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Impact of Error Control Code on Characteristic Distance in Wireless Sensor Network

Sultan Mahmood Chowdhury[1] · Ashraf Hossain[1] · Sunandita Debnath[1]

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Abstract In this paper we study the impact of error control code (ECC) on characteristic distance in wireless sensor network (WSN). In WSN nodes are energy constrained and the goal is to design an energy efficient network. Characteristic distance is important for such network. We consider Bose, Chaudhuri and Hocquenghem and Reed-Solomon codes with different error correction capabilities. Characteristic distance is studied for single node and all nodes transmitting case when decoding is done at all intermediate nodes and only at the destination node. The results show that there is significant improvement in characteristic distance when decoding is done at all intermediate nodes.

Keywords Wireless sensor network · BCH code · RS code · Characteristic distance · Multi-hop communication

1 Introduction

Recent developments 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). The most challenging task in a sensor network is to minimize the energy consumption of the nodes since they have limited power capabilities. Of the three domains (sensing, communicating and processing), a sensor node

✉ Ashraf Hossain
ashrafiit@gmail.com

Sultan Mahmood Chowdhury
sultan.smc@gmail.com

Sunandita Debnath
sunandita23.1990@gmail.com

[1] Department of Electronics and Communication Engineering, National Institute of Technology (NIT) Silchar, Silchar, Assam 788010, India

expends a significant amount of energy in data communication [1]. Also reliability is a primary requirement of any communication. The level of reliability provided by the link layer depends both on application requirements and user specified constraints. Source can send data to the sink using either single hop or multi-hop. There is a trade-off between energy consumption and mode of communication. In multi-hop communication if the hop distance is very small it leads to excessive receive energy. On the other hand if the hop distance is very large it leads to excessive transmit energy. The characteristic distance is the optimum distance for single hop in between these two extremes [2]. It is defined as the distance of a single hop for which energy consumption is minimized [3]. Finding the characteristic distance can help us determine the optimal number of hops required to cover a particular distance in case of multi-hop communication.

Designing energy efficient WSN is one of the most important research challenges. There are several schemes that have been proposed till date to reduce the energy consumption by the sensor nodes. A sensor node usually employs some kind of optimization techniques to reduce energy consumption. One such technique is to reduce the active period of the transceiver unit by switching it to sleeping mode when it is not transmitting or receiving i.e. activating the transmitter only when there are data to be transmitted and similarly activating the receiver only when there are data to be received [4]. Other approach like routing algorithms is used for reducing energy consumption. Several energy efficient routing algorithms have been proposed in the literature.

However, none of the above solutions addresses the channel impairments as any radio signal is affected by random noise and channel fading [5, 6]. There are mainly two mechanisms of error control in communication: Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC). ARQ is a retransmission procedure and its usefulness in sensor network is limited by the additional retransmission cost and overhead [1]. In [7], it is proved that ARQ can not improve the energy efficiency. FEC improves the error resiliency by sending redundant bits through the wireless channel. Therefore, lower signal-to noise ratio can be supported to achieve same error rate as an uncoded system. This advantage has been used in cellular networks to reduce the transmit power. This improves the capacity of cellular networks by reducing the interference. In multi-hop networks the advantages of FEC can be utilised by designing longer hop distance.

In this paper, we study the effect of FEC techniques (BCH and RS) on characteristic distance in WSN. Here we consider two cases (1) only the single node furthest from the sink transmits and (2) all nodes simultaneously transmit their data to the sink. We further consider two decoding scenario (1) decoding is done only at the sink node and (2) decoding is done at all intermediate nodes. The rest of the paper is organized as follows: Sect. 2 discusses the related work on characteristic distance. Section 3 describes radio and system model. Section 4 presents the characteristic distance for different cases. Simulation results are presented in Section 5. Finally Sect. 6 concludes the paper.

2 Related Work

2.1 Error Control Schemes

Several authors have studied error control techniques in WSN. However none of them have paid attention on the direct effect of ECC on characteristic distance, especially how the use of ECC can increase the characteristic distance in noisy environments which in essence reduces the number of hops required to reach a specific distance. These results in less number of motes required to be deployed to cover a region for monitoring purpose which reduces the total cost. Further in [8] it has been shown that in lossy environments and in high frequency situations, the benefits of error control outweigh the cost.

These above results motivate the study of ECC on characteristic distance in WSN. In [9], it has been shown that no convolutional code provides better energy efficiency for probability of bit error, $P_b > 10^{-5}$ than uncoded transmission. Similarly, in [7], energy efficiency of BCH and convolutional codes are compared to optimize packet size in WSN. The result shows that BCH code outperforms the most energy efficient convolutional code by 15 %. Therefore we are not considering convolutional code in our analysis due to their energy inefficiency. In [10], the authors have compared the energy efficiency of cyclic code, BCH code and ARQ scheme in IEEE 802.15.4 RF transceiver based sensor nodes and have shown that BCH is more energy efficient than the other schemes. In [11], the authors have compared RS, convolutional, Golay and Hamming codes with BPSK modulation in an AWGN channel. They have shown that RS code is the best choice for energy constrained WSN. LDPC codes require very long codewords to perform close to Shannon bound. The complexity, long processing delays, and large buffer implementation represents a challenge for practical implementation of long codewords, especially for delay sensitive traffic. For N packets generated from K original packets, $K(1 + \varepsilon)$ packets are required to decode the information [12]. This introduces decoding inefficiency that may increase the number of iteration before the decoding procedure is finished [13]. The use of Turbo codes is another possible solution, which are high performance code that closely approach the channel capacity [14]. They rely on convloutional codes and interleavers, which increase the decoding complexity. As the decoding process is iterative, it increases the processing time. Since the sensors have limited computational capabilities, Turbo codes are not recommended for WSN. Therefore in this paper we choose to investigate the effect of BCH and RS code on characteristic distance.

2.2 Study of Characteristic Distance

In [3], the authors have studied the effect of linear block code on energy consumption in multi-hop wireless sensor network. It has been shown that efficiency of different codes varies with channel conditions. For a particular BER the energy consumption is lowest when the single hop distances matches the transceiver characteristic distance. However, in the paper the authors have not considered the start-up and decoding energy consumption by the nodes. Furthermore, they have considered only the node furthest from the sink transmits data. But in most useful scenario all the nodes will transmit data. In [15], the authors have found the characteristic distance where a source sends data to a sink using optimum number of relay nodes. In [2], the authors have found the characteristic distance for any-to-any network by considering the idling state energy dissipation. In [16], multi-hop communication in WSN with equal spacing and optimal spacing has been presented. It has been shown in the paper that with FEC lowest energy consumption can be achieved if both the transmission power and number of hops are kept low. However, the analysis does not show how the characteristic distance or optimal numbers of hops are affected by FEC particularly for the all nodes transmitting scenario. In [17], the impact of energy dissipation model on characteristic distance for many-to-one and any-to-any has been presented. Although error control coding techniques in wireless sensor network have been studied in some of the previous works, none of them have studied the direct impact of coding on characteristic distance. This paper shows how the use of ECC can affect the characteristic distance in wireless sensor network.

3 Radio and System Model

3.1 System Model

Although network topology and nodes' location are random, a linear model (Fig. 1) is considered similar to [2, 3] to study the effect of error control coding on characteristics distance.

3.2 Radio Model

A radio model similar to the one presented in [3, 16] is used to represent and analyze energy consumption. Figure 2 illustrates the energy consumption for a hop distance of d for sending m bits over a wireless link of distance d

$$E_{Tx} = m(e_{TC} + e_{TA}d^{\alpha}) \tag{1}$$

$$E_{Rx} = me_{RC} \tag{2}$$

where E_{Tx} is the total energy consumption at the transmitter, e_{TC} is energy consumed by the transmitter circuitry, e_{TA} is the consumption of transmitter amplifier, d is the transmission distance and α is path loss exponent. E_{Rx} is the total energy consumption at the receiver; e_{RC} is energy consumption by the receiver circuitry. An explicit expression for e_{TA} is presented in [18] is given as

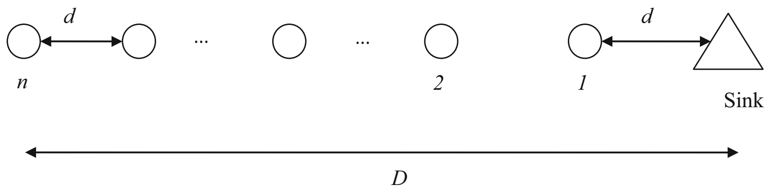

Fig. 1 Linear multi-hop model with equal hop distances

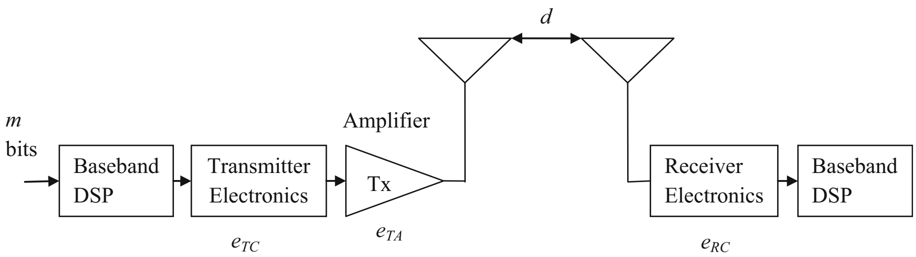

Fig. 2 Radio energy consumption model

$$e_{TA} = \frac{(S/N)_r (NF_{Rx})(N_0)(BW)(4\pi/\lambda)^\alpha}{(G_{ant})(\eta_{amp})(R_{bit})} \tag{3}$$

where $(S/N)_r$ is the desired signal-to-noise ratio at the receiver's demodulator, NF_{Rx} is the receiver noise figure, N_0 is the thermal noise floor in a 1 Hz bandwidth, BW is the channel noise bandwidth, λ is the wavelength in meters, G_{ant} is the antenna gain, η_{amp} is the transmitter efficiency and R_{bit} is the raw bit rate in bits per second. This expression for e_{TA} can be used for the cases where a particular hardware configuration is being considered as in this paper.

The bit error rate (BER) is a useful metric when comparing the energy consumption of different communication methods [3]. The BER depends on channel characteristics as well as on modulation technique. In this paper we assume a non-coherent FSK modulation which is simple but adequate for wireless sensor networks and a Rayleigh slow fading channel as in [3]. For this channel the probability of bit error can be expressed as

$$p_{FSK} = \frac{1}{2+\gamma} \tag{4}$$

where γ is the average signal-to-noise ratio.

4 Analysis for Characteristic Distance

In this section we present characteristic distance for different cases. Here we only consider the start up and decoding energies but neglecting the encoding energy as energy consumption for encoding is very small compared to energy consumption for decoding [19].

Case-I Single node transmitting case (when only the node furthest from the sink transmits its data to the sink node)

(i) *When decoding is done at all nodes*

For the topology shown in Fig. 1, the total energy consumed in sending a packet of length m bits from the nth node to the sink (using a multi-hop routing where downstream neighbours are used as relay node) can be written as

$$E_{linear} = nE_{Tx} + (n-1)E_{Rx} + nE_{st} + (n-1)E_{sr} + (n-1)E_{dec} \tag{5}$$

where n is the number of hops, E_{st} and E_{sr} are the start up energies for the transmitter and receiver respectively and E_{dec} is the energy consumed by each node during decoding of a packet.

Substituting the values of E_{Tx} and E_{Rx} from (1) and (2) into (5) we get

$$E_{linear} = n[m(e_{TC} + e_{TA}d^\alpha)] + (n-1)me_{RC} + nE_{st} + (n-1)E_{sr} + (n-1)E_{dec} \tag{6}$$

where d is distance of a single hop, i.e.$d = D/n$, where D is distance between the furthest node and sink. Thus

$$E_{linear} = m\left[n(e_{TC} + e_{RC}) - e_{RC} + \frac{e_{TA}D^\alpha}{n^{\alpha-1}}\right] + nE_{st} + (n-1)E_{sr} + (n-1)E_{dec} \tag{7}$$

since the characteristic distance is the single hop distance for which energy consumption is minimized, therefore our aim is to minimize E_{linear} with respect to n.

Setting $\frac{dE_{linear}}{dn} = 0$, we get

$$m\left[e_{TC} + e_{RC} - \frac{e_{TA}(D)^{\alpha}(\alpha - 1)}{n^{\alpha}}\right] + E_{st} + E_{sr} + E_{dec} = 0 \tag{8}$$

Rearranging we get

$$\left(\frac{D}{n}\right)^{\alpha} = \frac{m(e_{TC} + e_{RC}) + E_{st} + E_{sr} + E_{dec}}{me_{TA}(\alpha - 1)} \tag{9}$$

Therefore, we can write the single hop distance as

$$d = \sqrt[\alpha]{\frac{m(e_{TC} + e_{RC}) + E_{st} + E_{sr} + E_{dec}}{me_{TA}(\alpha - 1)}} \tag{10}$$

Hence, the characteristic distance for the case when decoding is done at all nodes can be written as,

$$d_{char} = \sqrt[\alpha]{\frac{m(e_{TC} + e_{RC}) + E_{st} + E_{sr} + E_{dec}}{me_{TA}(\alpha - 1)}} \tag{11}$$

The characteristic distance depends on the radio parameters (e_{TC}, e_{RC}, e_{TA}) as well as on the start up and decoding energy consumptions by the nodes. It also depends on the packet length m and path loss exponent α.

(ii) *When decoding is done only at the destination node*

In this case decoding is done at the destination node only and all the intermediate nodes simply act as relay nodes. They do not perform any decoding, they simply retransmits the received data to the next node. The total energy consumption by the network for this scenario can be expressed as

$$E_{linear} = m\left[n(e_{TC} + e_{RC}) - e_{RC} + e_{TA}\frac{D^{\alpha}}{n^{\alpha-1}}\right] + nE_{st} + (n-1)E_{sr} + E_{dec} \tag{12}$$

Setting $\frac{dE_{linear}}{dn} = 0$, gives characteristic distance

$$d_{char} = \sqrt[\alpha]{\frac{m(e_{TC} + e_{RC}) + E_{st} + E_{sr}}{me_{TA}(\alpha - 1)}} \tag{13}$$

From the expression it is clear that the characteristic distance is independent of the decoding energy consumption by the node when the decoding is done only at the destination node.

(iii) *Without using error control code*

The total energy consumption for the uncoded system (when no coding is used$E_{dec} = 0$) can be written as

$$E_{linear} = m\left[n(e_{TC} + e_{RC}) - e_{RC} + e_{TA}\frac{D^{\alpha}}{n^{\alpha-1}}\right] + nE_{st} + (n-1)E_{sr} \tag{14}$$

Setting $\frac{dE_{linear}}{dn} = 0$, gives characteristic distance

$$d_{char} = \sqrt[\alpha]{\frac{m(e_{TC} + e_{RC}) + E_{st} + E_{sr}}{me_{TA}(\alpha - 1)}} \quad (15)$$

The above expression for characteristic distance is similar to the expression the authors have found in [3] except that the authors in [3] have not considered the start up energy consumption by the transmitter and receiver. The above expression also shows that the characteristic distance for uncoded and when decoding is done at the destination node only are same, which implies that coding has no impact on the characteristic distance of the network if decoding is performed at the destination node only.

Case-II All node transmitting case (when all the nodes simultaneously sending data to the sink).

In Case-I we have considered only the nth node (furthest from the sink) transmits data. Here we derive the expression for characteristic distance for the scenario when all the nodes are transmitting their data simultaneously.

(i) *When decoding is done at all nodes*

The total energy consumption for this case can be written as

$$E_{linear}^{all} = \frac{n(n+1)}{2}\left[m\left(e_{TC} + e_{TA}\left(\frac{D}{n}\right)^{\alpha}\right) + E_{st}\right] + \frac{n(n-1)}{2}(me_{RC} + E_{sr} + E_{dec}) \quad (16)$$

Now, setting $\frac{dE_{linear}^{all}}{dn} = 0$, gives characteristic distance

$$d_{char} = \sqrt[\alpha]{\frac{(me_{RC} + E_{sr} + E_{dec})(2n-1) + (2n+1)(me_{TC} + E_{st})}{m[(n+1)\alpha - (2n+1)]e_{TA}}} \quad (17)$$

From (12) it is clear that the characteristic distance not only depends on the radio parameters and start up and decoding energies but also depends on the number of hops n.

(ii) *When decoding is done only at the destination node*

The total energy consumption by the network for this scenario is

$$E_{linear}^{all} = \frac{n(n+1)}{2}\left[m\left(e_{TC} + e_{TC}\left(\frac{D}{n}\right)^{\alpha}\right) + E_{st}\right] + \frac{n(n-1)}{2}(me_{RC} + E_{sr}) + (n-1)E_{dec} \quad (18)$$

Again, setting $\frac{dE_{linear}^{all}}{dn} = 0$, the characteristic distance is found to be

$$d_{char} = \sqrt[\alpha]{\frac{(me_{RC} + E_{sr})(2n-1) + 2E_{dec} + (2n+1)(me_{TC} + E_{st})}{me_{TA}[(n+1)\alpha - (2n+1)]}} \quad (19)$$

The above expression for characteristic distance shows that its dependency on decoding energy consumption is very less compared to the case when decoding is done at all the nodes especially if the number of hops is more.

(iii) *Without using error control code*

The total energy consumption by the network can be written as

$$E_{linear}^{all} = \frac{n(n+1)}{2}\left[m\left(e_{TC} + e_{TA}\left(\frac{D}{n}\right)^{\alpha}\right) + E_{st}\right] + \frac{n(n-1)}{2}(me_{RC} + E_{sr}) \tag{20}$$

Setting $\frac{dE_{linear}^{all}}{dn} = 0$, gives characteristic distance

$$d_{char} = \sqrt[\alpha]{\frac{(2n+1)(me_{TC} + E_{st}) + (2n-1)(me_{RC} + E_{sr})}{me_{TA}[\alpha(n+1) - (2n+1)]}} \tag{21}$$

Comparing (19) and (21) it is found that the error control code has much lesser impact on characteristic distance if decoding is done only at the destination.

After determining the characteristic distance the optimal number of hops can be calculated as [3]:

$$\eta_{opt} = \left\lceil \frac{D}{d_{char}} \right\rceil \tag{22}$$

5 Simulation Results

The following analysis has been carried out to study the effect of error control code on characteristics distance. We use MATLAB as our simulation tool. Here we consider (2047, 2036, 1), (2047, 1992, 5) BCH code and (255, 253, 1), (255, 245, 5) RS code for comparison as BCH codes of length 2047 are suitable to be compared with RS codes of length 255 symbols [20]. In [7] the start-up energy consumption is given as 24.86 μJ. In our analysis we consider equal start-up energies for both the transmitter and receiver nodes. When no coding is used we have assumed the packet length to be 2047 bits. The radio parameter values used are shown in Table 1. The decoding energy consumption for BCH and RS codes has been considered as in [20, 21].

Figures 3 and 4 show the characteristic distance d_{char} as a function of bit error probability for single node and all node transmitting case when decoding is done at all nodes

Table 1 Radio parameters

Parameter	Value
Receiver noise figure, NF_{Rx}	10 dB
Thermal noise floor, N_0	−173.8 dBm/Hz or 4.17 × 10^{-21} J
Raw bit rate, R_{bit}	19,200 bits/s
Wavelength, λ	0.3 m
Antenna gain, G_{ant}	−10 dB or 0.1
Transmitter efficiency, η_{amp}	0.2
Path loss exponent, α	3
Bandwidth, BW	19,200 Hz
Transmitter circuitry, e_{TC}	1.066 μJ/bit
Receiver circuitry, e_{RC}	0.533 μJ/bit
No. of hops, n	70
Receiver start up energy, E_{sr}	12.43 μJ
Transmitter start up energy, E_{st}	12.43 μJ

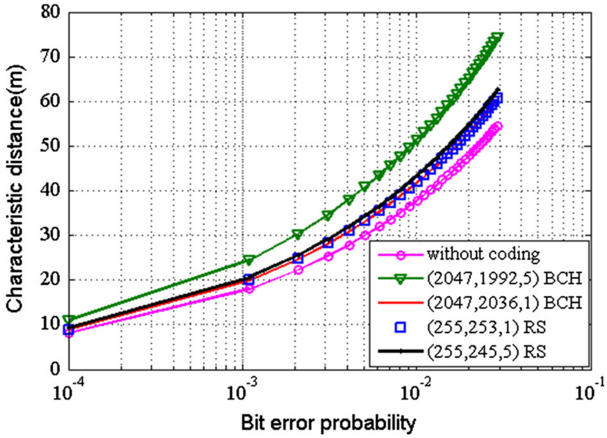

Fig. 3 Variation of characteristic distance with bit error probability when only the furthest node from the sink transmitting and decoding is done at all intermediate nodes

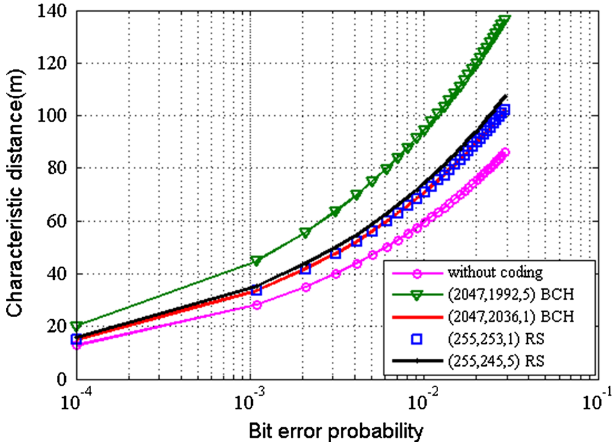

Fig. 4 Variation of characteristic distance with bit error probability when all the nodes are transmitting and decoding is done at all the intermediate nodes

respectively. It can be observed from the figures that for coded system d_{char} increase with increasing BER. The increase is more for 5 error correcting BCH code compared to 1 error correcting BCH and RS codes. For example, at the BER value of 10^{-2} for single node transmitting case the characteristic distance for the uncoded system is 37.71 m whereas for (2047, 1992, 5) BCH coded system this distance becomes 51.35 m. Therefore, an improvement of about 36 % is achieved through the use of BCH code. Similar result can be seen for all nodes transmitting scenario as well. For this case, with the 5 error correcting BCH code an improvement of about 59 % can be achieved in characteristic distance.

It is known that use of ECC over a noisy channel provides the same BER at lower SNR or can lower the BER for the same value of SNR than uncoded system (the difference of SNR for the same BER for coded and uncoded system is known as coding gain) [22], therefore a coded system requires a comparatively lower transmission power to achieve the same BER as an uncoded system. This implies that, with ECC and with the same transmission power as an uncoded system more distance can be reached for a particular BER. In other words, with same transmission power we can increase the hop distance. Therefore, the characteristic distance increases when ECC is used.

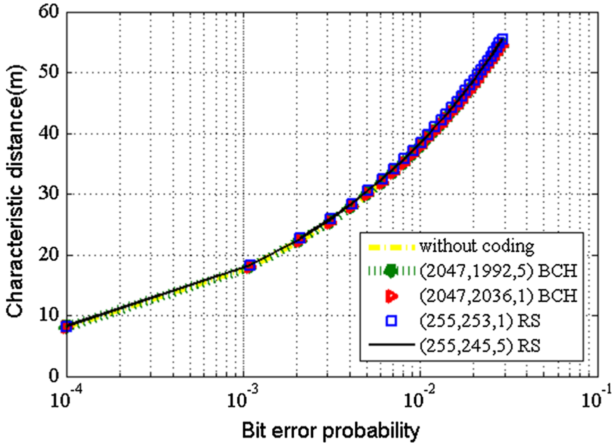

Fig. 5 Variation of characteristic distance with bit error probability when only the node furthest from sink transmitting and decoding is done at destination node only

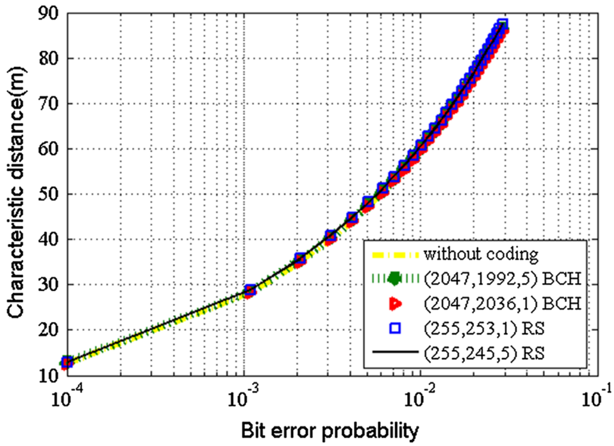

Fig. 6 Variation of characteristics distance with bit error probability for all nodes transmitting case when decoding is done only at the destination node

Figures 5 and 6 show the case when the decoding is done only at the destination node for single and all node transmitting case respectively. From these figures it can be observed that coding does not have much impact on the characteristic distance when decoding is done only at the destination node for both single and all nodes transmitting case. In fact as can be seen from (13) and (15) the expressions for d_{char} is exactly the same for coded and uncoded system for single node transmitting case. The reason is when decoding is done only at the destination node the error probability gets accumulated with increasing number of hops which reduces the coding gain. Therefore, if decoding is done only at the destination node, then as the BER increases with each hop the intermediate nodes require more transmitter power to transmit their data to the next nodes, which in effect reduces the impact of ECC on characteristic distance. Tables 2 and 3 summarize the results.

6 Conclusions

In this paper, the impact of ECC on characteristic distance is studied. It is shown that Forward error control (FEC) can improve the characteristic distance when decoding is done at all the intermediate nodes. This improvement in characteristic distance can be

Table 2 Characteristic distance for different cases when decoding is done at all intermediate nodes

BER	Characteristic distance d_{char} (m)				
	BCH ($t = 5$)	BCH ($t = 1$)	RS ($t = 5$)	RS ($t = 1$)	Uncoded
Only furthest node transmitting					
10^{-4}	10.9897	8.9162	9.2559	8.9650	8.0712
10^{-3}	23.6907	19.2209	19.9533	19.3262	17.3994
10^{-2}	51.3507	41.6621	43.2496	41.8904	37.7140
3×10^{-2}	75.0965	60.9277	63.2493	61.2615	55.1538
All node transmitting					
10^{-4}	20.1969	15.1292	15.8802	15.1054	12.7025
10^{-3}	43.5390	32.6144	34.2373	32.5632	27.3832
10^{-2}	94.3727	70.6933	74.2108	70.5822	59.3543
3×10^{-2}	138.0128	103.3835	108.5276	103.2210	86.8012

Table 3 Characteristic distance for different cases when decoding is done at the destination node only

BER	Characteristic distance d_{char} (m)				
	BCH ($t = 5$)	BCH ($t = 1$)	RS ($t = 5$)	RS ($t = 1$)	Uncoded
Only furthest node transmitting					
10^{-4}	8.0712	8.0712	8.2113	8.2113	8.0712
10^{-3}	17.3994	17.3994	17.7013	17.7013	17.3994
10^{-2}	37.7140	37.7140	38.3685	38.3685	37.7140
3×10^{-2}	55.1538	55.1538	56.1110	56.1110	55.1538
All node transmitting					
10^{-4}	12.7938	12.7335	12.9489	12.9409	12.7025
10^{-3}	27.5801	27.4284	27.9144	27.8972	27.3832
10^{-2}	59.7810	59.4523	60.5058	60.4684	59.3543
3×10^{-2}	87.4252	86.9445	88.4850	88.4303	86.8012

exploited by determining the optimum number of relay nodes required to maintain communication over a particular distance, which will help in designing an energy efficient WSN with minimum number of nodes. For a particular BER if the single hop distance matches the transceiver's characteristic distance then the energy consumption will be minimum. It has been shown that when decoding is done at all intermediate nodes the coding has a significant effect on characteristic distance but if decoding is done only at the destination node the effect is very less. The improvement is more for 5 error correcting BCH code than the single error correcting BCH and RS codes. The results also show that the improvement is more for stronger error correcting codes especially at higher BER. Therefore, using FEC we can reduce the optimal number of hops required for communication particularly in noisy environments.

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Sultan Mahmood Chowdhury received his M.Tech degree in Communication Engineering and B.Tech degree in Electronics and Communication Engineering from West Bengal University of Technology, West Bengal, India, in 2008 and 2005 respectively. He is currently pursuing Ph.D. in the Department of Electronics and Communication Engineering at National Institute of Technology (NIT), Silchar. His current research interests include Wireless Sensor Networks, Wireless Underground Sensor Networks. E-mail: sultan.smc@gmail.com.

Ashraf Hossain earned the Ph.D. degree in Electronics and Electrical Communication Engg., from Indian Institute of Technology (IIT), Kharagpur, India in 2011. He received the M.Tech. and B.Tech. degrees in Radio Physics and Electronics from the Institute of Radio Physics and Electronics, University of Calcutta, Kolkata, India in 2004 and 2002, respectively. He served Dept. of Electronics and Communication Engg., Aliah University, Kolkata and Haldia Institute of Technology as Asst. Professor. He is currently working as an Assistant Professor in the Dept. of Electronics and Communication Engg., National Institute of Technology (NIT), Silchar, Assam, India. His research interests include wireless sensor network, communication theory and systems. He is a member of IEEE and IE (India). E-mail: ashrafiit@gmail.com.

Sunandita Debnath received her M.Tech degree in 2013 and B.Tech degree in 2011 in Electronics and Communication Engineering from West Bengal University of Technology, West Bengal, India. She is currently pursuing Ph.D. in the Department of Electronics and Communication Engineering at National Institute of Technology (NIT), Silchar, India. Her research interests include Wireless Sensor Network, Mobile Wireless Sensor Network. E-mail: sunandita23.1990@gmail.com.