is the coding gain, $P_{amp} = \beta P_t$ is the power consumption of the power amplifier, and P_c is the power consumption of the circuit components of the transmitter and receiver.

The transmit power, P_t, can be determined from the SNR γ at the receiver and the bit error probability P_b. The SNR per symbol is defined as $\gamma = P_r/(2BN_0)$, where P_r is the received power, B is the signal bandwidth, and N_0 is the spectral power density of an AWGN channel. It is easy to find $\gamma = f(P_b)$ by using exponential approximation to the Q-function (Table II).

TABLE II
BIT ERROR PROBABILITIES AND BANDWIDTH EFFICIENCY FOR SELECTED COHERENT MODULATIONS/DEMODUATIONS

Modulation	$P_b(\gamma)$	η (bits/Hertz)
BPSK	$P_b \approx \frac{1}{2}e^{-\gamma}$	$\eta = 1$
MPSK	$P_b \approx \frac{1}{log_2 M} e^{-\gamma \sin^2(\frac{\pi}{M})}$	$\eta = log_2 M$
MQAM	$P_b \approx \frac{2}{log_2 M} e^{-\frac{3}{2(M-1)}\gamma}$	$\eta = log_2 M$
MFSK	$P_b \approx \frac{M-1}{2log_2 M} e^{-\frac{\gamma}{2}}$	$\eta = \frac{2log_2 M}{M}$

Also, based on the signal propagation model, we have $P_t = GP_r$,where $G \sim d^{3.5}$ represents the path loss. Therefore, the transmit power can be eventually denoted as

$$P_t = 2BN_0 G\gamma. \tag{3}$$

The power consumption of the circuit components of the transmitter and the receiver is defined as

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

where P_{mixer} is the power consumption of the mixers, P_{syn} is the power consumption of the frequency synthesizer, P_{filter} is the power consumption of the filters, and P_{LNA} is the power consumption of the low noise amplifier. The above power consumptions are assumed to be constant. The values for these

TABLE III
POWER CONSUMPTION VALUES

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

parameters are chosen based on typical implementations, as shown in Table III. 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. These power consumptions can be determined using the formulas in [7].

Hence, to transmit/receive a packet containing L_L information bits, the energy consumption is

$$E = (1+\beta)2BN_0G\gamma T_{on}/G_c + P_cT_{on}. \tag{4}$$

B. Optimization of Energy Consumption per Packet

We assume that there is no error in the PHY/MAC-header. This assumption is reasonable for two reasons. First, the length of the packet body is much larger than that of the PHY/MAC-header, so an error is more likely to happen in the packet body. Second, the robust modulation schemes used by the PHY/MAC-header ensure that errors rarely occur in the PHY/MAC-header. Also, we assume that whenever there is a bit error in the received packet, a retransmission is required. For a packet containing L_L information bits, the probability of a packet error is

$$P_{pe} = 1-(1-P_b)^{L_L+L_{UH}}. \tag{5}$$

Considering retransmission, the procedure for successfully transmitting/receiving one packet is shown in Figure 4. As shown in Figure 4, the inter packet space (IPS) is set as $T_{IPS} = 5$ ms. We assume that before transmission or reception of a packet, the transmitter and receiver will spend T_{tr} seconds to go from the off (sleep) state to an on (active) state. Also, for a given implementation, the time period to start up the frequency synthesizer, T_{tr}, is fixed. In this paper, we assume $T_{tr} = 5\mu s$ and the power consumption during T_{tr}, P_{tr} is approximately equal to P_{syn}, where P_{syn} is the power consumption of the frequency synthesizer [7]. T_{on} is the time duration for the transmission of one packet. Similarly, T_{ACK} is the time period when the transmitter listens for an acknowledgement. We set $T_{ACK} \approx \frac{L_H}{BR_c} + T_P$. The energy consumptions during each time period are as follows

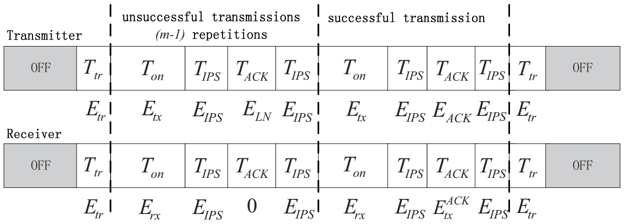

Fig. 4. The transmission and reception of one packet using m total transmissions.

$$\begin{aligned}
E_{tr} &= P_{syn}T_{tr},\\
E_{IPS} &= P_{syn}T_{IPS},\\
E_{LN} &= (P_{cr}-P_v)T_{ACK},\\
E_{ACK} &= P_{cr}T_{ACK},\\
E_{tx} &= [(1+\beta)2BN_0G\gamma/G_c+P_{ct}]T_{on},\\
E_{tx}^{ACK} &= [(1+\beta)2BN_0G\gamma/G_c+P_{ct}]T_{ACK},\\
E_{rx} &= P_{cr}T_{on}.
\end{aligned}$$

Assume that to successfully deliver one packet, the total number of transmissions is m. In the first $(m-1)$ transmissions, the energy consumption during the T_{ACK} period at the transmitter is E_{LN}, since the transmitter does not receive an acknowledgement from the receiver and decoding is not needed. In the last delivery, the energy consumption during the T_{ACK} period at the transmitter is E_{ACK}, since the transmitter receives and decodes the acknowledgement from the receiver. Also, we assume that during the inter frame space, T_{IPS}, only the frequency synthesizer contributes to the energy consumption. E_{tx}^{ACK} is the energy consumption of transmitting the acknowledgement after receiving the m^{th} packet. We assume that in the first T_{ACK} periods, the energy consumption at the receiver is zero.

Therefore, the total transmit and receive energy consumptions of the m deliveries are

$$\begin{aligned}
E_t(m) &= (2E_{IPS}+E_{tx}+E_{LN})(m-1)+2E_{tr}\\
&\quad +2E_{IPS}+E_{tx}+E_{ACK}.\\
E_r(m) &= (2E_{IPS}+E_{rx})m+2E_{tr}+E_{tx}^{ACK}.
\end{aligned}$$

Consequently, to successfully deliver a packet, the average energy consumption is

$$\bar{E} = \sum_{i=1}^{\infty}[E_t(i)+E_r(i)]Pr\{m=i\}, \tag{6}$$

where m is the number of transmissions and $Pr\{m=i\}$ denotes the probability that the number of transmissions equals i, which is given by $Pr\{m = i\} = P_{pe}^{i-1}(1-P_{pe})$. After simplification, we have

$$\begin{aligned}
\bar{E} &\approx \tfrac{(2E_{IPS}+E_{tx}+E_{LN})}{1-P_{pe}}+2E_{tr}+P_vT_{ACK}\\
&\quad +\tfrac{(2E_{IPS}+E_{rx})}{1-P_{pe}}+2E_{tr}+E_{tx}^{ACK}.
\end{aligned} \tag{7}$$

Each packet contains L_L information bits. Therefore, the average energy consumption per information bit is

$$\bar{E}_{bit} = \frac{\bar{E}}{L_L} \tag{8}$$

To minimize $\bar{E}_{bit}$ with respect to L_L, we set $\frac{\partial \bar{E}_{bit}}{\partial L_L} = 0$, which gives us

$$A_1L_L^2+B_1L_L+C_1 = 0, \tag{9}$$

where

$$\begin{aligned}
A_1 &= \tfrac{P_{on}P_b}{B\eta},\\
B_1 &= P_b(4E_{IPS}+E_{LN}+P_{on}T_p+\tfrac{P_{on}L_H}{BR_c}+\tfrac{P_{on}L_{UH}}{B\eta R_c}),\\
C_1 &= -(4E_{IPS}+E_{LN}+4E_{tr}+E_{tx}^{ACK}+P_vT_{ACK}\\
&\quad +P_{on}T_p+\tfrac{P_{on}L_H}{BR_c}+\tfrac{P_{on}L_{UH}}{B\eta R_c}),\\
\text{with}\quad P_{on} &= 2(1+\beta)BN_0G\gamma/G_c+P_c.
\end{aligned}$$

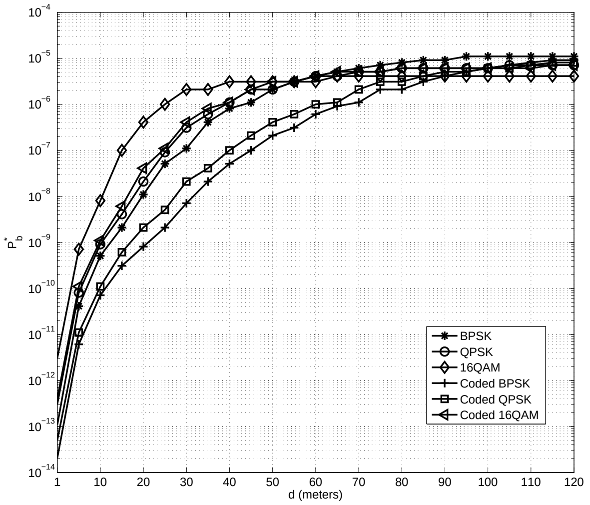

Fig. 5. Optimized target bit error probability vs. transmission distance ($L_L = L_L^*$).

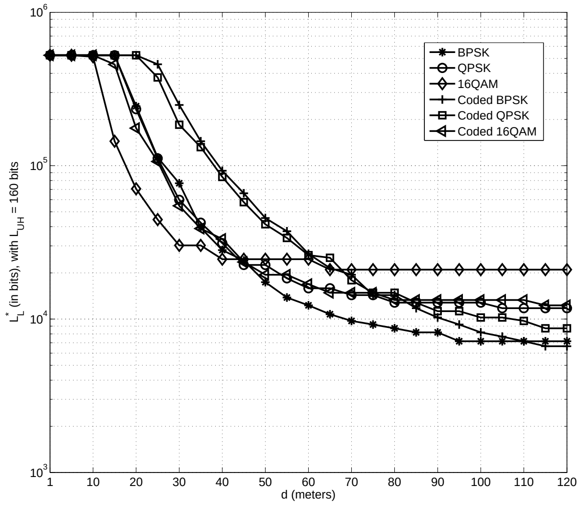

Fig. 6. Optimized packet length vs. transmission distance ($P_b = P_b^*$).

Solving (9) yields the optimum number of information bits per packet, L_L

$$L_L^* = \frac{-B_1 + \sqrt{B_1^2 - 4A_1C_1}}{2A_1}. \quad (10)$$

Correspondingly, the optimum target P_b can be found by solving $\frac{\partial \bar{E}_{bit}}{\partial P_b}|_{L_L^*} = 0$. The closed-form solution of the optimum target P_b can be found through the following approximations (for small P_b)

$$\begin{aligned} P_b \ln P_b &\approx P_b^{P_b} - 1, \\ P_b^{P_b} &\approx -10P_b + 1. \end{aligned}$$

Hence, when using M-QAM, we have

$$P_b^* \approx \frac{1}{1+(L_L+L_{UH})[\ln(\frac{2}{b})+10+\frac{P_cT_{on}+4E_{IPS}+E_{LN}}{\frac{2}{3}(2^b-1)A_2}]}, \quad (11)$$

where $A_2 = \frac{(1+\beta)2BN_0G(d)T_{on}}{G_c}$.

When transmission distance d is large, $A_2 \approx \infty$. Equation (11) becomes

$$P_b^* \approx \frac{1}{1+(L_L+L_{UH})[\ln(\frac{2}{b})+10]}. \quad (12)$$

Therefore, the target bit error probability will eventually converge to a value solely determined by the packet length and the modulation scheme. The optimum target bit error probabilities of other modulation schemes and their corresponding convergence values can be obtained similarly. Furthermore, equation (10) reveals a one-to-one relation between P_b^* and L_L^* at any given distance. Thus, as P_b^* converges, L_L^* will also converge for higher transmission distances.

IV. NUMERICAL RESULTS

We assume a bandwith of $B = 10$KHz, $L_{UH} = 160$ bits, $L_H = 32$ bits, $T_P = 20$ ms, $R_c = 1/2$, and $G_c = 6.47$. Furthermore, the packet length, L_L is limited to 64 kbytes.

Figure 5 presents P_b^* at different transmission distances. As shown in Figure 5, as the transmission distance increases, P_b^* will increase as well. This is because, as transmission distance increases, a higher target P_b is preferred lest the transmission energy increases dramatically to mitigate the path loss. Moreover, as transmission distance increases,a flattening of P_b^* can be observed, which is consistent with (12).

Figure 6 depicts L_L^* at different transmission distances. L_L^* decreases as transmission distance increases and converges to a certain value at large transmission distances. Recall that P_b^* increases as d increases, which gives rise to a higher retransmission probability. Therefore, to reduce the retransmission cost, a shorter packet length is preferred. Also, the convergence of L_L^* occurs at large transmission distances as P_b^* flattens.

The optimized total energy consumption per information bit at different transmission distances is shown in Figure 7. As transmission distance d increases, the total energy consumption per information bit increases, which is mainly caused by the increasing transmission energy. As shown in Figure 7, uncoded 16QAM, uncoded QPSK, and coded QPSK are preferred for short, medium and long distances, respectively. This observation is justified by noting the fact that at short distances, the energy consumption is dominated by that of the circuitry. Consequently, bandwidth efficient modulation schemes that lead to shorter on time will have an advantage. On the other hand, at longer distances, the energy consumption is dominated by the transmitted energy. Hence, modulation and coding schemes that require lower SNR will have an advantage.

The energy consumption gain achieved by optimization

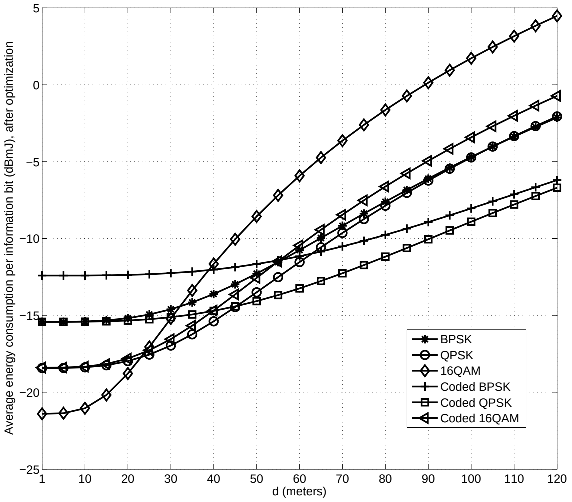

Fig. 7. The optimized total energy consumption per information bit vs. transmission distance.

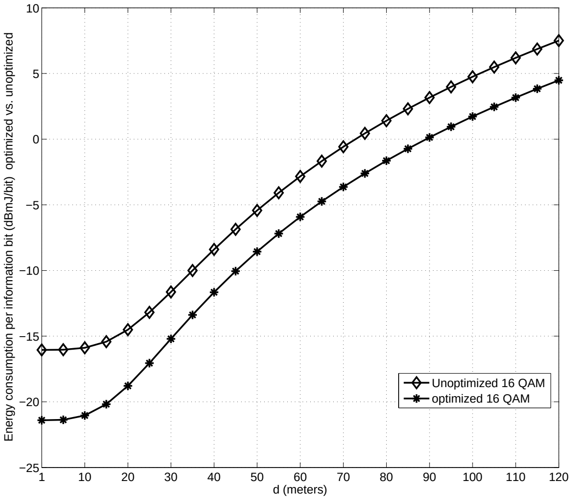

Fig. 8. Comparison of optimized energy consumption to that obtained from fixed values ($P_b = 10^{-4}$ and $L_L = 127$ bytes) for uncoded 16QAM.

for uncoded 16QAM is exemplified in Figure 8, where the optimized case is compared with a case where a fixed target P_b of 10^{-4} and packet length of $L_L = 127$ bytes are assumed. As shown in Figure 8, a 5.36dB and 3.03dB gain can be achieved by the optimization at $d = 5$m and $d = 120$m, respectively. The decreasing gain is caused by the fact that as the distance increases, P_b^* and L_L^* approach the fixed values assumed. Table IV presents a list of the optimization gains at $d = 5$m and $d = 120$m, for different modulation and coding schemes, with the fixed target P_b and L_L assumed above.

V. CONCLUSIONS

In this paper, we investigated the energy consumption minimization problem in transceivers in wireless sensor networks over an AWGN channel. An optimization over both target bit error probability and packet length is performed to minimize the energy consumption per information bit, with the consideration of retransmissions and a detailed packet structure and energy model. The closed forms for the optimum values of packet length and target bit error probability for a given transmission distance are provided for both coded and uncoded systems. The results reveal that when transmission distance is short, a system adopting large packet length, small target bit error probability, and high bandwidth-efficient modulation schemes (*e.g.*, high-order uncoded QAM) is more energy efficient. On the other hand, when transmission distance is large, a system using small packet length, large target bit error probability, and high energy-efficient modulation schemes (*e.g.*, coded BPSK) is energy efficient. Moreover, as transmission distance increases, a flattening of the optimum values of packet length and target bit error probability is observed.

TABLE IV
OPTIMIZATION GAIN COMPARED TO A CASE WITH FIXED VALUES $P_b = 10^{-4}$ AND $L_L = 127$ BYTES

Modulation and coding	Gain ($d = 120m$)	Gain ($d = 5m$)
BPSK	0.95dB	2.64 dB
Coded BPSK	0.76dB	2.05 dB
QPSK	1.77dB	3.75 dB
Coded QPSK	1.20dB	2.80 dB
16QAM	3.03dB	5.36 dB
Coded 16QAM	1.94dB	3.99 dB

REFERENCES

[1] J. G. Proakis, *Digital Communications*, 4th ed. MA: Addison-Wesley, 1972.

[2] T. S. Rappaport, *Wireless Communications : Principles and Practice*, 2nd ed. MA: Addison-Wesley, 1972.

[3] I. Akyildiz, S. Weilian, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks,” *IEEE Communications magzine*, vol. 40, pp. 102–114, Aug. 2002.

[4] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “An application-specific protocol architecture for wireless microsensor networks,” *IEEE Transactions on Wireless Communications*, pp. 660–670, Oct. 2002.

[5] O. Younis and S. Fahmy, “Distributed clustering in ad-hoc sensor networks: A hybrid, energy-efficient approach,” in *Proceedings of the 23rd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM)*, 2004.

[6] C. Schurgers, V. Tsiatsis, S. Ganeriwal, and M. Srivastava, “Optimizing sensor networks in the energy-latency-density design space,” *IEEE Transactions on Mobile Computing*, pp. 70–80, Jan. 2002.

[7] S. Cui, A. J. Goldsmith, and A. Bahai, “Energy-contrained modulation optimization,” *IEEE Transactions on Wireless Communications*, vol. 4, no. 8, pp. 2349–2360, Sep. 2005.

[8] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks,” *IEEE Communications Magazine*, pp. 102–114, Aug. 2002.

[9] V. Raghunathan, C. Schurgers, P. Sung, and M. Srivastava, “Energy-aware wireless microsensor networks,” *IEEE Signal Processing magzine*, vol. 19, pp. 40–50, Mar. 2002.