Energy Efficiency based Packet Size Optimization in Wireless Sensor Networks

Y. Sankarasubramaniam, I. F. Akyildiz and S. W. McLaughlin
School of Electrical & Computer Engineering
Georgia Institute of Technology, Atlanta, GA 30332
Email: {yogi,ian,swm}@ece.gatech.edu

Abstract—**This paper addresses the question of optimal packet size for data communication in energy constrained wireless sensor networks. Unlike previous work on packet length optimization in other wired and wireless networks, *energy efficiency* is chosen as the optimization metric. The use of fixed size packets is proposed in light of the limited resources and management costs in sensor networks. The optimal fixed packet size is then determined for a set of radio and channel parameters by maximizing the energy efficiency metric. Further, the effect of error control on packet size optimization and energy efficiency is examined. While retransmission schemes are found to be energy inefficient, it is shown that forward error correction can improve the energy efficiency eventhough it introduces additional parity bits and encoding/decoding energy consumptions. In this regard, binary BCH codes are found to be 15% more energy efficient than the best performing convolutional codes, which have thusfar been considered for error control in sensor networks.**

I. Introduction

The emergence of wireless sensor networks (WSN) [14], [3], [2] has altered our perspective on the collection and communication of information over the wireless channel. The collaborative effort of a vast number of microsensor nodes has profound implications for the future of wireless communications with wide-ranging applications from health, home and environmental to military, space and commercial [2]. While this seems an attractive possibility, the limited on-board energy poses a serious challenge. Tiny, microsensor nodes have reduced battery capacity that cannot be replenished in most application scenarios. Hence, the design of energy efficient strategies to prolong lifetime is of utmost importance. Many energy-efficient protocols have thus far been proposed for WSN [5], [6], [7], [18], [19], [26], [22], [27]. In this paper, we study packet size optimization in WSN based on the *energy efficiency* metric and examine the effect of error control on energy efficiency.

A WSN typically consists of numerous energy constrained *sensor nodes* scattered in the field of observation, called the *sensor field*. Each sensor node is capable of detecting events, locally processing the sensed data and communicating with neighbor nodes. A much smaller number of more powerful *sink nodes* act as data aggregators in the network. Hence, data packets from a source node typically hop through several intermediate sensors before reaching the sink. To reduce the communication burden, a sensor node may process and aggregate incoming data before relaying it to its neighbor node. Our aim in this work is to determine the optimal data packet size for communication between neighboring sensor nodes.

Although there have been several studies on packet size optimization in other wireless and wired networks [9], [1], [20], [13], [23], none of them are directly applicable to the WSN scenario. In [1], packet size adaptation with varying channel conditions is proposed for wireless ATM networks and throughput efficiency is used as the optimization metric. In [20], the authors study optimizing packet size under Rayleigh fading conditions using data throughput as the performance criterion. The effect of variable frame length on user-seen goodput, effective transmission range and transmitter power is studied in [9]. Adaptive packet size optimization in ARQ protocols is presented in [13]. In contrast to these and several other similar efforts, our approach differs in two major aspects

1) *Energy efficiency* is used as the optimization metric
2) The effect of retransmissions, error control parities and encoding/decoding energies on energy efficiency is examined

The effect of start-up transients [19] in energy constrained sensor nodes prompted the choice of energy efficiency as the optimization metric rather than goodput/throughput. As will be seen later, the energy efficiency depends on both channel conditions and energy consumption characteristics of a sensor node.

With the choice of energy efficiency as the performance criterion, error control cannot be treated independently from our optimization problem. Traditionally, forward error correction (FEC) is decoupled from link layer packet size optimization. However, in the case of sensor nodes, error control parities consume valuable transceiver energy which must be taken into account. The encoding/decoding energies also need to be incorporated. Our approach to packet length optimization is unique in this regard. Moreover, we propose the use of fixed size packets in light of the limited resources, energy constraints and management costs in WSN. To the best of our knowledge, this is the first such effort on packet length optimization for WSN.

The remainder of this paper is organized as follows. *Energy consumption characteristics* and *channel conditions* are briefly

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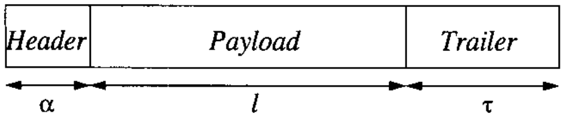

Fig. 1

THE LINK LAYER PACKET FORMAT.

examined in Section II. Both these factors are important in the definition of a suitable optimization metric. The optimal packet size is then determined in Section III by maximizing the energy efficiency metric. Packet size optimization without error control is first considered in Section III-A. It is then shown in Section III-B that the energy efficiency can be further improved with the use of FEC. The performance of binary BCH codes and convolutional codes are compared. The paper is then concluded in Section IV.

II. Choice of Suitable Optimization Metric

It is well known that longer packets experience higher loss rates, while short packets suffer from greater overhead. This has been the main theme behind packet size optimization in other wired and wireless networks. However, the energy consumption of start-up transients can be significant in the context of energy constrained sensor nodes. This must be taken into account while calculating the optimal packet size for data communication in WSN. In the following subsections, we briefly examine the energy consumption characteristics and channel conditions in WSN and define a suitable optimization metric.

A. Energy Consumption Characteristics

The link layer data packet is the smallest communication entity between neighboring sensor nodes in a WSN. It consists of a header field α bits long, payload of size l bits and a τ bit trailer, as shown in Fig. 1. The header field generally includes the current segment number, total number of segments in the corresponding higher layer packet, higher layer packet identifier and the source and destination identifiers. However, for typical WSN applications we may only need an event/location/attribute identifier rather than a node identifier and hence, α is expected to be only a few bytes. The payload contains information bits and the trailer is composed of parity bits for error control.

Based on this packet format and the energy model outlined in [19], we can express the energy required to communicate (transmit and receive) one bit of information (E_b) across a single hop as

$$E_b = E_t + E_r + \frac{E_{dec}}{l} \quad , \tag{1}$$

where E_{dec} represents the decoding energy per packet. The encoding energies are assumed to be negligibly small. This assumption is reasonable for both binary BCH and convolutional codes, which are considered for FEC in Section III-B. E_t and E_r are the transmitter and receiver energy consumptions, respectively and are given by,

$$\begin{aligned} E_t &= \frac{\left((P_{te}+P_o)\frac{(l+\alpha+\tau)}{R}+P_{tst}T_{tst}\right)}{l} \\ E_r &= \frac{\left(P_{re}\frac{(l+\alpha+\tau)}{R}+P_{rst}T_{rst}\right)}{l} \quad , \end{aligned} \tag{2}$$

where

$P_{te/re}$	:	*Power consumed in the transmitter/receiver electronics*
$P_{tst/rst}$	:	*Start-up power consumed in the transmitter/receiver*
$T_{tst/rst}$	:	*Transmitter/receiver start-up time*
P_o	:	*Output transmit power*
R	:	*Data rate (~ 20 Kbps)*

Equation (1) can be simplified in terms of radio parameters k_1 and k_2 as

$$E_b = k_1 + k_1\frac{(\alpha+\tau)}{l} + \frac{k_2 + E_{dec}}{l} \quad , \tag{3}$$

where k_1 and k_2 are given by

$$\begin{aligned} k_1 &= \frac{(P_{te}+P_o)+P_{re}}{R} \\ k_2 &= (P_{tst}T_{tst} + P_{rst}T_{rst}) \end{aligned} \tag{4}$$

Parameters k_1 and k_2 are constants for a given radio transceiver and data rate (R). k_1 can be thought of as the useful energy in the communication of an information bit and k_2 represents the start-up energy consumption[1]. For the RFM-TR1000 transceiver, a typical low-power, short range wireless transceiver that has been incorporated into the $MICA$ motes [11], k_1 and k_2 were calculated to be 1.85 μJ/bit and 24.86 μJ, respectively [17]. Clearly, the contribution of k_2 is significant, and is more so at higher data rates and small payload lengths. This reinforces the fact that energy consumption is important in determining the optimal packet size and prompted a different choice of performance metric from previous packet optimization studies in other wired and wireless networks.

B. Channel conditions

Next, we estimate the raw channel bit error rates (BERs) typically encountered in sensor network applications. We make the reasonable assumption of binary orthogonal non-coherent frequency shift keying (NCFSK) modulated data on a frequency non-selective, Rayleigh fading channel [19], [21]. The probability of bit error (p) in such a case is given by [16], [24]

$$p = \frac{1}{2+\overline{\gamma}} \quad , \tag{5}$$

where $\overline{\gamma}$ is the average received bit energy to noise ratio. Depending on the receiver implementation, $\overline{\gamma}$ further depends on the neighbor distance (d). For the RFM-TR1000 transceiver,

[1]If the radio operates in sleep mode apart from the transmit/receive mode, then $T_{tst/rst}$ is the transition time from the sleep mode to transmit/receive modes

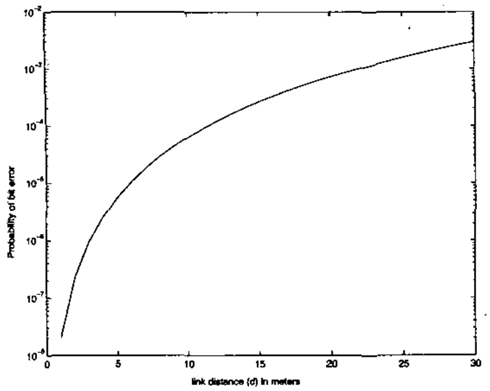

Fig. 2

THE PROBABILITY OF BIT ERROR FOR NCFSK MODULATED DATA UNDER FLAT RAYLEIGH FADING AS A FUNCTION OF NEIGHBOR DISTANCE.

with an average output power of -9 dBm, 7.5 dB receiver noise figure and 6 dB implementation losses, $\overline{\gamma}$ can be calculated (in dB) as [17]

$$\overline{\gamma} = 77 - 10\beta log(d) \quad , \qquad (6)$$

where β is the path loss exponent. A plot of the raw channel BER (p) against neighbor distance (d) for flat, Rayleigh fading with path loss exponent $\beta = 3.5$ is shown in Fig. 2.

For typical neighbor distances of 20-30 meters in WSN [21], it is seen from Fig. 2 that the raw BER ranges between $7*10^{-4}$ and $3*10^{-3}$. In this paper, we evaluate the optimal packet sizes for this range of raw BERs and radio parameters corresponding to the RFM-TR1000 transceiver. However, our approach is generic and can be applied to other sets of parameter values as well.

C. Choice of Optimization Metric

Note from (3) that for given α and τ, and assuming $\frac{E_{dec}}{l}$ to remain fairly constant, the energy per bit (E_b) is inversely proportional to the payload length (l). Hence, by arbitrarily increasing l, we can limit E_b to the constant k_1, but long packet sizes are associated with greater loss rates. On the other hand, shorter packets are more reliable, but are energy inefficient. Hence, we intuitively expect an optimal packet size that balances these conflicting interests.

A suitable metric that captures the energy and reliability constraints is the energy efficiency (η), which is defined as

$$\begin{aligned} \eta &= \eta_e r \\ &= \frac{k_1 l}{k_1(l+\alpha+\tau)+k_2+E_{dec}}(1 - PER) \quad , \end{aligned} \qquad (7)$$

where $(1 - PER) = r$ is the packet acceptance rate, which accounts for data reliability, and $\frac{k_1 l}{k_1(l+\alpha+\tau)+k_2+E_{dec}} = \eta_e$ denotes the energy throughput. Note that this definition of energy efficiency applies to a communication link between neighboring sensors.

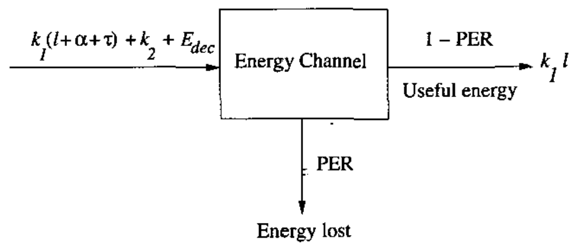

Fig. 3

THE NOTION OF ENERGY CHANNEL, WHICH GIVES RISE TO THE ENERGY EFFICIENCY METRIC.

Our choice of metric is better explained with the notion of the energy channel in Fig. 3. The energy input in the communication of a single data packet is $k_1(l+\alpha+\tau)+k_2+E_{dec}$. Depending on the channel conditions and built-in error correcting capability, we either recover all the l information bits correctly (useful energy) or the entire information is deemed to be corrupted (energy lost). Hence, the energy efficiency (η) represents the useful fraction of the total energy expenditure in a communication link between neighboring sensors.

The optimal packet size for a given set of radio and channel parameters can now be determined by maximizing the energy efficiency metric in (7).

III. Optimal Packet Size

We wish to emphasize here that our proposal is for the use of fixed size packets in WSN. It is well known that varying packet lengths with channel conditions can result in significant throughput enhancements. While graceful scaling/tunability has itself been a popular theme for energy conservation in WSN [12], we believe that the simplicity of such autonomous, resource constrained networks must not be compromised. Additional overhead and resource management costs are the primary reasons why variable packet sizes are not preferable for WSN. In this section, we will therefore determine the optimal fixed packet size based on parameter estimates available at the time of design.

We first determine the optimal packet size when no error control is used ($\tau, E_{dec} = 0$) and then show that significant improvements are possible with the use of FEC.

A. Without Error Control

In this case, a packet is considered to be in error in the presence of one or more bit errors. Assuming independent bit errors, the probability that the packet will be correctly received is given by $(1-p)^{l+\alpha}$, where p is the raw channel BER. This expression also closely approximates the packet reliability under bursty error conditions [23], provided p denotes the burst error rate (bER) rather than the bit error rate (BER).

TABLE I

THE BIT ERROR RATES, BURST ERROR RATES AND AVERAGE BURST SIZES FOR VARIOUS DOPPLER SHIFTS UNDER RAYLEIGH FADING CONDITIONS.

Doppler Shift (Hz)	*BER*	*bER*	*Average Burst Size (bits)*
100	$2.92 * 10^{-3}$	$1.63 * 10^{-3}$	*4.6*
10	$2.40 * 10^{-3}$	$2.38 * 10^{-4}$	*36*
1	$2.38 * 10^{-3}$	$2.00 * 10^{-5}$	*275*

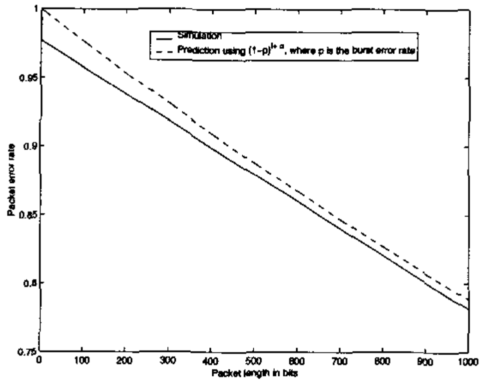

Fig. 4

THE DIFFERENCE BETWEEN THE ACTUAL AND PREDICTED PACKET ERROR RATES UNDER RAYLEIGH FADING CONDITIONS WITH A DOPPLER SHIFT OF 10HZ.

To illustrate this point, we simulated a fading envelope using the Jakes method [24] and then sampled it every bit period (50 μs) to generate a bit error process. Using this, we then calculated the packet reliability for various packet lengths. The results for a Doppler shift of 10Hz are shown in Fig. 4. The burst error rate and average burst size for Doppler shifts of 100,10 and 1 Hz with neighbor distance $d = 30$m are given in Table III-A. Similar trends were observed for other Doppler shifts and neighbor distances.

Equation (7) can hence be rewritten as

$$\eta = \frac{k_1 l}{k_1(l+\alpha)+k_2}(1-p)^{l+\alpha} \tag{8}$$

Our task now is to maximize η with respect to the payload length l. It can be shown that there exists a unique maximum for the optimization function in (8). The corresponding optimal payload size without coding (l^*_{nc}) is obtained by setting $\frac{d}{dl}(\eta) = 0$ in (8). This yields

$$l^*_{nc} = \frac{\sqrt{c_0^2 - \frac{4c_0}{ln(1-p)}} - c_0}{2} \quad , \tag{9}$$

where $c_0 = \alpha + \frac{k_2}{k_1}$. In practice, l^*_{nc} is usually rounded off to the nearest byte.

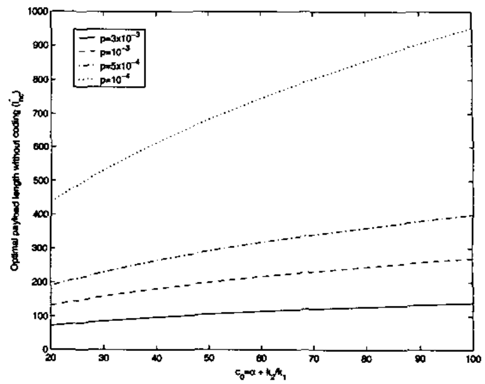

Fig. 5

THE OPTIMAL PAYLOAD SIZE AS A FUNCTION OF c_0 WHEN NO ERROR CONTROL IS USED.

Hence, the optimal packet size is effectively determined by just two parameters: c_0 and p. The variation of l^*_{nc} with c_0 is plotted in Fig. 5 for various values of p. The optimal packet size for a reasonable range of radio parameters k_1 and k_2, and header bits α, can be obtained from Fig. 5 by computing the value of c_0 and estimating the BER/bER p.

Fig. 6 shows the energy efficiency (η) against payload size (l) for $\alpha = 16$ bits for various values of p. As expected, both the maximum attainable energy efficiency (η^*_{nc}) and the optimal payload length (l^*_{nc}) increase with decreasing p. For a given p, it is seen that the energy efficiency shows a steep drop for payload lengths smaller than the optimal length. This behavior can be attributed to the higher overhead and start-up energy consumption of smaller packets. On the other hand, for payload lengths larger than the optimal length, the drop in energy efficiency is much slower and is more so as the channel reliability (r) increases, i.e., p decreases. At $p = 10^{-4}$ the curve almost attains a flat top. Hence, under reliable channel conditions, one can operate at significantly higher packet lengths and still achieve near-optimal energy efficiency, while the margin for error is much smaller under harsh channel conditions. However, in either case, a conservative packet size estimate can be highly energy inefficient and hence, packet size optimization is of utmost importance in WSN design.

B. With Error Control Coding

It is seen from Fig. 5 and Fig. 6 that for given c_0 and p, the energy efficiency without error control is upper bounded. The maximum attainable energy efficiency (η^*_{nc}) is as low as 54.84% for $p = 3*10^{-3}$. Naturally, we now pose the question "Can the energy efficiency of the communication link between neighboring sensors be improved further?". Recall from (7) that η is the product of two terms, the energy throughput (η_e) and reliability (r). η_e can be increased by increasing the payload length (l) beyond l^*_{nc}, but this brings down η, as is obvious from Fig. 6. This is due to the drastic reduction in

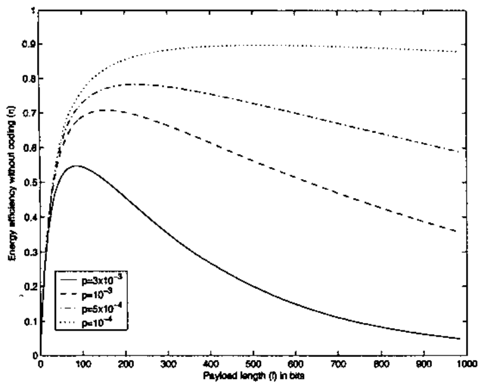

Fig. 6

THE PLOT OF ENERGY EFFICIENCY (η) AGAINST THE PAYLOAD SIZE (l) FOR $\alpha = 16$ BITS WHEN NO ERROR CONTROL IS USED.

reliability (r), which negates any further increase in η_e.

The other option is to use some form of error control to increase the reliability (r). Error control can be achieved primarily by two means: retransmissions and forward error correction (FEC). Let us first consider a cyclic redundancy check (CRC)-selective repeat request scheme. Assuming that the CRC can detect every possible errored packet and neglecting the messaging overhead, the energy efficiency using selective repeat request (η_{SRR}) can be bounded by

$$\eta_{SRR} \leq \frac{k_1 l}{k_1(l+\alpha)+k_2}(1-p)^{l+\alpha} = \eta \qquad (10)$$

Hence, retransmission schemes cannot improve the energy efficiency and we turn our attention to FEC strategies.

With the use of FEC, τ and E_{dec} in (7) are non-zero and the energy throughput (η_e) decreases due to these factors. However, depending on the values of τ and E_{dec}, the exponential increase in reliability can lead to a net increase in the energy efficiency.

This can also be seen from a different perspective. For a given reliability, the effect of coding is to allow greater payload lengths (l). This can increase the energy throughput (η_e) provided τ and E_{dec} are not too large. Hence, we conclude that *coding can improve the energy efficiency of a communication link between neighboring sensors in a WSN.* Already, it is clear that not all coding strategies are capable of achieving this. In the following discussion, we study and compare the energy efficiencies of binary BCH codes and convolutional codes, two classes of FEC codes that have efficient decoding algorithms.

We first consider binary BCH codes with hard decision, bounded distance decoding. The encoder at the data originator adds τ parity bits to the l payload and α header bits. In the (n,k) representation, $n = l+\alpha+\tau$ is the packet length and $k = l+\alpha$ is the message length. Decoding failures are detectable, but they are as bad as packet errors since no retransmission schemes are in use. Hence, the reliability (r) with coding can be given as,

$$r = 1 - PER = \sum_{j=0}^{t}\binom{n}{j}p^j(1-p)^{n-j} \quad , \qquad (11)$$

where t is the error correcting capability of FEC code. Note that (11) is valid only under the assumption of independent bit errors or when suitable interleaving strategies are employed in bursty error conditions. The energy efficiency (η) in (7) can now be written as

$$\eta = \frac{k_1(n-\alpha-\tau)}{k_1 n + k_2 + E_{dec}}\sum_{j=0}^{t}\binom{n}{j}p^j(1-p)^{n-j} \quad , \qquad (12)$$

where the change of variable from l to n is made for convenience.

An efficient decoding technique for binary BCH codes is based on the *Berlekamp-Massey* (BM) and *Chien's search* (CS) algorithm [25], [10]. This effectively shows only a linear dependence on block length n. Energy consumption models for these algorithms have been outlined in [4], [10]. Based on this, E_{dec} for a t error correcting binary BCH code of length n can be given as

$$E_{dec} = (2nt + 2t^2)(E_{add} + E_{mult}) \quad , \qquad (13)$$

where E_{add} and E_{mult} denote the energy consumptions in the addition and multiplication, respectively, of field elements in GF(2^m), $m = \lfloor log_2 n + 1 \rfloor$. They have been computed in [4] for $0.18\mu m$, $2.5V$ CMOS based implementation to be

$$\begin{aligned} E_{add} &= 3.3\times10^{-5}m \quad (mW/MHz) \\ E_{mult} &= 3.7\times10^{-5}m^3 \quad (mW/MHz) \end{aligned} \qquad (14)$$

For a BCH code, t is further related to the number of parities (τ) by the bound [10]

$$\tau \leq mt \qquad (15)$$

Hence, $\tau = mt$ is an indicator of the worst performing BCH code in terms of energy efficiency. We refer to this as the BCH lower bound.

We now investigate any possible improvements in the energy efficiency with the use of binary BCH codes, as compared to Section III-A where no error control was used. The energy efficiency (η) in (12) is now a function of two variables, the packet length (n) and the error correcting capability (t). It can be shown that for every t, there exists a unique maximum for energy efficiency ($\eta^*(t)$), with a corresponding optimal packet size ($n^*(t)$). However, unlike in Section III-A, there exists no closed form solution in this case.

Fig. 7 shows the energy efficiency (η) for various values of packet size (n) and error correcting capability (t) for raw BER $p = 10^{-3}$, $\alpha = 16$ bits. The energy efficiency without FEC ($t = 0$) is also shown. The maximum attainable energy efficiency ($\eta^*(t)$) and optimal packet length ($n^*(t)$) values are tabulated in Table II for $t = 0, 2, 4, 6$.

We now make the following observations from Fig. 7 and Table II.

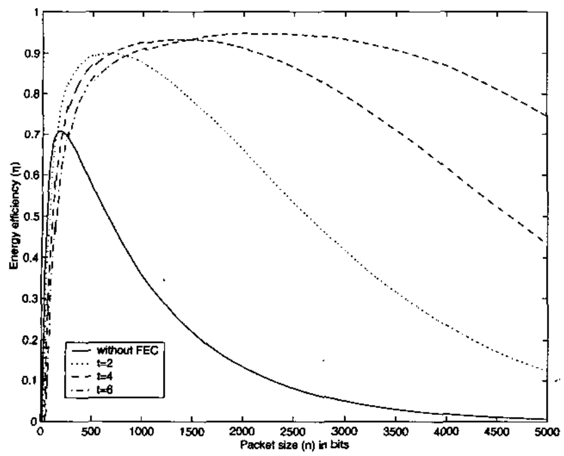

Fig. 7

THE ENERGY EFFICIENCY (η) AS A FUNCTION OF PACKET SIZE (n) FOR THE BCH LOWER BOUND WITH $t = 0, 2, 4, 6$, $p = 10^{-3}$ AND $\alpha = 16$ BITS.

TABLE II

THE MAXIMUM ATTAINABLE ENERGY EFFICIENCY AND OPTIMAL PACKET LENGTH FOR THE BCH LOWER BOUND WITH $t = 0, 2, 4, 6$.

t	$\eta^*(t)$	$n^*(t)$(bits)
0	0.7083	173
2	0.8994	663
4	0.9344	1391
6	0.9485	2047

1) Significant improvements in energy efficiency are possible with the use of binary BCH codes. A four error correcting binary BCH code improves the energy efficiency by as much as 23%.
2) The maximum attainable energy efficiency ($\eta^*(t)$) increases with t and the corresponding optimal packet size $n^*(t)$ grows as well. The maximum allowable packet length may be limited by application specific entities such as packetization delay and data latency.
3) As t increases from zero, we obtain diminishing returns in $\eta^*(t)$. This can be attributed to both the assumption of independent bit errors and the increase in decoding energy, with the former being more dominant.
4) All the above results are valid only under the assumption of independent bit errors. Under bursty error conditions with no interleaving, the gains from using FEC codes depends to a great extent on the bER and burst size.

Having investigated the energy efficiency of binary BCH codes, it is insightful to compare their performance to that of convolutional codes, which have thus far been considered for error correction in WSN [19]. Equation (7) can be re-written in terms of the code rate R_c as

$$\eta = \frac{k_1(nR_c - \alpha)}{k_1 n + k_2 + E_{dec}}(1 - PER) \tag{16}$$

Clearly, the maximum energy efficiency of a convolutional code is limited by its code rate R_c. It is well known that high rate convolutional codes are better implemented by puncturing low rate codes and decoding using the base code trellis [25], [15]. Viterbi decoding energies using $0.18\mu m$ TSMC ASIC technology have been measured for various constraint lengths for a base rate 1/2 convolutional code in [19]. Using their results for E_{dec} in (16), we plot in Fig. 8, the energy efficiency (η) against code rate (R_c = 1/2,2/3,3/4,5/6,8/9,10/11) for constraint lengths $K = 3$ through 9 with raw BER $p = 10^{-3}$. All simulations were carried out in MATLAB with a packet length of $n = 1000$ and hard decision decoding with a trace-back length of $5K$. The BCH lower bound for $t = 2, 4$ and the maximum attainable energy efficiency without FEC (η^*_{nc}) are also shown alongside. We do not consider soft decision decoding and software implementations as they are energy intensive.

From Fig. 8, we see that both low and high rate convolutional codes perform poorly. Low rate convolutional codes are highly reliable, but their energy efficiency is limited by low values of R_c. On the other hand, the poor reliability of high rate convolutional codes lowers their energy efficiency. In general, medium rate convolutional codes are the most energy efficient and their performance improves with increasing constraint length[2] (K). Also note from Fig. 8 that several coding strategies are energy inefficient, i.e, they decrease the energy efficiency from that without FEC (η^*_{nc}). Convolutional codes with code rates $R_c < \eta^*_{nc}$, all fall into this category.

Next, we compare the maximum attainable energy efficiency of convolutional codes to that of the BCH lower bound determined earlier. To this end, we need to assess the behavior of energy efficiency with varying packet length for convolutional codes. We only consider those coding strategies that can improve the energy efficiency above η^*_{nc}. From (16), the necessary conditions for $\eta > \eta^*_{nc}$ can be obtained as

$$\begin{aligned} R_c &> \eta^*_{nc} \\ n &> \frac{\frac{k_2}{k_1}\eta^*_{nc} + \alpha}{R_c - \eta^*_{nc}} \end{aligned} \tag{17}$$

Hence, we only consider code rates R_c=3/4,5/6,8/9,10/11 with constraint length $K = 9$ and examine their energy efficiencies for various packet lengths. Our results are shown in Fig. 9. The BCH lower bound for $t = 2, 4$ and the energy efficiency without FEC are also shown alongside.

It is seen that the BCH lower bound for $t = 4$ outperforms the most energy efficient convolutional code by almost 15%. This can be attributed to the significantly lesser number of parity bits required for the binary BCH code. It can be verified that for both the BM & CS algorithm and Viterbi decoding,

[2]We do not consider higher K due to the exponential increase in the implementation complexity of the Viterbi algorithm.

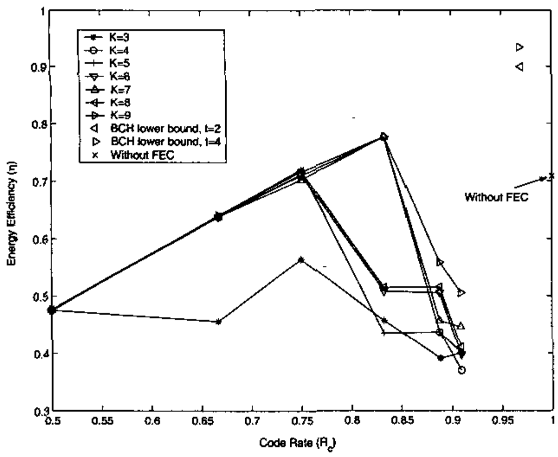

Fig. 8

THE PLOT OF ENERGY EFFICIENCY (η) AGAINST CODE RATE (R_c) FOR CONVOLUTIONAL CODES OF CONSTRAINT LENGTHS K=3 THROUGH 9. THE PERFORMANCE OF THE BCH LOWER BOUND FOR $t = 2, 4$ AND THE MAXIMUM ENERGY EFFICIENCY WITHOUT FEC ARE ALSO SHOWN.

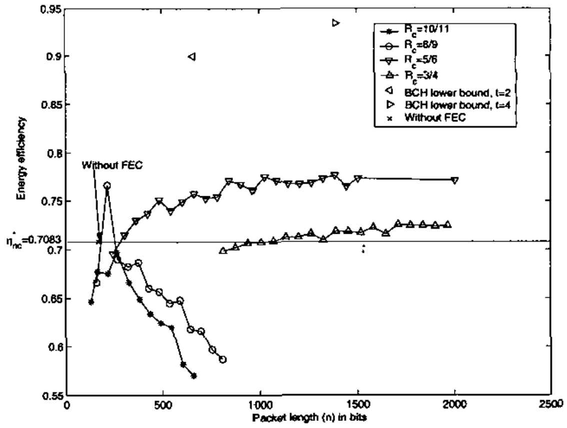

Fig. 9

THE ENERGY EFFICIENCY (η) OF RATE 3/4,5/6,8/9 AND 10/11 CONVOLUTIONAL CODES AS A FUNCTION OF THE PACKET LENGTH (n) FOR CONSTRAINT LENGTHS K=9. THE BCH LOWER BOUND FOR $t = 2, 4$ AND THE MAXIMUM ENERGY EFFICIENCY WITHOUT FEC (η^*_{nc}) ARE ALSO SHOWN FOR COMPARISON.

the decoding energy (E_{dec}) values are much lower than k_2 in (12) and (16), when implemented using CMOS and ASIC technologies, respectively. Under these conditions, the effect of decoding energies on the energy efficiency is negligible and the number of FEC parities is the determining factor. Convolutional codes with lesser number of parity bits (high R_c) are highly erroneous and this limits their energy efficiency.

Among the various convolutional codes, we once again observe that medium rate codes are the most energy efficient. The rate 5/6 code performs better than the higher rate 3/4 code and the lower rate 8/9,10/11 codes. The lower rate codes are unable to sufficiently recover from packet errors and hence, their performance goes down with increasing packet lengths. On the other hand, the rate 3/4 code shows good reliability, but its energy efficiency is limited by the relatively large number of parity bits.

IV. CONCLUSION

Existing packet size optimization techniques are not applicable in the case of energy constrained WSN. Rather than use goodput/throughput, *energy efficiency* was chosen as the optimization metric to incorporate the start-up energy consumptions in sensor nodes. The use of fixed size packets was proposed to ease management costs and reduce overhead.

The optimal fixed packet size was then determined for a given set of radio and channel parameters by maximizing the energy efficiency metric. The radio and channel parameters (k_1, k_2, BER/bER) must be estimated at the time of design. The importance of packet size optimization was further emphasized by the steep drop in energy efficiency for conservative packet size estimates, as seen in Fig. 6.

With the choice of energy efficiency as our optimization metric, the effect of error control cannot be ignored. It was shown that while some FEC coding schemes can improve the energy efficiency of a communication link, several others, including retransmissions, are energy inefficient. In particular, binary BCH codes with BM & CS decoding and convolutional codes with Viterbi decoding were considered with CMOS/ASIC implementations. It was found that the binary BCH code outperformed the best convolutional code by almost 15%, highlighting the fact that the number of FEC parities significantly impacts energy efficiency, more so than the decoding energy consumptions. Among convolutional codes, medium rate codes performed best.

The above results with regard to FEC are valid only under the assumption of independent bit errors. Future work includes investigating the energy efficiency of RS and burst error correcting codes.

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