An Energy Efficient Decoding Scheme for Wireless Body Area Sensor Networks

O. Rehman, N. Javaid, A. Haider, N. Amjad, A. A. Awan, M. Qamar, Z. A. Khan*, U. Qasim#

COMSATS Institute of Information Technology, Islamabad, Pakistan.
*Internetworking Program, Faculty of Engineering, Dalhousie University, Halifax, Canada.
#University of Alberta, Alberta, Canada.

ABSTRACT

One of the major challenges in Wireless Body Area Networks (WBANs) is to prolong the lifetime of network. Traditional research work focuses on minimizing transmit power; however, in the case of short range communication the consumption power in decoding is significantly larger than transmit power. This paper investigates the minimization of total power consumption by reducing the decoding power consumption. For achieving a desired Bit Error Rate (BER), we introduce some fundamental results on the basis of iterative message-passing algorithms for Low Density Parity Check Code (LDPC). To reduce energy dissipation in decoder, LDPC based coded communications between sensors are considered. Moreover, we evaluate the performance of LDPC at different code rates and introduce Adaptive Iterative Decoding (AID) by exploiting threshold on the number of iterations for a certain BER ($10^{-4}$). In iterative LDPC decoding, the total energy consumption of network is reduced by 20 – 25%.

KEYWORDS: Error correction, Low Density Parity Check, Iterative decoding, Block codes, Convolutional codes, Adaptive Iterative Decoding

I. INTRODUCTION

A WBAN is a special case of Wireless Sensor Networks (WSNs) that enables remote monitoring of various sensors in several environments. One of the most studied application of WBANs is health care monitoring, where few or large number of patients can be observed, diagnosed, and prescribed remotely. Smart sensor nodes can be connected to various parts of the body or fabricated inside the clothes to transmit the information to a base station. Thus WBANs emerged as a promising alternative for traditional wired network systems. Recent advances in wireless communications, signal processing and digital electronics enabled the development of tiny wireless sensors with small batteries and the capability to sense, process and communicate with each other. In WBANs, area occupation and energy consumption are important aspects.

The issue of energy consumption is very critical and needs to be minimized at the design levels like modulation/demodulation, Media Access Control (MAC) protocols, routing protocols and error correction coding. Reliable communication primarily depends on the applications and user specified constraints such that, receiver should embed the error correction strategies to recover original data. In a particular error correction code, the amount of energy spent to perform channel coding should be significantly less than the energy saved by transmitter.

Fig. 1 shows a Wireless Body Area Network (WBAN). To tackle erroneous transmission in WBAN, Automatic Repeat Request (ARQ) strategy is usually implemented by using ARQ protocol. In this protocol sensor nodes implement error detection code for identifying corrupted frames and then requests for a retransmission. However, this technique is inefficient when we deal with energy and delay. For a lossy channel Error Correcting Codes (ECC) are commonly used to reduce the number of retransmissions. Incase of packet encoding and decoding, ECC requires more processing power at
sensor nodes. To recover errors before a transmission request is sent, HARQ protocol is used.

For ECC error correction, it is directly related with complexity. Powerful codes increase the processing energy consumption at the receiver. So, there is a trade-off between transmission and processing energy consumption at decoder. FEC uses simple error correction techniques like Reed-solomon, Bose and Ray Chaudhuri (BCH) and conventional codes and their ability to correct errors is obtained by introducing high redundancy in transmitted data. Coding and decoding process introduces delay in delivering packets to the base station. For bad quality of communication channels, LDPC codes are used to achieve low BER with low redundancy.

ECC introduces redundancy into an information sequence $U$ of length $k$ by adding extra parity bits, based on various combinations of bits of $u$, to form a codeword $x$ of length $n_c > k$. The redundancy provided by these extra $n_c - k$ parity bits allows the decoder to possibly decode noisy received bits of $x$ correctly which if uncoded, would be demodulated incorrectly. Compared to an uncoded system, ECC over noisy channel provides better BER performance for the same Signal to Noise Ratio (SNR). In comparison to an uncoded system, to achieve a certain BER at required SNR for coding and decoding algorithms is known as the coding gain for that code and decoding algorithm. Typically there is trade-off between coding gain and decoder complexity. Very long codes provide higher gain. However, require larger decoders with high power consumption, and similarly for more complex decoding algorithms. ECC are mainly categorized into two types:

1. Block Codes have fixed length $n_c$ that include $n_c - k$ parity bits. These codes are decoded one codeword at a time. (2) Conventional codes have a code rate $\frac{k}{n_c}$, where $k$ are number of input bits and $n_c$ are number of output bits that are decoded in a continuous stream of length $L \gg n_c$. Block codes include Hamming codes, repetition codes, Reed-Solomon (RS) codes. The terminology $(n_c, k, d_{\text{min}})$ represents a code of length $n_c$ with input bits of length $k$ and minimum distance $d_{\text{min}}$. 

![Wireless Body Area Sensor Network](image)
ECC are also categorized in terms of decoding algorithms:

1. Non iterative decoders are divided into two types. (a) Hard decision decoder is a threshold detector stage of a decoder where decision is based on binary signaling that includes 1 or 0. (b) In soft decision decoders more than one voltage levels are considered for a single bit. These Soft information are calculated in the form of Log Likelihood ratios (LLRs).

2. For each iteration, iterative decoders require soft information as an input. These algorithms provide higher coding gain. However, they require complex decoder and consume significant power. LDPC codes are applicable in WSNs because of Joint source coding and channel coding. Basic communcation model has been depicted in Fig. 2.

The rest of the paper is organized as follows: In section 2, we briefly discuss related work. Section 3 focuses on our motivation for research work. In Section 4, we discuss LDPC Codes. Section 5 presents AID scheme for LDPC. Simulation results are shown in Section 6 and Section 7 concludes our research work.

II. BACKGROUND AND MOTIVATION

This work is an extension of [2]. Recent research in WSNs mostly deals with the aim to maximize energy efficiency ([3]). In this regard, some authors worked at routing layer ([4], [5], [6]) while others ([7], [8], [9]) explored MAC layer. However, our directions are more focused on different decoding schemes to achieve maximum energy efficiency. In [10], P. Grover et al. investigate the perspective of interference on decoding power. They suggest that in short range communication the transmit power is smaller than decoding power and uncoded transmission requires more transmit power than coded transmission. Andrea et al. designed LDPC decoder architecture for WSN. Different LDPC codes are considered to analyze the energy saving w.r.t un-coded communication, depending on distance, BER and Environment [11]. S.L.Howard et al. calculate critical distance dc at which the decoder’s energy consumption per bit is equal to transmit energy per bit. In comparison to an un-coded system, authors provide results for dc in different environments over a wide frequency range [12]. Marcelo et al. investigate the tradeoff between transmission and processing energy consumption in sensor nodes by employing convolutional codes. For each sensor node, authors select appropriate complexity for ECC to prolong network lifetime [13]. Z. Hajarian et al. define the relationship between the number of quantization bits and decoder’s energy consumption using LDPC in WSN. Decoder’s complexity is reduced by replacement of functional blocks with look up tables. They suggest that LDPC codes are more energy efficient than conventional and block codes. Using iterative decoding, the network lifetime is increased up to four times with regular LDPC codes [14]. In [15], authors propose a packet error reduction technique for reliable communication in WBAN. Firstly, they calculate Received Signal Strength (RSS) around the human body. Secondly, based on these calculations of RSS, they calculate Packet Error Rate (PER). LT codes are considered for
WBAN to reduce the PER. In [16], authors use rateless codes to provide an adaptive duty cycling for power management. Analytical results show that with same structure used for WSNs, up to 80 percent of energy is saved as compared to IEEE 802.15.4 physical layer standard. Z. H. Cai et al. propose an efficient early stopping method to reduce number of iterations for LDPC decoders. This method is very efficient at low SNR [17]. Energy efficiency plays a vital role in enhancing the lifetime of a network. As in [18] – [40], many efforts have been made to improve the energy efficiency and, hence, the improving the lifetime of network.

WBAN consists of small sensors with limited battery power. In this paper, our objective is to increase the network lifetime or to minimize the energy consumption of network. Reliability is another primary requirement for communication. The level of reliable communication depends on applications and user specific constraints. Error correction schemes provide reliable communication between transmitter and receiver by reducing $P_b$. In practical situations, such as WBAN there are two ways to reduce $P_b$.

1. Increasing the transmit power improves the SNR:

   For Additive White Gaussian Noise (AWGN) channel, $p(b)$ for BPSK modulation is expressed as:
   
   $p_b = Q \sqrt{\frac{2E_b}{N_0}} \quad (1)$
   
   where $Q$ is a scaled form of the complementary Gaussian error function.

2. Use complex decoder by increasing the decoding power:

   In the case of WBAN an increase in transmit power is not sufficient because increase in transmit power damages the human tissues. Another problem is the existence of small distance between transmitter and receiver. The transmit power increases the Signal to Interference and Noise Ratio (SINR). In this case how we can improve SINR? This is done by increasing the distance between transmitters. However, in WBAN it is not possible because of limited area. In any communication system a tradeoff between transmit power and decoding power exists. WBAN requires low transmitting power so, there is need to implement energy efficient decoder to reduce the decoding power consumption to enhance the network lifetime. We use LDPC, because its performance for low BER communication is same as complex decoders such as viterbi decoding algorithms.

III. LDPC CODES

LDPC codes are a class of linear block codes, their parity check matrix contains only a few number of 1s in comparison of 0s. The main advantage of this code provides decoding performance very close to the capacity and linear time complex algorithms for different AWGN and fading channels. Like all linear block codes, LDPC codes can be represented in two different possibilities. They can be described via graphical representation and matrices. LDPC codes are represented as as Tanner Graph that contain two set of nodes: Check Nodes (CNs) and Variable Nodes (VNs). VNs are associated with N bits of codeword and CNs corresponds to M parity-check constraints. Edges in Tanner graph correspond to 1's in H and exchange of information along these edges as shown in Fig. 3.
Belief Propagation (BP) algorithm is commonly used to decode LDPC codes. VNs receive LLR from the channel and update it according to parity check matrix computed at CNs. This process is iterated until iterations reach a maximum level. This criteria helps in successful decoding of a codeword. BP algorithm has two main scheduling schemes: two phase scheduling and layered scheduling. In layered scheduling, parity check constraints are grouped in the form of layers. Each layer is associated with a component code. One iteration is complete when all layers are successfully decoded. To achieve a reliable pattern of information, the whole process is iteratively repeated up to several times.

Let $S_j$ represents the LLR of the bit in column $j$ of $H$. LLR is initialized to the corresponding received soft value. For each parity constraint $m$ in a given layer, the following operations are executed [5]:

$$H = \begin{bmatrix} 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix}$$

$$Q_{mj} = S_j^{(old)} - R_{mj}^{(old)} \quad (2)$$

$$A_{mj} = \sum_{\eta \in N_m, \eta \neq j} \psi(Q_{mn}) \quad (3)$$

$$s_{mj} = \sum_{\eta \in N_m, \eta \neq j} sgn(Q_{mn}) \quad (4)$$

$$R_{mj}^{(new)} = -s_{mj} \cdot \psi(A_{mj}) \quad (5)$$

$$S_j^{(new)} = Q_{mj} + R_{mj}^{(new)} \quad (6)$$

$S_j^{(old)}$ is the extrinsic information received from previous layer and updated in equation (5). This information is propagated to succeeding layer. $R_{mj}^{(old)}$ is used to compute equation (1) then updated in equation (4). Term, $R_{mj}^{(new)}$ is used again in following iteration. $N_m$ in equations (2) and (3) represents set of all bits connected to parity constraint $m$. Whole operation of LDPC decoder is given in Fig. 4.
IV. SENSOR NODES ENERGY MODEL

For encoded data of transmission, the energy consumption per bit of a node is the sum of radio energy per bit $E_r$ and computation energy per bit $E_{comp}$. Radio energy is sum of SLEEP, TRANSIENT, and ON mode energies. The transceiver is off all the times and keeping it ON only when data is transmitting or receiving.

The radio energy per bit for transmitting $N$ bits is calculated as in [12]:

$$E_r = \frac{p_{sleep} T_{on} + p_{trans} T_{trans} + p_{on} T_{on}}{N}$$  \hspace{1cm} (7)

Power consumed in radio during ON-mode is the sum of transmitting power $p_t$ and power consumption in circuitry $p_{ckt}$. The radio energy consumption is:

$$E_r = \frac{(p_t + p_{ckt}) T_{on}}{N}$$  \hspace{1cm} (8)

Transmission power in free space is expressed by using Friis equation:

$$p_t = \frac{P_r}{G_t G_r} \times \frac{4\pi}{\lambda} n^2 d^n$$  \hspace{1cm} (9)

The received power is calculated as:
\[ p_r = SNR_{uncod} \frac{bN_0}{2} NF \]  \hspace{1cm} (10)

Where, \( SNR_{uncod} \) is SNR for transmitting uncoded data, \( b \) is the number of bits per modulation symbol, \( B \) is bandwidth, \( \frac{N_0}{2} \) is noise spectral density and \( NF \) is Noise Figure.

For coded data received power is:

\[ p_r = SNR_{coded} bB \frac{N_0}{2} NF \]  \hspace{1cm} (11)

Transmission energy for coded data frame is expressed as:

\[ E_{trans}^{frame} = E_{dec}^{bit} f_{size}^C \]  \hspace{1cm} (12)

The required processing energy to decode a bit is \( E_{dec}^{bit} \). Therefore, the energy required to decode a frame \( E_{dec}^{frame} \) is computed as:

\[ E_{dec}^{frame} = E_{dec}^{bit} f_{size}^C \frac{r}{J/F} \]  \hspace{1cm} (13)

where \( r \) is the coding rate.

There is tradeoff between transmitting power and decoding power. To reduce the total power consumption, transmitting power must strictly be larger than Shannon limit. In [9] the Shannon capacity limit for both coded and uncoded systems is shown in Fig. 5.

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**Fig. 5**: Shannon Capacity estimation for coded and uncoded system
V. AID

In this paper, we propose an efficient early stopping method to reduce the number of iterations for LDPC decoders. This method is efficient at low SNR.

AID predicts the threshold at number of iterations for undecodable blocks. Another advantage is reduction in processing delay. LDPC codes yield excellent performance when they are decoded with iterative message passing algorithms. The performance of an iteratively decoded LDPC code is typically reported in terms of $p_e$ for a specific SNR value. For high SNR values, the value $p_e$ is small that requires a large number of iterations in order to obtain reliable estimate. In AID, we introduce a threshold on the number of iterations after achieving a certain BER ($10^{-4}$). The whole process of AID is shown in Fig. 6.

We assume that each PE consumes a fixed $E_{node}$ joules of energy per iteration. We assume that the $R_{dec}$ is equal to data rate $R_{data}$ measured in information bits per second. The power received at distance $x$ meter is given in Eq [9]. In Eq [13] the $E_{dec}$ is the energy consumed in decoder operation. For any rate $R_{data}$ the average probability of error ($p_e$) $\to 0$. Let the number of decoding iterations be denoted by $l$, the number of computational nodes can be lower bounded by $m$, the
number of received channel outputs. Since each node consumes $E_{node}$ joules of energy in each iteration, the decoding energy $E_{dec}$ is lower bounded in [2] as: $E_{dec} \geq E_{node} \times m \times l$. We assume channel encoding is free. This result is the following lower bounds on the weighted total power is $E_{tot} \geq P_T + \frac{E_{node} \times m \times l}{T_{dec}}$, and $E_{tot} = P_L P_R + \frac{E_{node} \times m \times l}{T_{dec}}$. Where $T_{dec} = \frac{k}{R_{dec}}$ is the time consumed in decoding. Thus, $p_{total} \geq P_L P_R + \frac{E_{node} \times m \times l \times R_{dec}}{k}$ and $p_{total} = P_L P_R + \frac{E_{node} \times l \times R_{dec}}{R_c}$, where, $P_L$ is power loss and $P_R$ is received power.

VI. RESULTS AND DISCUSSIONS
LDPC code with Code Rate ($R_c$) has been used in simulation over AWGN channel with an iterative probabilistic decoding algorithm. The bandwidth is large (3GHZ) and the throughput is 1.5 Gbps. The power of a PE is 10 pico-Joules. For indoor environment, path-loss exponent are assumed to be 3 and noise figure is 3dB. The transmitter power is in few milli Watts for 3m distance between sensor and base station. If the transmit power $P_T$ is extremely close to that required for channel capacity then large number of iterations $l$ are required. Large number of iterations consume high decoding power. Encoder should have larger power as compared to its Shannon limit in order to minimize decoding power consumption.

Simulations parameters are shown in Fig. 10.
Fig. 7, shows the relationship between the SNR and BER, as we increase the SNR, BER decreases. By imposing five iterations ($l = 5$), it is observed that targeting a specific BER of $10^{-4}$ the required SNR is 3.5 at $R_c$ 0.75 and SNR 2.5 at $R_c$ 0.5. Fig. 8, shows the relationship between number of iterations and BER. For a fixed SNR (1.5dB) our target is to achieve a BER of $10^{-4}$ and calculate the number of iterations till desired BER of $10^{-4}$ is achieved. Results show that at $R_c$, 0.75 the required iterations are 16 and at $R_c$ 0.5, 12 iterations are required.

Fig. 9, shows the relationship among the total number of iterations and total power consumption by using LDPC decoder and AID. For the case of LDPC code, we use 50 iterations at a code rate of 0.75. There is no threshold for achieving a certain value of $P_e$. As $P_e \to 0$ the total power consumption $p_T \to \infty$. Simulation results show that $p_T$ increases by increasing the number of iterations. For 50 iterations $p_T$ is 1.3 joule. In AID, our requirement is to achieve a BER of $10^{-4}$, it is achieved at 16th iteration. Hence, we save the energy consumption of 35 iterations and also minimize the processing delay of decoder. This scheme is equally performed well for such applications in which we cannot afford delay. Simulation results show that the total energy consumption of error correction code is exactly 1.05 joule. With the code rate of 0.5, energy consumed is 0.5 joule in total. We save 22% of total energy as compared to LDPC codes. Hence, AID defines threshold on the number of iterations for a desired BER. Benefit of this

| Parameter          | Value       |
|--------------------|-------------|
| $P_{Tr}$           | 144mW       |
| $w$                | 1           |
| pathloss Exponent  | 1           |
| $d$                | 3m          |
| Boltzmann Constant | $1.38065 \times 10^{-23}$ |
| temperature        | 300         |
| $R_{data}$         | 1.5Gbps     |
| $R_{dec}$          | 1.5Gbps     |
| $E_{node}$         | 10^{-12}    |
| degree             | 2           |
| $R_c$              | 0.5         |
| LDPC               | 7.4         |
| frequency          | 60 GHz      |

Fig. 10: Simulation Parameters
decoding scheme is that it reduces the processing time of decoder and decoding energy consumption in WBAN.

VII. CONCLUSION

In this paper, we proposed AID Scheme to reduce the decoding power consumption and to prolong the lifetime of WBANs. To achieve BER to \((10^{-4})\), we calculate the total number of iterations required for LDPC decoder. As \(p_b\) approaches 0, iterations approach infinity and iterations stop after achieving a desired BER. We reduce decoding energy consumption by stopping the iterations after achieving a certain BER. By using this scheme, 20 – 25% of total energy consumption is reduced.

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