Error Correction Codes in Wireless Sensor Network: An Energy Aware approach

Mohammad Rakibul Islam

Abstract—Link reliability and transmitted power are two important design constraints in wireless network design. Error control coding (ECC) is a classic approach used to increase link reliability and to lower the required transmitted power. It provides coding gain, resulting in transmitter energy savings at the cost of added decoder power consumption. But the choice of ECC is very critical in the case of wireless sensor network (WSN). Since the WSNs are energy constraint in nature, both the BER and power consumption has to be taken into count. This paper develops a step by step approach in finding suitable error control codes for WSNs. Several simulations are taken considering different error control codes and the result shows that the RS(31,21) fits both in BER and power consumption criteria.

Keywords—Error correcting code, RS, BCH, wireless sensor networks

I. INTRODUCTION

The recent development in micro-electro-mechanical systems technology, signal processing, wireless communications and digital electronics have enabled the development of wireless sensor nodes in a wireless sensor network (WSN). These tiny sensor nodes are able to sense, process and communicate with each other [1],[2]. Since the battery capacity in each node is limited and the goal is to maximise the lifetime of the network, there are strict energy consumption constraints in WSNs [8]. Of the three domains (sensing, communicating and processing), a sensor node expends a considerable amount of energy in data communication. Reliability is the primary requirement of any communication. The level of reliability provided by the link layer depends on the requirements of application and the users specified constraints.

A sensor node device usually employs some optimization strategy to reduce energy consumption, like switching the transceiver unity to the sleeping mode, significantly reducing the consumption with respect to the active mode. As the radio transceiver is the most demanding energy module, a classical strategy is to minimize his active period of time, which obviously depends on transmission and reception traffic demands. A first strategy is to activate the transmitter only when there are data to be transmitted, but keeping the receiver awake for capturing data packets addressed to the node. Such solution certainly is not efficient for energy preservation, because the receiver is active even if there is no data to be received. A way to circumvent this problem is to keep also the receiver in the sleeping mode, activating it only for short periods of time to verify the channel activity and receive data, turning back to the sleeping mode if no signal is detected [3]

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Another approach to reduce consumption is to improve the network routing algorithms, distributing the load for forwarding the information to the destination node. It is also possible to apply local data aggregation (cluster). In this scenario the data forwarding to the destination occurs in multiple hops through concentration nodes (cluster heads). The cluster head nodes consume more energy, since they have a higher active period and transmission power. Using periodic or random intervals, the cluster head function is switched to other nodes, aiming at better distributing the energy consumption in the network [4].

However, the aforementioned solutions are susceptible to channel impairments, because any radio signal is affected by random noise and channel fading [5], [6]. If a node receives a corrupted data packet, the data can be discarded and the node keeps waiting for a new transmission or the node employs an Automatic Repeat reQuest (ARQ) procedure (a retransmission procedure). However, in both cases there is a waste of energy in the network. A particularly undesirable situation occurs when the channel condition is bad, causing successive retransmissions. Another method to increase the energy conservation in WSN is to apply forward error correction (FEC) strategies, reducing the frame error rate and consequently the number of retransmissions. Basically there are two classes of error control codes: block codes and convolutional codes. The convolutional encoding technique is a strategy widely used in wireless communication environments like sensor networks, since they usually present a simpler implementation for the same performance of a competitor block code [7].

The issue of applying error control codes to WSNs is the topic for some of the previous works where the performance of block codes and Viterbi decoded convolutional codes is investigated [9]-[11]. Also, the iterative decoding algorithm justifies the ability of turbo codes in solving the hot-spot problem and prolong the network lifetime [12]. Error control coding (ECC) is a classic approach used to increase link reliability and lower the required transmitted power. However, lowered power at the transmitter comes at the cost of extra power consumption due to the decoder at the receiver. Stronger codes provide better performance with lower power requirements, but have more complex decoders with higher power consumption than simpler error control codes. If the extra power consumption at the decoder outweighs the transmitted power savings due to using ECC, then ECC would not be energy-efficient compared with an uncoded system.

Previous research using ECC in wireless sensor networks focused primarily on longtime industry-standard codes such as Reed-Solomon and convolutional codes. A hybrid scheme choosing the most energy-efficient combination of ECC and

ARQ is considered in [13], using checksums, CRCs, Reed-Solomon and convolutional codes. A predictive error correction algorithm is presented in [14] which uses data correlation, but is not an error control code, as there is no encoding. Power-aware, system-level techniques including modulation and MAC protocals, as well as differing rate and constraint length convolutional coding, are considered in [15] to reduce system energy consumption in wireless microsensor networks. Depending on the required bit error rate (BER), a higher rate convolutional code, or no coding at all, could be the most energy-efficient approach. In this paper, a suitable error correction code is chosen from a list of existing codes for wireless sensor network.

The rest of the paper is organised as follows. Section II discusses the wireless sensor network channel error characteristics. In section III, several error correction codes are explained. Energy model for wireless sensor network is discussed in section IV. Selection procedure of error correction code is developed in section V and finally, section VI concludes the paper.

II. Wireless Sensor Network channel error characteristics

Our system model is a centralized wireless sensor network suitable to applications like IEEE 1451.5 standard, where many clusters with several sensors are connected wirelessly with the DGN using multihop communication and is shown in Fig. 1. This section examines the characteristics of bit errors in sensor networks to determine whether their BER varies smoothly enough to be traced down. When wireless channel is modeled as a state machine and a state is specified as BER, Adaptive FEC Code Control (AFECCC) adaptability is determined by the average duration of a state and the BER difference between two adjacent states. If BER varies more rapidly than the adaptation delay taken for detecting BER variation and calculating the suitable FEC level, it hardly accomplishes any improvement. If the channel BER is constant, furthermore, it may be useless. Fig. 2 shows NCBPP (the Number of Corrupted Bytes Per Packet) standard deviation distribution of 10 traces at each TR distance (standing for the distance between the transmitter and receiver) by incrementing 1m from 6m to 13m. Each trace represents 4-hour traffic from a sensor network where a Mica Mote sender continues to transmit 100-byte packets to its receiver at the maximum speed of 3.2Kbps by FSK (Frequency Shift Keying) modulation with 915 MHz carrier signal and 90mW transmission power.

Fig. 2 indicates that the average NCBPP gradually increases from 2-byte within close distances less than 11m to 11-byte as TR distance approaches 13m, the threshold distance for distinguishing signal. The standard deviation range also widens from 2-byte up to 10-byte as TR distance gets larger. The growth of the average NCBPP as a function of TR distance is explained by LSF (Large Scale Fading) effect that the signal power fades in proportion to TR distance. The expansion of the standard deviation span is due to that SSF (Small Scale Fading) effect mainly caused by multi-path interferences gets stronger as the signal power becomes weaker.

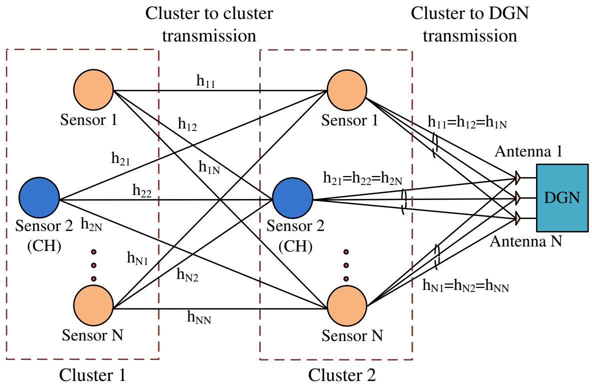

Fig. 1. System model for a typical wireless sensor network

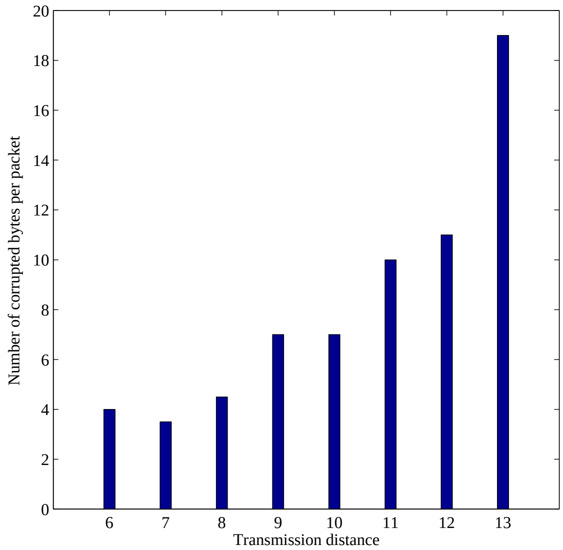

Fig. 2. Number of corrupted bytes per packet distribution as a function of transmission distance

Based on Fig. 2, we can say that AFECCC is indispensable to accommodate the wide BER distribution when receivers move around or even when they are statically located apart further than 10m from their sender. When a receiver roams around within $13m$ radius from its sender, for instance, the sender needs to add 36-byte RS (Reed-Solomon)[16] code to correct the worst 18 damaged bytes at 13m TR distance. Note that RS code requires 2-byte correction code for 1-byte error. This static FEC algorithm, however, leads to 24-byte waste at TR distance less than 11m where the maximum number of erroneous bytes is less than 6.

Fig. 3 shows how fast the channel BER changes by plotting Allan deviation [17]. For Allan deviation, we divide a packet trace into time slots, compute NCBPP average of each time slot, and finally calculate Allan deviation, namely the variance of two neighbor time slots NCBPP. Allan deviation represents the smoothness of BER changes. Fig. 3 displays five Allan deviation graphs for five different TR distances as the time

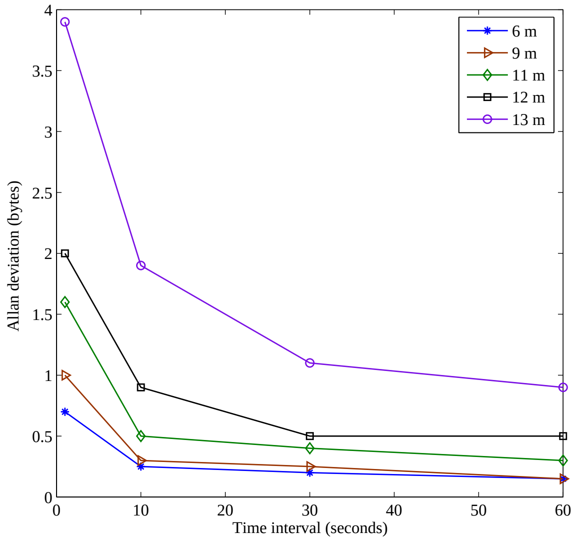

Fig. 3. Allan deviation of number of corrupted bytes per packet distribution

slot width for averaging NCBPP expands. In Fig. 3, the Allan deviation of 13m trace is 4-byte at 1s (second) time span while it rapidly decreases up to 1-byte at 60s interval. This Allan deviation plots again verify that NCBPP slowly changes at close TR distances while it abruptly varies at distant ones. This observation also illustrates the appropriate FEC code size difference between two adjacent FEC levels depends on the time scale to track down. When AFECCC aims at tracing 1s BER variations, for example, its levels should be apart further than 4-byte at least. On the other hand, when it tries to follow long-term variations, the difference between two neighbor levels should be more than 4-byte.

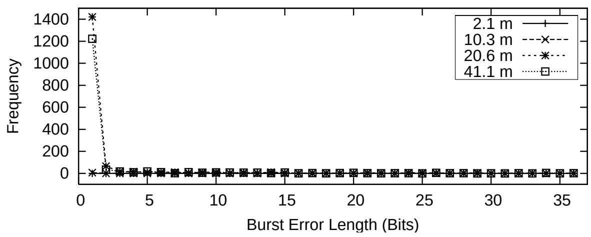

Fig. 4. Graph of Frequency Against Burst Error Length (Bits) Per 10000 Packets

From a preliminary measurement in Fig. 4, we can observe that most bit errors are single-bit or double-bit errors and burst errors are present but rare. Thus, it is likely that an encoding scheme that corrects single and double-bit errors can reduce a significant portion of the errors. Another measurement in Fig. 5 shows that the packet loss due to preamble misdetection Ppre is very small. For example, at a distance of $41.1m$, $P_pre = 0.4\%$. Thus, we confirmed that preamble misdetection does not cause significant packet loss and most of the packet losses are due to errors in other parts of the packet.

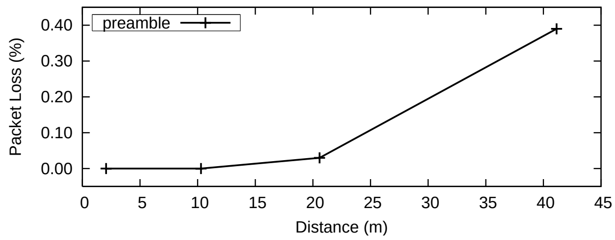

Fig. 5. Graph of Packet Loss over distance for different causes: preamble misdetection and corruption in data payload

III. Error correction codes

Error control coding (ECC) introduces redundancy into an information sequence u of length k by the addition of extra parity bits, based on various combinations of bits of u, to form a codeword $\mathbf{x}$ 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 $\mathbf{x}$ correctly which, if uncoded, would be demodulated incorrectly. This ability to correct errors in the received sequence means that use of ECC over a noisy channel can provide better bit error rate (BER) performance for the same signal-to-noise ratio (SNR) compared to an uncoded system, or can provide the same BER at a lower SNR than uncoded. This difference in required SNR to achieve a certain BER for a particular code and decoding algorithm compared to uncoded is known as the coding gain for that code and decoding algorithm. Typically there is a tradeoff between coding gain and decoder complexity. Very long codes provide higher gain but require larger decoders with high power consumption, and similarly for more complex decoding algorithms.

Several different types of ECC exist, but we may loosely categorize them into two divisions: (1) block codes, which are of a fixed length n_C, with $n_C - k$ parity bits, and are decoded one block or codeword at a time; (2) convolutional codes, which, for a rate k/n_C code, input k bits and output n_C bits at each time interval, but are decoded in a continuous stream of length $L >> n_C$. Block codes include repetition codes, Hamming codes [18], Reed-Solomon codes [19], and BCH codes [20], [21]. The terminology (n_C, k) or (n_C, k, d_{min}) indicates a code of length n_C with information sequence of length k, and minimum distance (the minimum number of different bits between any of the codewords) d_{min}. Short block codes like Hamming codes can be decoded by syndrome decoding or maximum likelihood (ML) decoding by either decoding to the nearest codeword or decoding on a trellis with the Viterbi algorithm [22] or maximum a posteriori (MAP) decoding with the BCJR algorithm [23]. Algebraic codes such as Reed-Solomon and BCH codes are decoded with a complex polynomial solver to determine the error locations. Convolutional codes are decoded on a trellis using either Viterbi decoding, MAP decoding, or sequential decoding. Another categorization is based on the decoding algorithms: (1) noniterative decoding algorithms, such as syndrome decoding for block codes or maximum likelihood (ML) nearest-codeword decoding for short block codes, algebraic decoding for Reed-Solomon and

BCH codes, and Viterbi decoding or sequential decoding for convolutional codes; (2) iterative decoding algorithms, such as turbo decoding with component MAP decoders for each component code, and the sum-product algorithm (SPA) [24] or its lower complexity approximation, min-sum decoding [25],[26], for low-density parity-check codes (LDPCs). The noniterative decoding category may be further divided into hard- and soft-decision decoders; hard-decision decoders output a final decision on the most likely codeword, while soft-decision decoders provide soft information in the formof probabilities or log-likelihood ratios (LLRs) on the individual codeword bits. Viterbi decoding can be either hard-decision or soft-decision, with a 2 dB gain in performance for soft-decision decoding. Category (2) are all softdecision algorithms by nature, as iterative decoding requires soft information as a priori input for each iteration. Iterative decoding algorithms provide significant coding gain, at the cost of greater decoding complexity and power consumption.

IV. Energy model for Wireless Sensor Network

For this model the final decoding energy has also been ignored since the base station is not power constrained and only the encoding energy for first node is considered. The energy consumed at node level can be computed as follows:

$$E_{total} = E_{enc} + E_{TX} + E_{RX} \tag{1}$$

where
E_{total} : Total energy consumed in the network
E_{enc} : Energy consumed by the encoder at the first node
E_{TX} : Energy consumed in transmission by all nodes
E_{RX} : Energy consumed in receiving the data by all nodes except first one

$$E_{total} = E_{enc} + \sum_{i=1}^{m} N_b E_{tx} + \sum_{i=1}^{m-1} N_b E_{rx} \tag{2}$$

where
m : Number of hops
N_b : Total number of bits transmitted
E_{tx} : Energy consumed in transmitting a single bit from a node
E_{rx} : Energy consumed in receiving a single bit at a node

The term E_{tx} can be represented as [28]:

$$E_{tx} = E_{te} + E_{ta} d^{\alpha} \tag{3}$$

where, E_{te} is the power consumption at transmitter electronics α is the path loss component usually varies between $2-4$ with $\alpha = 3$ being a typical value when scattering is considered [29]. E_{ta} is the power consumption of transmitter amplifier and can be given as:

$$E_{ta} = \frac{(\frac{S}{N})_{r(i)} (NF_{RX})(N_0)(BW)(\frac{4\pi}{\lambda})^{\alpha}}{(G_{ant})(\eta_{amp})(R_{bit})} \tag{4}$$

where, $(\frac{S}{N})_{r(i)}$ is the desired SNR at the i_{th} receiver, NF_{RX} is noise figure at receiver, N_0 is the thermal noise, BW is the bandwidth of channel noise, λ is wavelength, G_{ant} is antenna gain, η_{amp} is the transmitter efficiency and R_{bit} is the raw channel rate in bps. If the channels have low noise, this scheme may completely recover the original data with the additional advantage of low energy consumption.

V. Error correction code selection in Wireless Sensor Network

Wireless sensor network is a special wireless network where power consumption is an important issue. Since the wireless sensors are energy constraint, not all the error correcting codes are suitable for this application. Fig. 6 shows the typical BER characteristic for different error correction schemes. Result shows that the convolution and RS code performs better BER characteristics than the other counter parts. Convolution code is not suitable as it requirs high power consumption [27]. Therefore different RS codes are taken to compare their BER and is shown in Fig. 7.

RS code is considered to be the best choice for WSN having maximum energy efficiency in proper channel conditions or when relay nodes are sufficient in numbers i.e. greater than 5 [10].
Considering,
k : Number of information symbols.
n : Length of the code word.
E_{total} : Evaluated from equation 5

We consider the cases for uncoded and RS coded data to evaluate the total energy consumption. For later comparisons uncoded data is transmitted first through the network. The number of bits transmitted is equal $k\log_2(q^2)$.

$$E_{total} = k\log_2(q^2)[mE_{tx} + (m-1)E_{rx}] \tag{5}$$

In the case of Reed-Solomon Codes, energy consumed in encoding is considered as E_{RS}. The length of the code is (q^2-1) for RS codes which is equivalent to $(q^2-1)\log_2(q^2)$ bits transmitted.

$$E_{total} = E_{RS}(q^2-1)\log_2(q^2)[mE_{tx} + (m-1)kE_{rx}] \tag{6}$$

Power consumption analysis are also taken into consideration and is shown in Table I.

From the simulations results shown in Fig. 7, RS (31,21) shows the best BER performance among the list but from Table I, it is clear that RS (31,26) offers the lowest power consumption. RS (31,21) also offer insignificant power consumption compared to the other counterparts. Since both power consumption and BER are important tools, RS (31,21) can be selected as optimum error correction tool.

VI. Conclusion

The use of error correcting code (ECC) can allow a system to operate at significantly lower SNR than an uncoded system, for the same BER. But the choice of ECC is a very important

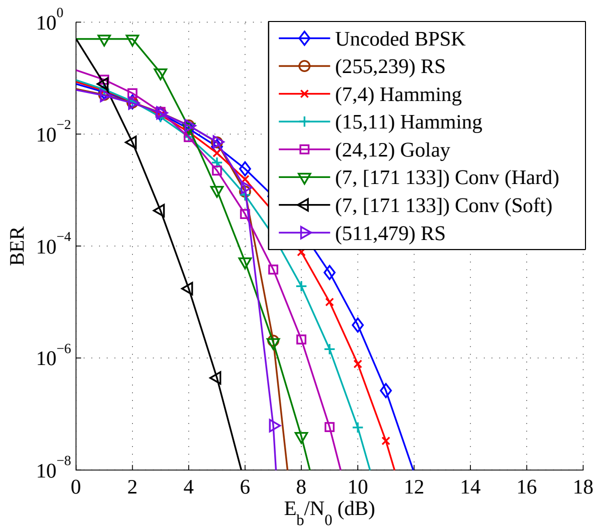

Fig. 6. BER analysis for different error correcting codes

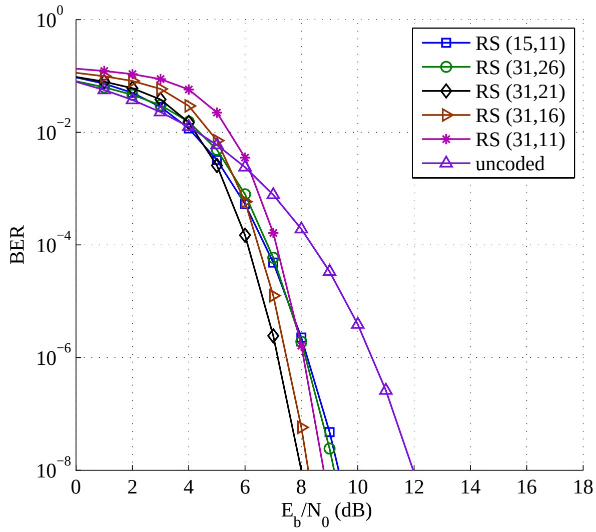

Fig. 7. BER analysis for different Reed Solomon codes

for a wireless sensor network. In this paper, the wireless channel is analyzed and several ECC techniques are simulated. Power consumtion values for several selected ECC are shown. After the comparison of power consumption and BER analysis, RS (31,21) turns out to be the optimal choice of ECC at the wireless sensor network environment.

TABLE I
POWER CONSUMPTION IN RS CODES

RS code	Power consumption(nW)
RS(15,11)	200
RS(31,26)	125
RS(31,21)	150
RS(31,16)	275
RS(31,11)	450

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