Applied Mathematics & Information Sciences
An International Journal

http://dx.doi.org/10.12785/amis/090229

Error Correcting Codes in Wireless Sensor Networks: An Energy Perspective

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Received: 31 May 2014, Revised: 29 Aug. 2014, Accepted: 31 Aug. 2014
Published online: 1 Mar. 2015

Abstract: Wireless Sensor Networks (WSNs) are energy constraint networks that require reliable data communication at a low cost of energy. Only one particular error correcting code (ECC) cannot be adopted for all applications and scenarios of WSNs. The use of a specific ECC depends on the requirements of the application and the constraints of the WSN. Hence it is very challenging to choose an optimum error correcting code for a WSN where both, the performance and energy consumption are taken into account. The selection of an optimum error correcting code for wireless sensor network has been widely studied by many researchers in the past but a standard is yet to be set. Therefore, we present a survey paper to provide reference of existing work on ECCs in WSN and help scholars find a standard ECC for WSNs. We survey different techniques used for error correction in WSNs. Furthermore we study the implementation strategies of error control techniques in WSNs and analyze some energy models to find the energy efficiency of different ECCs. The performance of various ECCs is evaluated on the basis of stated energy models and optimization criteria. Based on the comparison, we can identify the code that would be suitable for a particular implementation strategy.

Keywords: Wireless Sensor Network, Error Correcting Code, Energy efficiency

1 Introduction

Wireless Sensor Networks (WSNs) consists of a large numbers of wireless sensor nodes dispersed in an area of interest with one or more base stations, where data is collected. Base stations have external network connectivity to the end user as shown in Fig. 1.

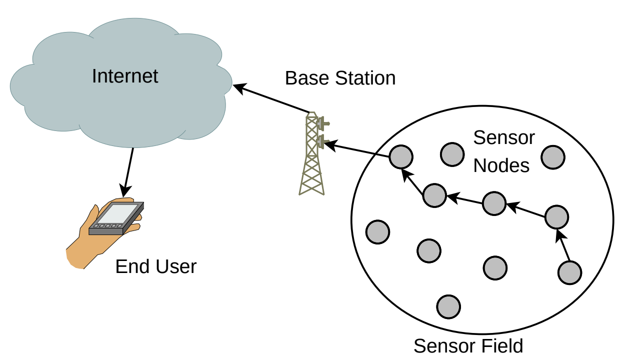

Fig. 1: A Typical Wireless Sensor Network

Sensor nodes can be deployed on ground, in air, under water, in or on human bodies,in vehicles and buildings [1]. A sensor node is normally a small device that is composed of four basic components: the sensing unit which is equipped with sensors that are able to take measurements of the specific physical or environmental condition like temperature, humidity, sound,vehicular movement, lightning condition, pressure, soil makeup, noise levels, the presence or absence of certain kinds of objects, mechanical stress levels on attached objects, and the current characteristics such as speed, direction, and size of an object [2], the processing subsystem which is generally associated with a small storage unit, accomplishes procedures that make sensor node to cooperate withother nodes to carry out the assigned sensing tasks [3], the communication subsystem has a

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transceiver that is used for transmitting and receiving data within the network. The most important part of sensor node isthe power unit which can be regarded as the soul of the sensor node because it supplies energy to node tocarry out the assigned tasks. The power unit, in most cases, consists ofbatteries that have limited energy. Commonly, sensor nodes are deployed in remote unattended geographical areas where it is difficult or sometimes even impossible to replace batteries that supply energy to nodes. So the sensor nodes are generally operated by irreplaceable power sources. However WSNapplications including industrial, security surveillance, medical, environment and weather monitoring among others need the network to operate for a longer time period even in some cases the required life time of network is in years. Therefore the problem of how to extend life of WSN has been quite extensively studied in the past few years [4–11].Researchers have proposed different energy efficient protocols for each layer so as to prolong the network life time,see for example [12–19]. All processes of a sensor node consume considerable amount of energy, however experimental measurements have shown that data transmission is very expensive in terms of energy consumption, while data processing consumes significantly less [20] . For that reason it is very necessary to employ strategies that result in less energy consumption in data communication for example, avoid unnecessary transmission by aggregating the data of correlated sensor nodes.Likewise the transceiver consumes higher energy in transmission and reception even in idle state it consumes significant amount of energy, so the transceiver should be put to sleep (or turned off) whenever possible. All these solutions play an important role in extension of life of WSN but they are useless if reliability is not provided. For the reason that data transmitted from the source node to another node or to the base station (depending on the routing protocol being used) is prone to noise and interference which induces errors in it.Whereas the applications of wireless sensor network need reliable data communication as reliability is the fundamental requisite of every communication. Therefore to provide reliable data communication normally two techniques are used one is automatic repeat request (ARQ) and the other one is forward error correction (FEC). In ARQ the sender node adds error detection codes i.e. Cyclic redundancy check or parity check codes to the data. Sink node checks the correctness of the received data if erroneous packet is received it is simply discarded and the sender node is requested to retransmit the same packet. This is the simple less complex technique which improves the throughput, requires less overhead and computation cost is cheap butthe retransmitting strategy cannot improve the overall energy efficiency in WSN. Some researchers have termed it as energy inefficient as it consumes more energy due to retransmitting every erroneous packet [21] . Research study shows that energy cost of transmitting a single bit of information is approximately the same as that needed for processing a thousand operations in a typical sensor node [22] .This makes a strong case in favor of second technique used for reliable data transmission which is forward error correction (FEC). In FEC source node encodes data using some error correcting code which lets the receiver node to correct errors in data packet if present, thus making retransmission outdated. Error control coding also provides coding gain which lowers required transmitting power for specific bit error rate (BER) or frame error rate (FER). However this happens at cost of extra energy consumption in encoding, transmitting redundant bits and decoding. In most cases encoding energy is considered to be negligible while decoding process consumes significant amount of energy. Complex decoders provide better performance in term of BER but on the other hand consume more energy. WSNs are energy constraint and also require reliable data communication, so the data reliability must be provided at low energy cost.Hence it is very challenging to choose an optimum error correcting code for wireless sensor network where both, the performance and energy consumption are taken into account. Someresearchers have studied hybrid automatic repeat request (HARQ) schemes which exploit advantages of both error correcting schemes by combining ARQ and FEC. HARQ is good for some scenarios in wireless sensor networks [23, 24] but it is limited to only specific applications and consumes a significant amount of energy [25] .

The selection of an optimum error correcting code for wireless sensor network is widely studiedby many researchers in the past decade [13, 14, 26–30] , but a standard is yet to be set.So to help the scholars in finding a standard optimum error correcting code (ECC) and to provide the reference of existing work on ECCs in WSN to the new researchers so that they can have knowledge of the recent research issues in this field. In this paper we survey different techniques used for error correction in WSN specifically we focus on ECCs. Furthermore we study the implementation strategies of error control techniques in wireless sensor networks andalso analyze some energy models that are used to find energy efficiency of ECCs.The performance of various ECCs is evaluated on the basis of stated energy models and optimization criteria.

The rest of the paper is organized as follows.In section 2, we give a brief discussion on error correcting codes; various strategies used to implement error control techniques in WSN are discussed, and performance of some of the ECCsis presented. In section 3, we study energy models used to find the effect of error correcting codes on energy consumption of wireless sensor node, Optimization metric used to compare the performance of different error correcting codes is examined, and various error correcting schemes are evaluated on the basis of stated optimization criteria. In section 4, existing work in literature on errorcontrol coding in wireless sensor networks is reviewed. Finally section 5 concludes the paper.

2 Error Correction Codes in Wireless Sensor Networks

Error correcting codes insert parity bits into message sequence in a proper way depending on type of code being used. The parity bits allow the receiver to correct errors in message sequence if introduced due to noise or interference during transmission. The system with error control coding provides better BER performance as compared to un-coded system for same SNR. We can also say that system with error control coding can provide same BER performance at lower SNR as compared to un-coded system. The relief in SNR for specific bit BER achieved due to error control coding is called coding gain. There are basically two types of error correction codes: (1) Block codes and (2) Convolutional codes.

In block codes, encoder transforms message of k data bits into a larger block of n bits known as code word. Hamming [31] , Golay [32] , Bose-Chadhuri-Hocquenghem(BCH) [33] and Reed-Solomon [34] , are among the widely known block codes. Despite of the traditional block codes there exist a powerful code known as low density parity check (LDPC) code [35] , which is also regarded as a class of block codes [36] . The ratio of message bits to total bits k/n is called as code rate. The error correction capability of block codes depends on minimum hamming distance (minimum weight of its nonzero code word) and decoding algorithm used for decoding. Hamming distance can be increased by lowering code rate. Increasing the hamming distance improves performance but no of redundant bits also increases and as a result energy consumption increases. Similarly using complex decoding algorithm improves performance but overall complexity also rises and thus energy consumption is increased. Different decoders are available for each of the block code for example BCH codes can be decoded using the Gorenstein-Zieleralgorithm [37] or maximum-likelihood soft-decision decoding [38] .Similarly maximum likelihood (ML) decoding on the trellis with the Viterbi algorithm [39] or maximum a posteriori (MAP) decoding [40] can be used to decode Hamming codes. List decoding [41, 42] are used to decode Reed Solomon codes. The most common algorithms used to decode LDPC codes are belief propagation algorithm (BPA), message passing algorithm (MPA) and sum-product algorithm (SPA) [43] [44] [45] .In convolutional codes encoding is performed in a continuous fashion rather than accumulating k data bits and then encoding into n bit code word as in block codes [46] . In case of convolutional codes code word depends on both current k data bits but also on some earlier bits. The no of shifts a particular bit can influence output, depends on constraint length. Convolutional codes can be decoded using Viterbi (soft decision or hard decision) decoding, sequential (soft decision or hard decision) decoding and feedback decoding [47] .The performance of convolutional code in terms of both BER and coding gain depends on constraint length and type of decoding algorithm. Convolutional codes with higher constraint length perform better but on the other hand complexity of code also grows. As the constraint length goes higher, as a result the decoding energy per information bit also increases as shown in the Fig. 2 . Similarly Soft Decision Decoding (SDD) performs better than Hard Decision Decoding (HDD) but requires highly complex circuitry [48] .

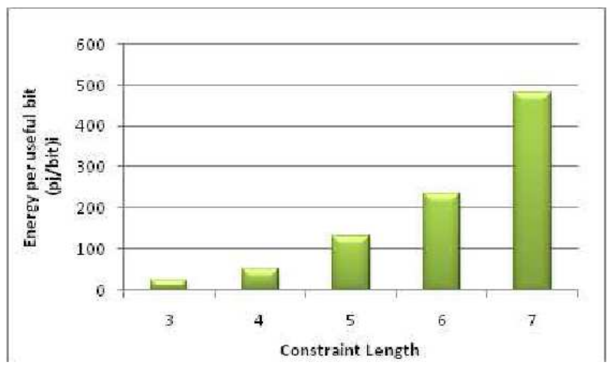

Fig. 2: Decoding energy per information bit for various constraint lengths of half rate convolutional code

In addition there exists a more powerful code, the turbo code that can be thought of as a refinement of concatenated encoding structure plus an iterative decoding algorithm for decoding associated code sequence [47] . One of the most common configurations of turbo code is parallel concatenation of two recursive systematic convolutional (RSC) encoders as shown in Fig. 3.

Generally feedback decoder and maximum a posteriori (MAP) decoder are used to decode turbo codes.

2.1 Implementation Strategies of Error Control Techniques

WSN is a multi-hop network in which data from source node passes through different routing nodes before

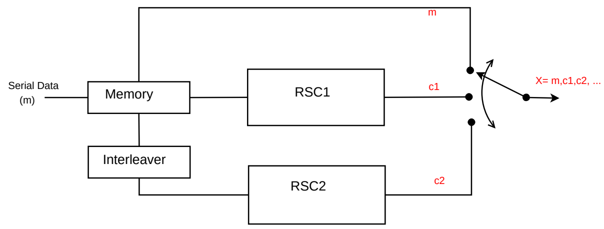

Fig. 3: Parallel concatenated convolutional encoder (turbo code)

reaching sink node as shown in Fig 4. Errors in data packet increaseexponentiallyin multi-hop scenario. The error in data packet received at base station will beaccumulation of errors introduced by each individual routing node. Basically two methods are used to implement error control techniquesin order to providereliability in multi-hop WSN.

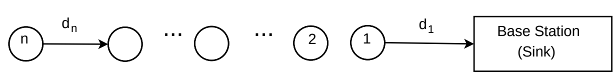

Fig. 4: Multi hop structure of a wireless sensor network

End-to-End Error Control
It can be thought of as error control employed at transport layer. In case of end to end error control for both ARQ and FECencoding is done at source node and decoding is done only at base station. The intermediate nodes only forward the received packets to the next node. This type of error control is adopted for applications that are delay sensitive. Most of researchers have assumed this strategy to study forward error correction in WSN. They argue that decoding consumes significant amount of energyso decoding is performed only at base station which is not energy constraint thus this strategy saves energy at node level.However sometimes accumulated error in packet received at base station, is more than useful information. Therefore decoders at base station are unable to decode thesetypes of received packets.

Node-to-Node Error Control Node to node error control can be thought of as error control employed at data link layer. In case of node to nodeerror control encoding and decoding is performed at every intermediate node.The routing-nodes, upon receiving data-packetschecks errors in them. If an error is detected, it corrects it before transmitting the packet tothe next node. The error correction depends on error correction technique used i.e. ARQ or FEC. In case of ARQ receiver node requests the sender node to resend the same packet. While in case of FEC decoder at receiving node corrects error with help of redundant bits added to data at sender node.This scheme will increase reliability the most but on the other hand it is very expensive in terms of energy consumption.

2.2 Performance of error correcting codes in WSNs

Only one particular error correcting scheme cannot be adopted for all applications and deployed scenarios of WSNs. The use of specific ECC depends on the requirements of application and WSN constraints. As some applications needs high reliability while some can tolerate even lower reliability. Therefore to provide required level of reliability a suitable ECC should be used. But then again choosing an optimum ECC is a very critical job as both, the performance in terms of bit error rate and energy consumption must be taken into account. Stronger codes provide better performance but on the other hand consumes more energy and vice versa. The Fig. 5 shows BER of different error correcting codes it can be observed from figure that convolutional code performs better in terms of bit error rate (BER) than all other codes. But the complex decoder of convolutional codes consumes more energy, hence shortens the life of wireless sensor network. The performance of Hamming code is lower than all the observed error correcting codes, but on the other hand its simple decoder consumes less energy and thus lengthens the overall life of WSNs.

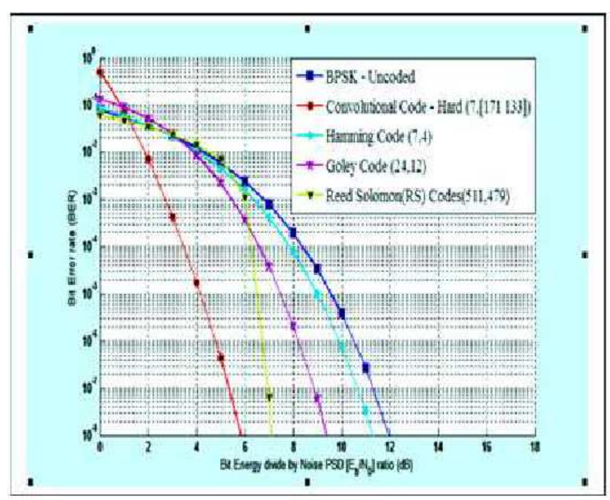

Fig. 5: BER characteristic of different error correcting codes

3 Energy Models for ECCs in WSNs

To find the energy consumption of ECCs in WSN we study two energy models. One is for end to end control strategy and other one is for node to node error control strategy.

3.1 Energy Model for End-to-End Error Control Strategy

The energy modelfor end to end error control strategy does not consider decoding energy as decoding is performed at base station which is not energy constraint. Encoding energy only for the first node is taken into account. However most of researchers have treated encoding energy as negligibly small and does not taken it in to account for analysis of an error correcting code. The energy consumed in wireless sensor network can be computed as:

$$E_{Total} = E_{Tx} + E_{Rx} \tag{1}$$

where, E_Total is the total energy spent in the network, E_{Tx} is the energy spent in data transmission by all nodes and E_{Rx} is the energy spent in data reception by all nodes excluding the source node. Eq. 1 can further be written as:

$$E_{Total} = \sum_{i=1}^{m} NE_{Tx}(b) + \sum_{i=1}^{m} NE_{Rx}(b) \tag{2}$$

where m is the total number of hops, N is the total number of bits, $E_{Tx}(b)$ and $E_{Rx}(b)$ are the energies spent on transmission and reception of a single bit respectively.

3.2 Energy Model for Node-to-Node Error Control Strategy

The energy model for node to node error control coding strategy considers decoding energy for all nodes except source node. While energy consumed in encoding is considered for all the nodes except the last node. However energy spent in encoding is negligibly small as encoding is very simple process hence it is not taken into account.The energy needed to transmit and receive one information bit is given as:

$$E_b = E_{Tx} + E_{Rx} + E_{Dec} \tag{3}$$

where E_{dec} is the energy spent on decoding a single bit. The transmission and reception energies can be written as:

$$E_{Tx} = \frac{((P_{Tx} + P_o)\frac{n}{R} + P_{ST}T_{ST})}{k} \tag{4}$$

$$E_{Rx} = \frac{(P_{Rx}\frac{n}{R} + P_{SR}T_{SR})}{k} \tag{5}$$

where P_o is the transmit power, P_{Tx},P_{Rx} are the power consumption in the transmit and receive circuitry respectively, P_{ST},P_{SR} are the start-up power consumption at the transmitter and receiver respectively, T_{ST},T_{SR} are the start-up time and transmitter and receiver respectively, R is the data rate in kpbs, n is the length of a packet in bits and k is the number of information bits.

Considering L_1 and L_2 as the the useful energy for communication of an information bit and the start-up energy consumption respectively, and mathematically representing them as:

$$\begin{aligned} L_1 &= ((P_{Tx} + P_o) + P_{Rx})/R \\ L_2 &= P_{ST}S_{ST} + P_{SR}T_{SR} \end{aligned} \tag{6}$$

Eq. 3 can therefore be written as:

$$E_b = L_1 + L_1\frac{n}{k} + (L_2 + E_{Dec})/k \tag{7}$$

The cost of decoding a single information bit is thus [30]:

$$E_{Dec} = \frac{P_{Total}}{R} \tag{8}$$

where

$$P_{Total} = CV_{dd}^2 f + I_{leak}V_{dd} \tag{9}$$

where R is information transmission rate, C is the total switched capacitance, V_{dd} is the power supply voltage f is the operating or clock frequency and I_{leak} is the leakage current.

3.3 Optimization Criteria

In this section we study the optimization metric which we have used to compare the performance of the various error correcting schemes.

Decoding Energy per bit We have used decoding energy per bit (DEB) as a metric to conduct a fair comparison between the performances of different error correcting codes. It represents the per bit energy consumption in decoding. Encoding energy is consumed to be negligible. Decoding energy per bit can be given as [49]

$$DEB = \frac{P}{S}V_{dd}^2 \tag{10}$$

Where P is the decoder power consumption (mW), S is the decoding throughput (Mbps) and V_{dd} is the code power supply.

3.4 Analysis of different ECCs on the basis of the above optimization criteria

Error control coding also provides coding gain which lowers the required transmitted power for specific BER. However this happens at cost of extra energy consumption due to the decoder. Normally there is a tradeoff between coding gain and energy consumption of the decoder of ECCs.Stronger codes provide high coding gain but they make use of complex decoders which consumes a lot of energy. Alternatively simple codes though provide lower coding gain but they require less complex decoders with low energy consumption. To select a best suitable error correcting scheme for a specific application according to its required level of reliability and energy constraints of wireless sensor network. We first compare coding gains of different error correcting codes in Fig. 6 and then in Fig. 7 compare the decoding energy per bit (DEB) of these codes, Fig. 8 compares overall decoder power consumption.

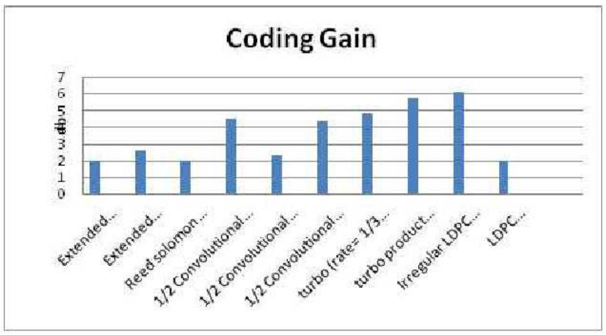

Fig. 6: Coding gain of different error correcting codes compared to uncoded BPSK at a BER of 10^{-4}

We can observe from Fig. 6 that irregular LDPC code provides highest coding gain than all the other ECCs but it can also be noticed in Fig 7 and Fig. 8 that irregular LDPC code consumes highest decoding energy per bit and decoder power. Conversely it can be noticed from same figures that hamming codes although provide low coding gain but on the other hand consume low decoding energy per bit and low power in decoding process. Now it depends on the implementation strategy of error control techniques that which code is suitable to be used. Such as when end to end error control strategy is employed then it is better to use LDPC codes as decoding will be done only on base station which is not energy constraint. Similarly when node to node error control strategy is implemented then it will be suitable to use hamming code or some other simple code.

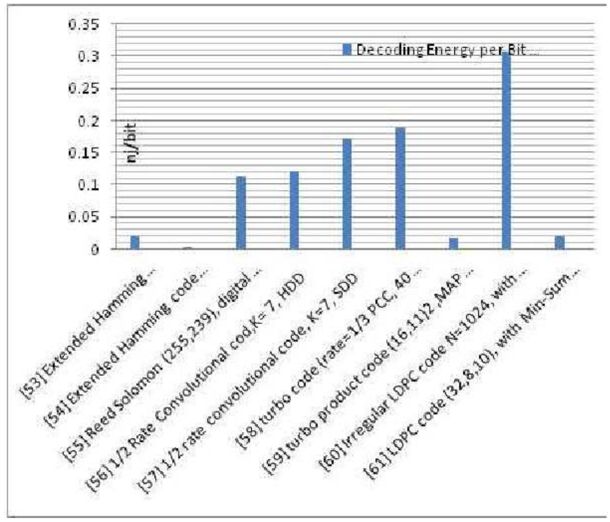

Fig. 7: Comparison of decoding energy per bit (DEB) of different error correcting codes

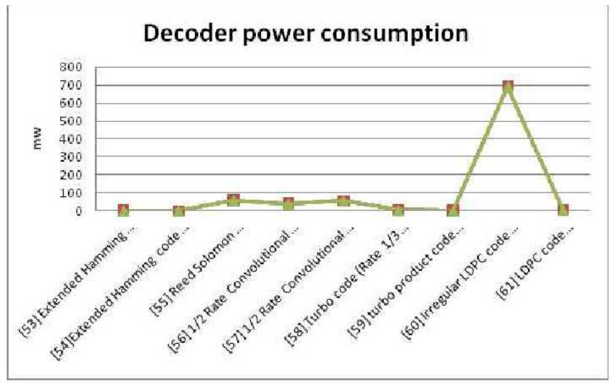

Fig. 8: Decoder power consumption of different error correcting codes

4 Existing Work

There exists a considerable amount of work on error control coding in wireless sensor network however some of the remarkable studies on error control coding in wireless is reviewed in the following section.

In [13] Eugene shih et al study the convolutional codes with varying code rates and constraint lengths to examine their power consumption in frequency non selective slow Rayleigh fading channel Results show that higher constraint length significantly lowers the transmit power but the consumption of energy also increases exponentially with the increase in constraint length of the code. Encoding consumes negligible amount of energy while the Viterbi decoding consumes a lot of energy. Therefore it is identified that it is energy inefficient to use strong ARM processor for Viterbi decoding however it is preferred to use integrated circuit to perform decoding.

In [21] Y. Sankarasubramaniamet al study energy efficiency as the optimization metric to propose the optimal data packet size for communication in wireless sensor network. Energy efficiency is equal to the product of energy throughput and reliability. Energy throughput can be increased by the packet size for which optimum fixed size data packet is determined. Improvement in the reliability can further increase the energy efficiency which can be achieved by the error control strategies.Basically two mechanisms are used for error control one is ARQ and the other is forward error correction however ARQ due to retransmission strategy cannot improve the energy efficiency. Similarly all coding techniques are not able to improve energy efficiency. Therefore they study the energy efficiency of the binary BCH and convolutional codes, as they have efficient decoding algorithm. Simulation results show that BCH codes can improve the energy efficiency up to 23% as compared to the un-coded. Low and high rate convolutional codes have poor performance compared to the medium rate convolutional codes. It is noticed from the comparison of the BCH and convolutional codes that BCH outperforms convolutional codes by 15%.

In [26] G. Balakrishnan et al study the performance of BCH, Reed Solomon and convolutional codes in terms of bit error rate (BER), complexity and power consumption on field programmable gate array (FPGA) and application specific integrated circuit (ASIC).Results show that convolutional codes with higher memory order perform better but at the same time the Viterbi decoder consumes more power than the un-coded channel so convolutional codes are not suitable for wireless sensor network.Based on the comparison the binary BCH code with ASIC implementation is stated to be best choice for wireless sensor network.

In [27] Heikkikarvonenet al studythe effects of DC balanced BCH and Goolay code on the energy efficiency and the effect of the reliability of the codes and start-up energies on energy consumption in single hop case where fixed transmission power mode is assumed. The study is also expanded to analyze the effect of channel coding in multi-hop scenario where start up energies are not considered ,encoding and decoding energies are assumed to be negligible and variable transmission power mode is assumed. For which they study the energy consumption of Hamming, Goolay, shortened Hamming and Extended Goolay codes.

In [28] Zhen Tianet al claim that the conclusion made by many researchers that ?ARQ cannot improve the energy efficiency in wireless sensor networks? is not accurate.It is proved mathematically and the simulation results are produced which reveal that the energy efficiency of ARQ mechanism does not depend on the no of retransmission but it does depend on the size of the transmitting packet and the distance between the nodes.ARQ is compared with BCH in terms of energy efficiency the results obtained from the simulation show that when the size of the data packet is small the BCH outperforms ARQ because the ACK in the ARQ will consume more energy than the decoding energy of BCH code but when the size of packet is large the ARQ performs better because the decoding energy of BCH code increases in this case while the energy consumed by ACK in ARQ remain the same. For larger distance BCH code is more energy efficient while for shorter distance ARQ performs better.

In [29] NashatAbughalieh et al study turbo codes in wireless sensor network. They use parallel concatenated convolutional code (PCCC) circuit for encoding at source node and as detect and correct circuit at the forwarding nodes while the iterative decoding is performed at base station. Detect and correct circuit limits the propagation of a highly corrupted data packet through the network by detecting and correcting some of the errors. The simulation results of tests performed with different SNRs and number of hops show improvement in bit error rate (BER) and frame error rate (FER) due to the detect correct circuit independent of number of hops.

In [50] the authors propose to use low density parity check (LDPC) codes for both channel coding and source coding in order to reduce the transmission power usage in wireless sensor network. They report founded on the results obtained from the simulation that low density parity check (LDPC) codes are 42% more energy efficient than the BCH codes.

In [51] JaeinJeong, Cheng-TienEe observed from the measurements taken from the practical test performed by sending the same encoded packet 5,000 times in two different test beds indoor and outdoor in University of California, Berkeley that errors occurred during the transmission of data packets without using error correcting codes are mostly single bit errors or double bit errors and occurring of burst errors is very rare. In outdoor environment mostly single bit error occurshowever in the indoor environment occurring of multiple bit error is higher.

In [52] Ghaida A. AL suhail et al put forward a scheme for wireless sensor network that the source node has the ability to adapt the error correction capability for each transmission. They have compared the adaptive error correction code scheme with non-adaptive error correction code in terms of energy efficiency based on various communication distances and packet sizes. The result show that the AECC is more energy efficient than non AECC at all distances and packet size.

In [53] ShraddhaSrivastava et al compare energy consumption and error correction capability of

Reed-Solomon (RS), list Decoded RS codes, multivariate interpolation decoded RS codes (MIDRS) and Hermitian codes. They consider encoding at the first node and powerful decoding only at the base station to save energy at node level which might extend the network life.

In [54] Sonalichouhan et al study the effect of error correcting codes and modulation together on the energy consumption of a sensor node They have analyzed the energy consumption in signal transmission with respect to different error correcting capability and variation in the length of Reed Solomon code word for different modulation schemes beyond cross over distance as below the cross over distance the energy consumed in computation is more than the energy consumed in transmission hence it is preferred to have un-coded transmission at this range Reed Solomon (63, 59, 5) with BPSK modulation is reported as the optimum choice. In [55] the authors propose a scheme in which they use LDPC code for encoding the data at the source node the intermediate nodes decode the received data packet for less number of iterations and then forward the partially decoded packet to the next hope while complete decoding is done at base station.

5 Conclusion

We have presented various implementation strategies of error control techniques in WSNs. Aimed at particular implementation strategy energy models are discussed to find the energy consumption of ECCs in WSN. The performance evaluation of different ECCs shows that stronger codes provides good performance but are energy inefficient in contrast performance of simple codes is poor but are most energy efficient. Implementation strategy of error control plays an important role in selection of a specific ECC. Stronger codes are optimal to be used with end to end error control strategy while simple codes arebest for node to node error control strategy. The paper also reviews the existing work in literature on error control coding in WSNs.

In future we are looking forward to implement ECCs in such a way so that strong codes like LDPC codes can be used in more energy efficient manner in WSNs. This implementation strategy of error correction mechanism for WSN will take into account the conservation of energy at nodes as well as good decoding performance. It could open new ways of setting standard ECC for WSN.

Acknowledgement

The authors extend their appreciation to the Research Centre, College of Applied Medical Sciences and to the Deanship of the Scientific Research at King Saud University for funding this paper.

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