

Journal of Electrical and Electronics Engineering

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Vol. 18. No. 2, October 2025 - ISSN:  
1844-6035 University of Oradea Publisher

JEEE - Journal of Electrical and Electronics Engineering, Vol. 18, No. 2, October 2025



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Journal of  
Electrical and Electronics Engineering

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Vol. 18, No 2, October 2025  
University of Oradea Publisher

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## Journal of Electrical and Electronics Engineering

Years currently covered by Scopus: from 2008 to 2025

Publisher: Editura Universitatii din Oradea

ISSN: 1844-6035 E-ISSN: 2067-2128

Subject area: Engineering: Electrical and Electronic Engineering

Source type: Journal

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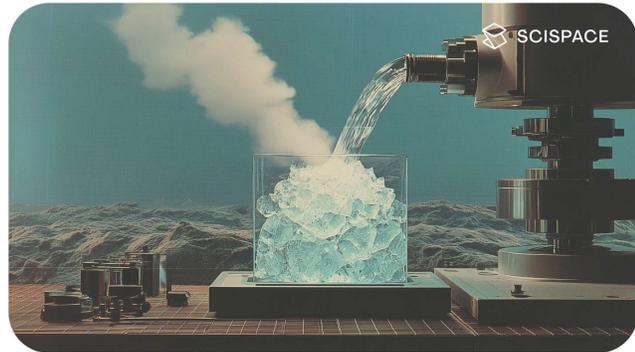
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**SUBJECT AREA AND CATEGORY**

Engineering  
Electrical and Electronic Engineering

**PUBLISHER**

Editura Universitatii din Oradea

**SJR 2024**

**0.163** Q4

**H-INDEX**

**10**

**PUBLICATION TYPE**

Journals

**ISSN**

18446035, 20672128

**COVERAGE**

2008-2024

**INFORMATION**

- [Homepage](#)
- [How to publish in this journal](#)
- [livi@uoradea.ro](mailto:livi@uoradea.ro)



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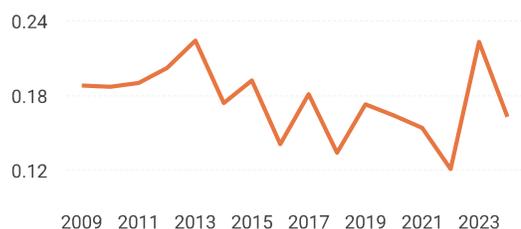


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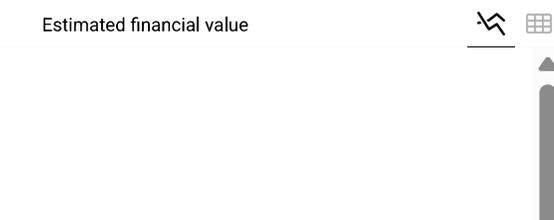
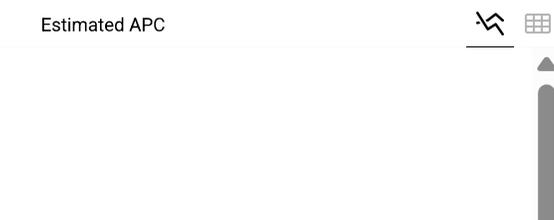
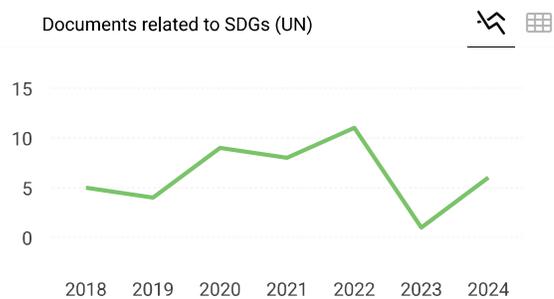
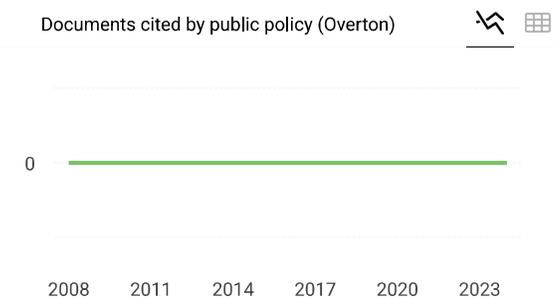
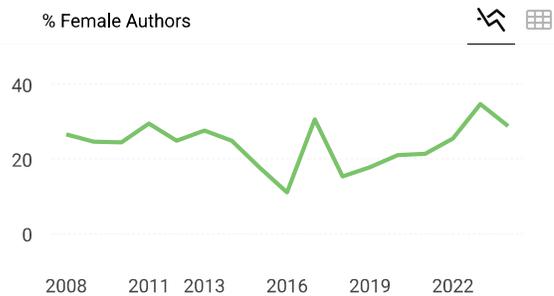
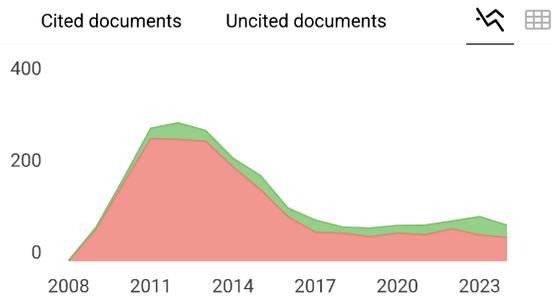
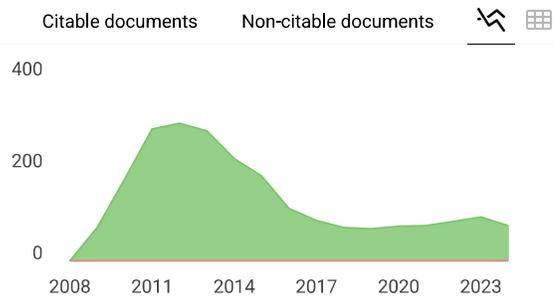
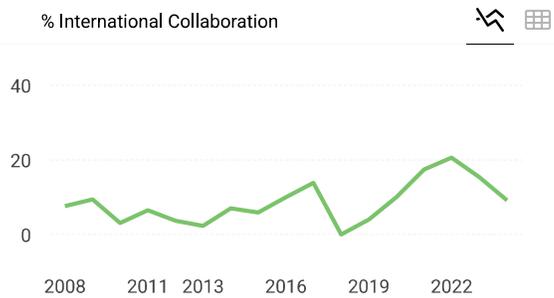
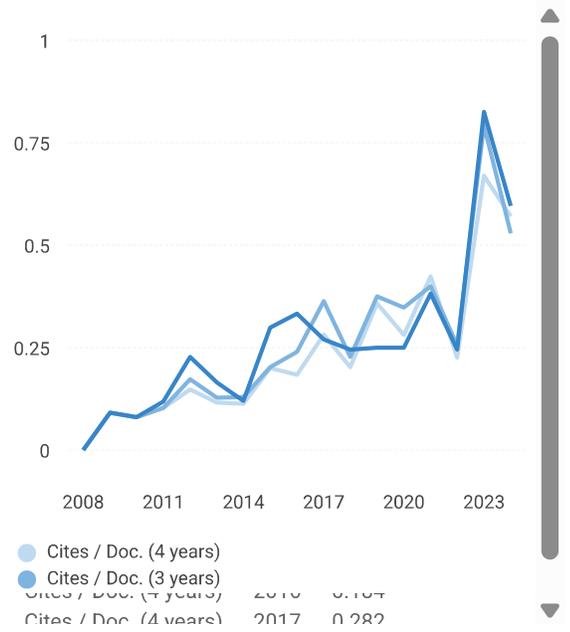
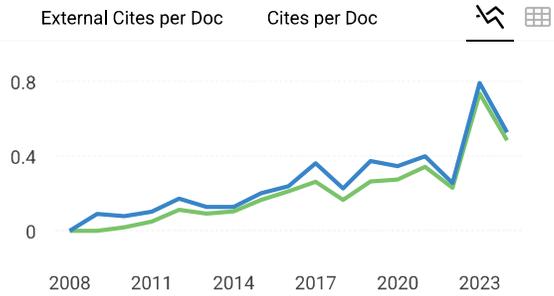
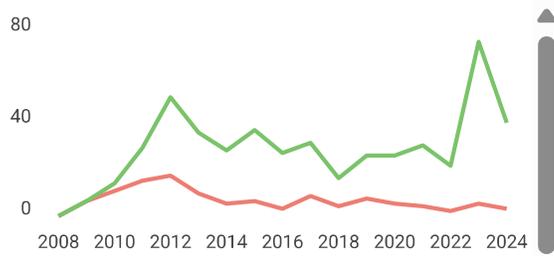
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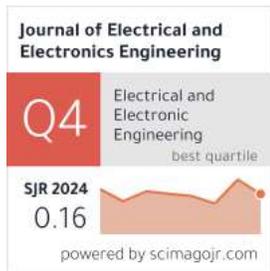
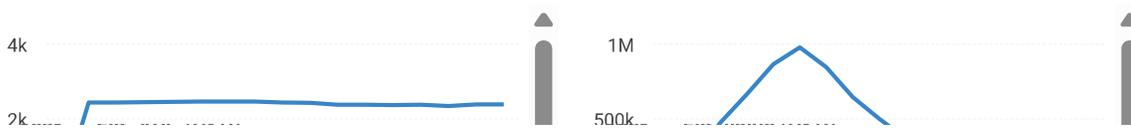


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# Application of LT Code with BCH Precode for Wireless Body Area Network

SARI Lydia, ALAM Syah, MARDIAN Raden Deiny, SURJATI Indra

Universitas Trisakti, Indonesia

Electrical Engineering Department, Faculty of Industrial Technology  
Jl. Kyai Tapa 1, Jakarta 11440, Indonesia, E-Mail: lydia\_sari@trisakti.ac.id

**Abstract** – *Wireless body area network (WBAN) is a key component in telehealth system. The reliability of data transmission is of utmost importance in a WBAN system, as a loss of transmitted data or erroneous data at the receiver may lead to diagnosis errors or delayed treatment. As WBAN typically has limited data processing capability and limited energy, the coding schemes for WBAN transmission must be low in complexity. In this research, we propose the use of Luby Transform (LT) code, known for its simplicity and capability to recover data transmitted in erasure channels, combined with Bose–Chaudhuri–Hocquenghem (BCH) as a precode. BCH precode is used to ensure the recovery and correction of the transmitted symbols which are not recovered by the LT code. Simulations are done to compare the BER versus Eb/No performance of standalone BCH code with LT code equipped with BCH precode, as well as the performance of LT codes with various BCH precodes. It is shown that LT with BCH precode outperforms standalone BCH code. It is also shown that BCH with higher error correction capability namely BCH (63,36,11) and (127,64,21) when combined with LT code will outperform LT codes with BCH (15,7,3) and (31,21,5) precodes.*

**Keywords:** *Wireless body area network (WBAN); telehealth; Luby Transform; Bose–Chaudhuri–Hocquenghem (BCH) code.*

## I. INTRODUCTION

Telehealth system based on Wireless Body Area Network (WBAN) has been developed and becoming more common recently, especially considering the high number of people with chronic health problem who reside in remote areas not easily accessible by health professionals [1], [2]. Telehealth system also enables health professionals to assist patients with mobility problems, before health complications occurs. The role of WBAN is critical in telehealth systems. Typically a WBAN consists of sensors, transmitters and actuators worn on, or implanted in the body to transmit physiological data such as heart rate and body

temperature to a receiver in the form of a remote data processor, without being limited to the person's ongoing activities[3], [4], [5], [6]. A reliable transmission scheme is essential in a WBAN to ensure data integrity at the receiver, as a loss of a patient's physiological data during the transmission or erroneous received data may result in diagnosis errors or delayed treatment [7], [8], [9], [10]. Therefore, a channel coding scheme is required to protect the data against noise and interference which will most likely occur during the wireless transmission [11], [12].

The considerations for a WBAN channel coding scheme are decoding complexity and energy efficiency, as WBAN equipment are designed to be lightweight and naturally have limited energy [13]. Luby Transform (LT) code is a type of Fountain code which features low-complexity encoding and decoding process, and is therefore suitable for WBAN applications[11], [14]. LT code uses a degree distribution function for the encoding process. The degree distribution is also the key component to define the complexity and the success probability of the encoding and decoding process [15]. An extension of LT code is Raptor code, where a high-rate code is used to precode the source symbols and produce the intermediate symbols [14]. Subsequently, an LT code is applied to the intermediate symbols to generate the encoded symbols. The precode will recover all encoded symbols which may be left unrecovered by the LT decoders. In [16], Raptor-coded data transmission in WBAN over Nakagami, Rice, and Rayleigh fading schemes are simulated. The performance metrics evaluated are total energy transmission versus transmission distance. Simulations are also done to compare the energy consumption of Raptor-coded symbols and standalone Bose–Chaudhuri–Hocquenghem (BCH) code. The results show that the BCH-coded data require lower energy consumption to Raptor-coded data in short transmission distance (< 10 meters). The energy requirement of both BCH code and Raptor code will increase as the transmission distance increases. However, it is noted that for Raptor-coded data the energy requirement increase is gradual, as opposed to the steep increase shown by the BCH-coded data. The Bit Error Rate (BER) performance is not

studied in [16]. In [17], simulations are done to analyse the performance of Raptor code, BCH code, and Automatic Repeat Request (ARQ) error control scheme in WBAN. The results show that Raptor code is more energy efficient compared to other error control schemes. The energy requirement for LT code is 40% greater than Raptor code requirement, while the BCH code requires 70% more energy than Raptor code. This confirms that Raptor code is suitable for WBAN applications.

Research [18] investigates the performance of Analog Fountain Code (AFC), which is a rateless code equipped with a fixed-rate precode. A density evolution (DE) analysis framework is used to find the optimum weight set of AFC. The proposed optimised weight set is shown to enable the attainment of good performance both in low and high SNRs in the short block regime.

Based on previous researches, both LT and Raptor codes are highly suitable for WBAN applications. To achieve an optimum Raptor code for different channel fading scenarios, the precode to be used with LT code must be chosen appropriately. In this research, we investigate the use of BCH code as a precode to LT code. BCH is known for its capability to correct random patterns of  $t$  errors with simple encoding and decoding algorithms [19], [20]. We compare the performance of the LT code with BCH precoding in terms of bit error rate versus signal-to-noise ratio across AWGN, Rayleigh, and Rician fading channels, which constitutes the novelty of our paper.

This paper is organized as follows. A summary of LT and BCH codes features is given in section 2. The simulation setup and parameters for LT with BCH precode are given in section 3, and the results are described in section 4. The conclusion is given in section 5.

## I. LUBY TRANSFORM (LT) AND BCH CODES

LT code is the first class of efficient Fountain codes which are rateless, meaning that theoretically, there is no limit on the number of encoded symbols resulting from the original data [21], [22]. The decoder can recover the transmitted data from any set of the encoding symbols that arrive at the receiver side. LT code is suitable for use in erasure channels, as the encoded symbols can be generated continuously until all original data can be recovered by the decoder. The LT encoding process can be described in the following steps [21]:

1. Divide the input symbol into  $k$  bits
2. Choose degree  $d$  randomly from a degree distribution
3. Choose  $d$  input symbols randomly, then combine them using XOR operation to form a codeword
4. Each codeword contains  $k$  bits or multiple of  $k$  bits of information and transmitted to the receiver. In different codewords, there are redundant bits which allow the receiver to recover the input symbols even if some codewords are lost or impaired due to noise or interference in the channel.

The encoder uses a degree distribution,  $\Omega(x)$ , which determines the number of source symbols to be combined for each encoded symbol. A commonly used degree distribution is the Soliton Distribution [14], [23]:

$$\Omega(x) = \frac{x}{k} + \sum_{k \geq d \geq 2} \frac{x^d}{d \cdot (d-1)} \quad (1)$$

where  $x = i/k$ , and  $i$  denotes the step number and  $0 < x < 1$ . The encoded symbols can be stated as

$$C = S_1 \oplus S_2 \oplus \dots \oplus S_d \quad (2)$$

where  $S_1$  to  $S_d$  denotes the input symbols as described in step 3 of the LT encoding process. To recover the original symbols from the codewords, the decoder must have information on the neighbours of each received codeword. This information can be sent to the receiver in the form of a data packet containing the codewords information and a list of their neighbours. The decoding process of LT is as follows [14]:

1. Release: all codewords with degree 1, meaning that the codeword is equivalent to the information symbol, are released to recover their neighbours.
2. Cover: all released codewords will cover all of their neighbouring codewords with degree 2. In this step, an input symbol which has been covered but not yet processed is sent to a set called a ripple.
3. Process: an information symbol is selected from the ripple to be processed.

It is apparent that the decoding process can start only if there is a codeword with degree 1.

BCH code is one of the best-known codes for moderate block lengths [24], [25], [26]. The binary BCH code has a block length of  $n = 2^m - 1$  for some integer  $m \geq 3$  and can correct at least  $t$  errors for any  $t = 2^{m-1}$ . For the BCH encoding, the input message of length  $k$  bits is processed to form a codeword of length  $n$  bits, by appending  $n-k$  parity bits. A generator polynomial is used to append the parity bits to the input message to form a codeword. The generator polynomial  $g(x)$  is

$$g(x) = p(x)p_3(x)p_5(x)\dots p_{2t-1}(x) \quad (3)$$

where  $p(x)$  is a dealprimitive polynomial and the other polynomials  $p_3(x^3)$ ,  $p_5(x^5)$ , ...,  $p_{2t-1}(x^{2t-1})$  must be divisible by  $p(x)$ . For a systematic encoding of BCH, we use the relations:

$$p(x)x^{n-k} = q(x)g(x) + r(x) \quad (4)$$

where  $q(x)g(x)$  is the codeword, and  $r(x)$  is a polynomial with a degree less than  $n-k$ . Therefore, the encoded symbol can be stated as

$$c(x) = p(x)x^{n-k} - r(x) \quad (5)$$

For BCH decoding, two steps are done namely syndrome calculation and error correction. In the syndrome calculation stage, the received codeword is evaluated at powers of  $\alpha$ , specifically  $\alpha^i$  for  $i = 1, 2,$

...,  $2t$  where  $t$  is the number of correctable errors. Assuming that the received polynomial  $y(x)$  is:

$$y(x) = c(x) + e(x) \quad (6)$$

where  $c(x)$  is the codeword and  $e(x)$  is the error polynomial, the values of  $y(x)$  at  $\alpha^i$  where  $\alpha$  is the root of the polynomial, are termed the syndromes and defined by

$$\begin{aligned} S_i &= y(\alpha^i) \\ &= c(\alpha^i) + e(\alpha^i) \quad 1 \leq i \leq t \\ &= e(\alpha^i) \end{aligned} \quad (7)$$

If  $e(x)$  is zero, the syndromes are all zero. The syndrome can be computed from the received sequence  $y(x)$ .

Assuming that there are  $v$  errors in transmissions of  $c(x)$  where  $v \leq t$ , and the location of these errors are denoted as  $j_1, j_2, \dots, j_v$ , where  $0 \leq j_1 < j_2 < \dots < j_v \leq n-1$ , subsequently:

$$e(x) = x^{j_v} + x^{j_{v-1}} + \dots + x^{j_2} + x^{j_1} \quad (8)$$

Using (7) and (8), the syndromes can be stated as

$$\begin{aligned} S_1 &= \alpha^{j_1} + \alpha^{j_2} + \dots + \alpha^{j_v} \\ S_2 &= (\alpha^{j_1})^2 + (\alpha^{j_2})^2 + \dots + (\alpha^{j_v})^2 \\ &\vdots \\ S_{2t} &= (\alpha^{j_1})^{2t} + (\alpha^{j_2})^{2t} + \dots + (\alpha^{j_v})^{2t} \end{aligned} \quad (9)$$

The error locations  $j_1, j_2, \dots, j_v$  can be determined by finding  $\alpha^{j_i}$  from (9), and subsequently bit-flipping is done at the error locations to correct erroneous bits.

## II. SIMULATION PARAMETERS AND SETUP

The simulation parameters to examine the performance of LT code with BCH code is given in Table 1. The performance metric is Bit Error Rate (BER) versus Eb/No. The first simulation is done to compare the performance of standalone BCH code with LT code equipped with BCH precode. The subsequent simulations are done with different BCH code rates as the precode for LT code. The modulation scheme used is BPSK and the channel model used are AWGN, Rayleigh fading, and Rician fading. AWGN channel is chosen as it is a general channel suitable for modelling the transmission channel in a WBAN system, while Rayleigh and Rician fading depict more realistic channel condition compared to AWGN. The physiological data generated by the WBAN sensor is modelled as random binary data sequences, which length is adjusted to the BCH code lengths. To simulate the performance of standalone BCH code, the coded data are simply transmitted through the channel after BPSK modulation. The demodulation and decoding process are done at the receiver, where the decoded data are compared with the original data to calculate the BER. An additional step is taken for the simulations of LT code with BCH precode. For these simulations, the BCH-coded symbols are

processed using LT encoding. At the receiver side, the received symbols are firstly processed using LT decoding. The output of the LT decoder is processed using BCH decoder, to recover any remaining uncovered symbols. The BER is subsequently calculated for each Eb/No value.

TABLE 1. Simulation Parameters

Parameter	Value
BCH Code Length	(15,7,3), (31,21,5), (63,36,11), (127,64,21)
LT Code	Applied with BCH as precode
Modulation Scheme	BPSK
Channel Model	AWGN, Rayleigh, Rician
Number of Simulations	10,000

The BCH encoding algorithm encodes an input message of length  $k$  to yield a codeword of length  $n$ , where  $n > k$ . During the encoding process, the message is represented as a polynomial over a finite field  $GF(2)$  and subsequently multiplied by standard generator polynomials provided by Matlab. The decoding algorithm used is Berlekamp-Massey to find the positions of erroneous bits in the received codeword, and then corrects these bits by performing bit-flipping. A degree distribution function is used to implement the LT code with ideal soliton distribution as a starting point, namely :

$$\rho(1) = \frac{1}{k}, \quad \rho(d) = \frac{1}{d(d-1)} \quad \text{for } d = 2, 3, \dots, k \quad (10)$$

which ensures that there is at least one codeword that has a degree of 1 and therefore decodable. When the decoding fails after some iteration, the simulation takes an alternative function, which is the Robust Soliton distribution. The robust parameter  $R$  can be stated as

$$R = c \ln(k/\delta) \sqrt{k} \quad (11)$$

where  $c$  is Robust Soliton constant = 0.1 for the simulations, and  $\delta$  is the failure probability and set as 0.1 for the simulations.

The simulations are run for degree  $d = 1$  to  $k-1$ , and because  $d = 1$  has the probability of  $1/k$ , the following steps are used in the simulation:

1. Set  $\rho(1) = \frac{1}{k}$
2. For  $d = 2, 3, \dots, k$ , use Eq.(10)
3. For  $d = 1$  to  $k-1$ , if  $d$  is less or equal to  $(k/R)$  then use:

$$\tau(d) = \tau(d) + \frac{R}{dk} \quad (12)$$

4. For  $d = k$ , the following is used:

$$\tau(d) = \tau(d) + \frac{R}{k} \log \frac{R}{\delta} \quad (13)$$

To yield codewords,  $d$  random input symbols are chosen and XOR-ed with each other. The decoding process is done using a belief propagation approach. For each iteration, the received symbol is evaluated based on its reliability, which threshold can be stated as

$$T = \frac{1}{\sqrt{SNR}} \quad (14)$$

If the reliability of a received symbol is higher than the threshold, it is processed using soft decision decoding. Otherwise, the decoding value will take on the sum of soft decisions for other reliable symbols.

### III. RESULTS

Figure 1 depicts the simulation results of a standalone BCH(31,21,5) and an LT code with said BCH code. At  $E_b/N_0 = 0$  dB, the BER of standalone BCH code is 0.2234 while that of LT with BCH precode is 0.1096. At  $E_b/N_0 = 2$  and 4 dB, the BER of LT with BCH precode are 0.0788 and 0.0467 respectively, lower than the BER of standalone BCH which are 0.1546 and 0.0940. At  $E_b/N_0$  range of 0 to 4 dB, the BER of LT with BCH precode ranges between 50% to 51% of the standalone BCH BER. When the  $E_b/N_0$  values are 6 and 8 dB, the BER of standalone BCH are 0.0305 and 0.0026, respectively, while that of LT with BCH precode are 0.0142 and 0.0013. The BER of LT with BCH precode are 46.55% to 52.3% of the standalone BCH at this  $E_b/N_0$  range. At  $E_b/N_0 = 8$  dB, the BER of LT with BCH code has reached 0 while the BER for standalone BCH still continues to decrease. It is also shown that the LT with BCH precode consistently shows better performance compared to the standalone BCH code in low and moderate  $E_b/N_0$  values, and therefore the subsequent simulations are done for LT code with different BCH precodes.

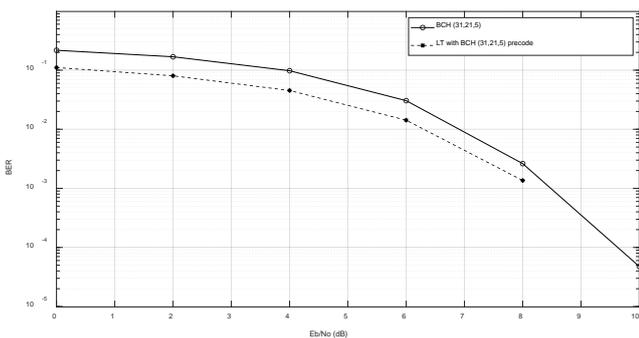


Fig. 1. Performance of BCH (31,21,5) and LT Code with BCH (31,21,5) precode in AWGN channel

Figure 2 shows the simulation results of an LT code with different BCH precodes, namely BCH (15,7,3) and (31,21,5). The BCH(31,21,5) can correct up to 5 errors as opposed to 3 errors that can be corrected by BCH(15,7,3), and this capability is reflected in the simulation results. It can be observed that the LT code

with BCH(31,21,5) precode has lower BER in all  $E_b/N_0$  region plotted, compared to LT code with BCH (15,7,3). The BER of LT code with BCH(31,21,5) is 40% to 69.66% of the LT-BCH(15,7,3) code, with the highest gap observed in the high  $E_b/N_0$  region.

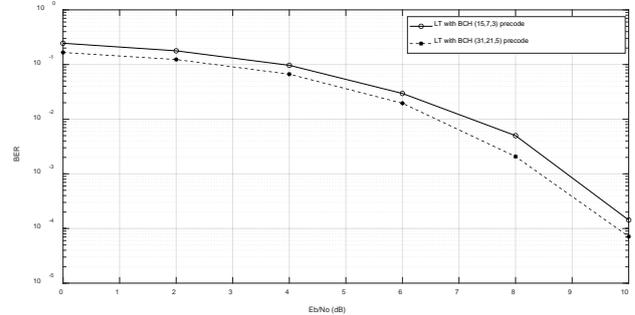


Fig. 2 Performance of LT with BCH (15,7,3) and BCH (31,21,5) precodes in AWGN channel

Figure 3 illustrates the performance of LT codes with BCH(63,36,11) and (127,64,21). At 0 dB, the BER of LT with BCH(63,36,11) is 0.228 while that of LT with BCH(127,64,21) is 0.1556. It is observed that BCH(127,64,21) presents better error protection compared to BCH (63,36,11) for all  $E_b/N_0$  values.

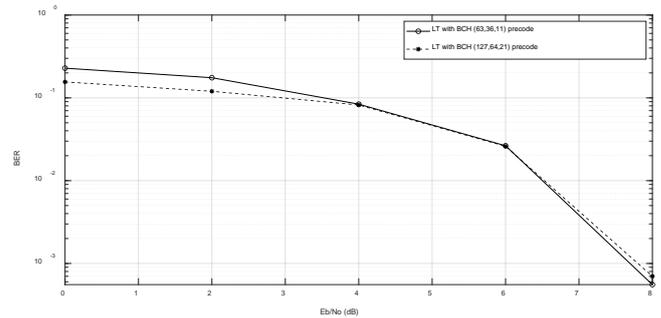


Fig. 3 Performance of LT with BCH (63,36,11) and BCH (127,64,21) precodes in AWGN channel

The simulation results for LT with BCH(15,7,3) and (31,21,5) in Rayleigh and Rician fading channels are given in Figure 4 and 5, consecutively. From Figure 4, it can be observed that the performance of LT-BCH(15,7,3) and (31,21,5) is comparable at low  $E_b/N_0$  region (0-6 dB). The performance of LT-BCH(31,21,5) is slightly better than that of LT-BCH(15,7,3) at very high  $E_b/N_0$  (18-20 dB). A similar result is observed from Figure 5, where LT-BCH(31,21,5) shows higher BER compared to LT-BCH(15,7,3) for all  $E_b/N_0$  values, most notably above 6 dB. This shows that LT code equipped with low coding rate, despite being able to correct more errors, do not necessarily perform well in rapidly changing fading channels. The codes with low coding rates are able to correct a large number of errors spread across the data. However, these codes may not be suitable to correct burst errors that are often introduced during deep fades.

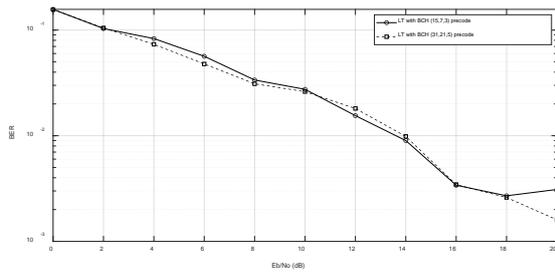


Fig. 4 Performance of LT with BCH (15,7,3) and BCH (31,21,5) precodes in Rayleigh fading channel

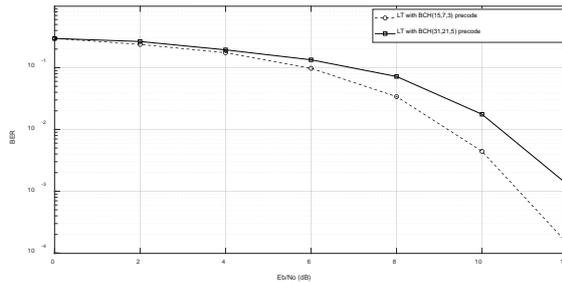


Fig. 5. Performance of LT with BCH (15,7,3) and BCH (31,21,5) precodes in Rician channel

Figures 6 and 7 show the simulation results for LT with BCH(63,36,11) and (127,64,21) in Rayleigh and Rician fading channels, consecutively. The performance of both codes are better compared to the codes depicted in Figures 4 and 5. It is shown that LT-BCH(63,36,11) outperforms LT-BCH(127,64,21) in a Rayleigh fading channel when Eb/No is within the range of 6 to below 16 dB. At Eb/No values of 16-20 dB, LT-BCH(127,64,21) shows better performance than LT-BCH(63,36,11). This indicates that LT-BCH(127,64,21), in addition to having more redundant bits than LT-BCH(63,36,11), also needs high Eb/No values to perform well in Rayleigh fading channel. In a Rician fading channel however, the LT-BCH(127,64,21) shows better performance compared to LT-BCH(63,36,11) when Eb/No values are within the range of 0 to just below 6 dB. At Eb/No = 6 dB, both LT-BCH(63,36,11) and LT-BCH(127,64,21) show the same BER performance. Based from the simulation results, the LT-BCH with high code rates are favorable in fading channels as the short block lengths can handle burst errors effectively.

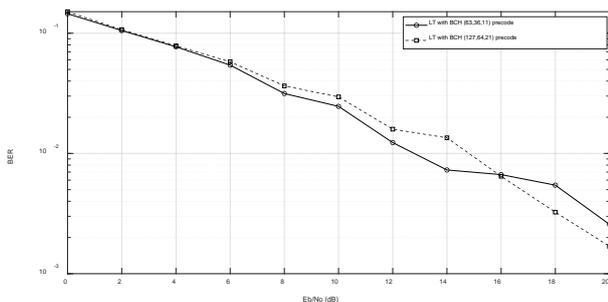


Fig. 6 Performance of LT with BCH (63,36,11) and BCH (127,64,21) precodes in Rayleigh channel

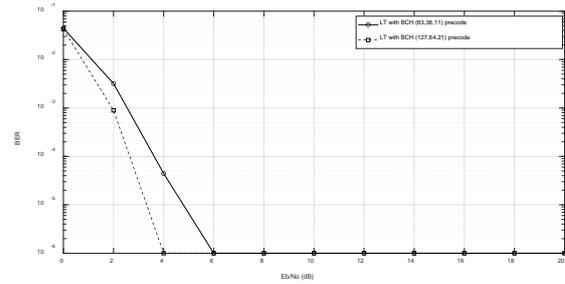


Fig. 7 Performance of LT with BCH (63,36,11) and BCH (127,64,21) precodes in Rician channel

#### IV. CONCLUSIONS

LT codes with different BCH precodes have been simulated and analyzed based on the BER versus Eb/No metric. A simulation has also been done to show that the performance of LT code with BCH precode is better compared to standalone BCH, consistently for Eb/No values ranging from 0 to 20 dB. It is shown that the BCH precodes capable of correcting more erroneous bits, namely BCH (63,36,11) and BCH (127,64,21) when combined with LT codes, will outperform LT codes with BCH (15,7,3) and (31,21,5) precodes. However, the LT-BCH with high code rates are shown to have good performance in fading channels. This error-correcting capability makes LT with BCH precodes a good candidate for WBAN applications, which necessitate low error tolerance.

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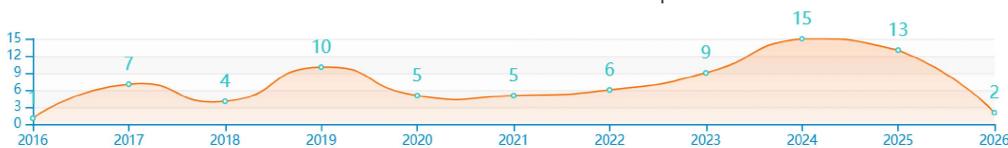
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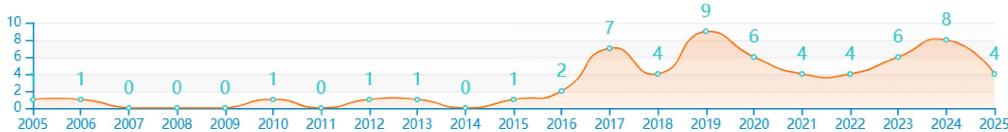
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# Application of LT Code with BCH Precode for Wireless Body Area Network

SARI Lydia, ALAM Syah, MARDIAN Raden Deiny, SURJATI Indra

Universitas Trisakti, Indonesia

Electrical Engineering Department, Faculty of Industrial Technology

Jl. Kyai Tapa 1, Jakarta 11440, Indonesia, E-Mail: lydia\_sari@trisakti.ac.id

**Abstract** – *Wireless body area network (WBAN) is a key component in telehealth system. The reliability of data transmission is of utmost importance in a WBAN system, as a loss of transmitted data or erroneous data at the receiver may lead to diagnosis errors or delayed treatment. As WBAN typically has limited data processing capability and limited energy, the coding schemes for WBAN transmission must be low in complexity. In this research, we propose the use of Luby Transform (LT) code, known for its simplicity and capability to recover data transmitted in erasure channels, combined with Bose–Chaudhuri–Hocquenghem (BCH) as a precode. BCH precode is used to ensure the recovery and correction of the transmitted symbols which are not recovered by the LT code. Simulations are done to compare the BER versus Eb/No performance of standalone BCH code with LT code equipped with BCH precode, as well as the performance of LT codes with various BCH precodes. It is shown that LT with BCH precode outperforms standalone BCH code. It is also shown that BCH with higher error correction capability namely BCH (63,36,11) and (127,64,21) when combined with LT code will outperform LT codes with BCH (15,7,3) and (31,21,5) precodes.*

**Keywords:** *Wireless body area network (WBAN); telehealth; Luby Transform; Bose–Chaudhuri–Hocquenghem (BCH) code.*

## I. INTRODUCTION

Telehealth system based on Wireless Body Area Network (WBAN) has been developed and becoming more common recently, especially considering the high number of people with chronic health problem who reside in remote areas not easily accessible by health professionals [1], [2]. Telehealth system also enables health professionals to assist patients with mobility problems, before health complications occurs. The role of WBAN is critical in telehealth systems. Typically a WBAN consists of sensors, transmitters and actuators worn on, or implanted in the body to transmit physiological data such as heart rate and body

temperature to a receiver in the form of a remote data processor, without being limited to the person's ongoing activities[3], [4], [5], [6]. A reliable transmission scheme is essential in a WBAN to ensure data integrity at the receiver, as a loss of a patient's physiological data during the transmission or erroneous received data may result in diagnosis errors or delayed treatment [7], [8], [9], [10]. Therefore, a channel coding scheme is required to protect the data against noise and interference which will most likely occur during the wireless transmission [11], [12].

The considerations for a WBAN channel coding scheme are decoding complexity and energy efficiency, as WBAN equipment are designed to be lightweight and naturally have limited energy [13]. Luby Transform (LT) code is a type of Fountain code which features low-complexity encoding and decoding process, and is therefore suitable for WBAN applications[11], [14]. LT code uses a degree distribution function for the encoding process. The degree distribution is also the key component to define the complexity and the success probability of the encoding and decoding process [15]. An extension of LT code is Raptor code, where a high-rate code is used to precode the source symbols and produce the intermediate symbols [14]. Subsequently, an LT code is applied to the intermediate symbols to generate the encoded symbols. The precode will recover all encoded symbols which may be left unrecovered by the LT decoders. In [16], Raptor-coded data transmission in WBAN over Nakagami, Rice, and Rayleigh fading schemes are simulated. The performance metrics evaluated are total energy transmission versus transmission distance. Simulations are also done to compare the energy consumption of Raptor-coded symbols and standalone Bose–Chaudhuri–Hocquenghem (BCH) code. The results show that the BCH-coded data require lower energy consumption to Raptor-coded data in short transmission distance (< 10 meters). The energy requirement of both BCH code and Raptor code will increase as the transmission distance increases. However, it is noted that for Raptor-coded data the energy requirement increase is gradual, as opposed to the steep increase shown by the BCH-coded data. The Bit Error Rate (BER) performance is not

studied in [16]. In [17], simulations are done to analyse the performance of Raptor code, BCH code, and Automatic Repeat Request (ARQ) error control scheme in WBAN. The results show that Raptor code is more energy efficient compared to other error control schemes. The energy requirement for LT code is 40% greater than Raptor code requirement, while the BCH code requires 70% more energy than Raptor code. This confirms that Raptor code is suitable for WBAN applications.

Research [18] investigates the performance of Analog Fountain Code (AFC), which is a rateless code equipped with a fixed-rate precode. A density evolution (DE) analysis framework is used to find the optimum weight set of AFC. The proposed optimised weight set is shown to enable the attainment of good performance both in low and high SNRs in the short block regime.

Based on previous researches, both LT and Raptor codes are highly suitable for WBAN applications. To achieve an optimum Raptor code for different channel fading scenarios, the precode to be used with LT code must be chosen appropriately. In this research, we investigate the use of BCH code as a precode to LT code. BCH is known for its capability to correct random patterns of  $t$  errors with simple encoding and decoding algorithms [19], [20]. We compare the performance of the LT code with BCH precoding in terms of bit error rate versus signal-to-noise ratio across AWGN, Rayleigh, and Rician fading channels, which constitutes the novelty of our paper.

This paper is organized as follows. A summary of LT and BCH codes features is given in section 2. The simulation setup and parameters for LT with BCH precode are given in section 3, and the results are described in section 4. The conclusion is given in section 5.

## I. LUBY TRANSFORM (LT) AND BCH CODES

LT code is the first class of efficient Fountain codes which are rateless, meaning that theoretically, there is no limit on the number of encoded symbols resulting from the original data [21], [22]. The decoder can recover the transmitted data from any set of the encoding symbols that arrive at the receiver side. LT code is suitable for use in erasure channels, as the encoded symbols can be generated continuously until all original data can be recovered by the decoder. The LT encoding process can be described in the following steps [21]:

1. Divide the input symbol into  $k$  bits
2. Choose degree  $d$  randomly from a degree distribution
3. Choose  $d$  input symbols randomly, then combine them using XOR operation to form a codeword
4. Each codeword contains  $k$  bits or multiple of  $k$  bits of information and transmitted to the receiver. In different codewords, there are redundant bits which allow the receiver to recover the input symbols even if some codewords are lost or impaired due to noise or interference in the channel.

The encoder uses a degree distribution,  $\Omega(x)$ , which determines the number of source symbols to be combined for each encoded symbol. A commonly used degree distribution is the Soliton Distribution [14], [23]:

$$\Omega(x) = \frac{x}{k} + \sum_{k \geq d \geq 2} \frac{x^d}{d \cdot (d-1)} \quad (1)$$

where  $x = i/k$ , and  $i$  denotes the step number and  $0 < x < 1$ . The encoded symbols can be stated as

$$C = S_1 \oplus S_2 \oplus \dots \oplus S_d \quad (2)$$

where  $S_1$  to  $S_d$  denotes the input symbols as described in step 3 of the LT encoding process. To recover the original symbols from the codewords, the decoder must have information on the neighbours of each received codewords. This information can be sent to the receiver in the form of a data packet containing the codewords information and a list of their neighbours. The decoding process of LT is as follows [14]:

1. Release: all codewords with degree 1, meaning that the codeword is equivalent to the information symbol, are released to recover their neighbours.
2. Cover: all released codewords will cover all of their neighbouring codewords with degree 2. In this step, an input symbol which has been covered but not yet processed is sent to a set called a ripple.
3. Process: an information symbol is selected from the ripple to be processed.

It is apparent that the decoding process can start only if there is a codeword with degree 1.

BCH code is one of the best-known codes for moderate block lengths [24], [25], [26]. The binary BCH code has a block length of  $n = 2^m - 1$  for some integer  $m \geq 3$  and can correct at least  $t$  errors for any  $t = 2^{m-1}$ . For the BCH encoding, the input message of length  $k$  bits is processed to form a codeword of length  $n$  bits, by appending  $n-k$  parity bits. A generator polynomial is used to append the parity bits to the input message to form a codeword. The generator polynomial  $g(x)$  is

$$g(x) = p(x)p_3(x)p_5(x)\dots p_{2t-1}(x) \quad (3)$$

where  $p(x)$  is a dealprimitive polynomial and the other polynomials  $p_3(x^3)$ ,  $p_5(x^5)$ , ...,  $p_{2t-1}(x^{2t-1})$  must be divisible by  $p(x)$ . For a systematic encoding of BCH, we use the relations:

$$p(x)x^{n-k} = q(x)g(x) + r(x) \quad (4)$$

where  $q(x)g(x)$  is the codeword, and  $r(x)$  is a polynomial with a degree less than  $n-k$ . Therefore, the encoded symbol can be stated as

$$c(x) = p(x)x^{n-k} - r(x) \quad (5)$$

For BCH decoding, two steps are done namely syndrome calculation and error correction. In the syndrome calculation stage, the received codeword is evaluated at powers of  $\alpha$ , specifically  $\alpha^i$  for  $i = 1, 2,$

where  $t$  is the number of correctable errors. Assuming that the received polynomial  $y(x)$  is:

$$y(x) = c(x) + e(x) \quad (6)$$

where  $c(x)$  is the codeword and  $e(x)$  is the error polynomial, the values of  $y(x)$  at  $\alpha^i$  where  $\alpha$  is the root of the polynomial, are termed the syndromes and defined by

$$\begin{aligned} S_i &= y(\alpha^i) \\ &= c(\alpha^i) + e(\alpha^i) \quad 1 \leq i \leq t \\ &= e(\alpha^i) \end{aligned} \quad (7)$$

If  $e(x)$  is zero, the syndromes are all zero. The syndrome can be computed from the received sequence  $y(x)$ .

Assuming that there are  $v$  errors in transmissions of  $c(x)$  where  $v \leq t$ , and the location of these errors are denoted as  $j_1, j_2, \dots, j_v$ , where  $0 \leq j_1 < j_2 < \dots < j_v \leq n-1$ , subsequently:

$$e(x) = x^{j_v} + x^{j_{v-1}} + \dots + x^{j_2} + x^{j_1} \quad (8)$$

Using (7) and (8), the syndromes can be stated as

$$\begin{aligned} S_1 &= \alpha^{j_1} + \alpha^{j_2} + \dots + \alpha^{j_v} \\ S_2 &= (\alpha^{j_1})^2 + (\alpha^{j_2})^2 + \dots + (\alpha^{j_v})^2 \\ &\vdots \\ S_{2t} &= (\alpha^{j_1})^{2t} + (\alpha^{j_2})^{2t} + \dots + (\alpha^{j_v})^{2t} \end{aligned} \quad (9)$$

The error locations  $j_1, j_2, \dots, j_v$  can be determined by finding  $\alpha^{j_i}$  from (9), and subsequently bit-flipping is done at the error locations to correct erroneous bits.

## II. SIMULATION PARAMETERS AND SETUP

The simulation parameters to examine the performance of LT code with BCH code is given in Table 1. The performance metric is Bit Error Rate (BER) versus Eb/No. The first simulation is done to compare the performance of standalone BCH code with LT code equipped with BCH precode. The subsequent simulations are done with different BCH code rates as the precode for LT code. The modulation scheme used is BPSK and the channel model used are AWGN, Rayleigh fading, and Rician fading. AWGN channel is chosen as it is a general channel suitable for modelling the transmission channel in a WBAN system, while Rayleigh and Rician fading depict more realistic channel condition compared to AWGN. The physiological data generated by the WBAN sensor is modelled as random binary data sequences, which length is adjusted to the BCH code lengths. To simulate the performance of standalone BCH code, the coded data are simply transmitted through the channel after BPSK modulation. The demodulation and decoding process are done at the receiver, where the decoded data are compared with the original data to calculate the BER. An additional step is taken for the simulations of LT code with BCH precode. For these simulations, the BCH-coded symbols are

processed using LT encoding. At the receiver side, the received symbols are firstly processed using LT decoding. The output of the LT decoder is processed using BCH decoder, to recover any remaining uncovered symbols. The BER is subsequently calculated for each Eb/No value.

TABLE 1. Simulation Parameters

Parameter	Value
BCH Code Length	(15,7,3), (31,21,5), (63,36,11), (127,64,21)
LT Code	Applied with BCH as precode
Modulation Scheme	BPSK
Channel Model	AWGN, Rayleigh, Rician
Number of Simulations	10,000

The BCH encoding algorithm encodes an input message of length  $k$  to yield a codeword of length  $n$ , where  $n > k$ . During the encoding process, the message is represented as a polynomial over a finite field  $GF(2)$  and subsequently multiplied by standard generator polynomials provided by Matlab. The decoding algorithm used is Berlekamp-Massey to find the positions of erroneous bits in the received codeword, and then corrects these bits by performing bit-flipping. A degree distribution function is used to implement the LT code with ideal soliton distribution as a starting point, namely :

$$\rho(1) = \frac{1}{k}, \quad \rho(d) = \frac{1}{d(d-1)} \text{ for } d = 2, 3, \dots, k \quad (10)$$

which ensures that there is at least one codeword that has a degree of 1 and therefore decodable. When the decoding fails after some iteration, the simulation takes an alternative function, which is the Robust Soliton distribution. The robust parameter  $R$  can be stated as

$$R = c \ln(k/\delta) \sqrt{k} \quad (11)$$

where  $c$  is Robust Soliton constant = 0.1 for the simulations, and  $\delta$  is the failure probability and set as 0.1 for the simulations.

The simulations are run for degree  $d = 1$  to  $k-1$ , and because  $d = 1$  has the probability of  $1/k$ , the following steps are used in the simulation:

1. Set  $\rho(1) = \frac{1}{k}$
2. For  $d = 2, 3, \dots, k$ , use Eq.(10)
3. For  $d = 1$  to  $k-1$ , if  $d$  is less or equal to  $(k/R)$  then use:

$$\tau(d) = \tau(d) + \frac{R}{dk} \quad (12)$$

4. For  $d = k$ , the following is used:

$$\tau(d) = \tau(d) + \frac{R}{k} \log \frac{R}{\delta} \quad (13)$$

To yield codewords,  $d$  random input symbols are chosen and XOR-ed with each other. The decoding process is done using a belief propagation approach. For each iteration, the received symbol is evaluated based on its reliability, which threshold can be stated as

$$T = \frac{1}{\sqrt{SNR}} \quad (14)$$

If the reliability of a received symbol is higher than the threshold, it is processed using soft decision decoding. Otherwise, the decoding value will take on the sum of soft decisions for other reliable symbols.

### III. RESULTS

Figure 1 depicts the simulation results of a standalone BCH(31,21,5) and an LT code with said BCH code. At  $E_b/N_0 = 0$  dB, the BER of standalone BCH code is 0.2234 while that of LT with BCH precode is 0.1096. At  $E_b/N_0 = 2$  and 4 dB, the BER of LT with BCH precode are 0.0788 and 0.0467 respectively, lower than the BER of standalone BCH which are 0.1546 and 0.0940. At  $E_b/N_0$  range of 0 to 4 dB, the BER of LT with BCH precode ranges between 50% to 51% of the standalone BCH BER. When the  $E_b/N_0$  values are 6 and 8 dB, the BER of standalone BCH are 0,0305 and 0,0026, respectively, while that of LT with BCH precode are 0.0142 and 0.0013. The BER of LT with BCH precode are 46.55% to 52.3% of the standalone BCH at this  $E_b/N_0$  range. At  $E_b/N_0 = 8$  dB, the BER of LT with BCH code has reached 0 while the BER for standalone BCH still continues to decrease. It is also shown that the LT with BCH precode consistently shows better performance compared to the standalone BCH code in low and moderate  $E_b/N_0$  values, and therefore the subsequent simulations are done for LT code with different BCH precodes.

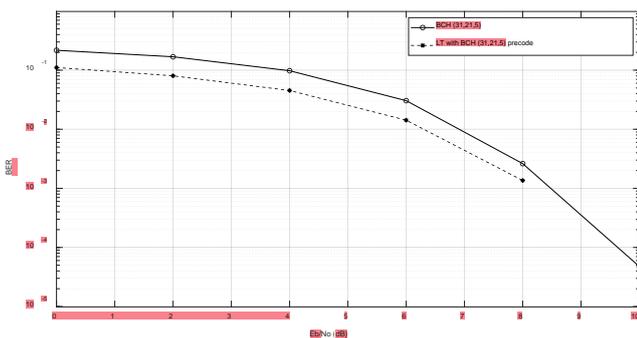


Fig. 1. Performance of BCH (31,21,5) and LT Code with BCH (31,21,5) precode in AWGN channel

Figure 2 shows the simulation results of an LT code with different BCH precodes, namely BCH (15,7,3) and (31,21,5). The BCH(31,21,5) can correct up to 5 errors as opposed to 3 errors that can be corrected by BCH(15,7,3), and this capability is reflected in the simulation results. It can be observed that the LT code

with BCH(31,21,5) precode has lower BER in all  $E_b/N_0$  region plotted, compared to LT code with BCH (15,7,3). The BER of LT code with BCH(31,21,5) is 40% to 69.66% of the LT-BCH(15,7,3) code, with the highest gap observed in the high  $E_b/N_0$  region.

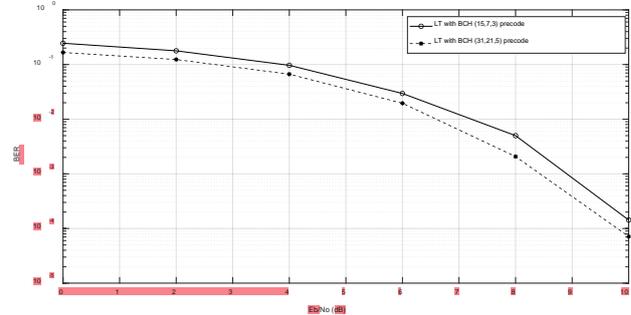


Fig. 2 Performance of LT with BCH (15,7,3) and BCH (31,21,5) precodes in AWGN channel

Figure 3 illustrates the performance of LT codes with BCH(63,36,11) and (127,64,21). At 0 dB, the BER of LT with BCH(63,36,11) is 0.228 while that of LT with BCH(127,64,21) is 0.1556. It is observed that BCH(127,64,21) presents better error protection compared to BCH (63,36,11) for all  $E_b/N_0$  values.

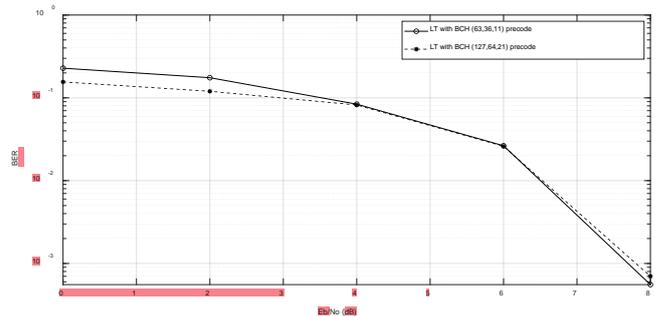


Fig. 3 Performance of LT with BCH (63,36,11) and BCH (127,64,21) precodes in AWGN channel

The simulation results for LT with BCH(15,7,3) and (31,21,5) in Rayleigh and Rician fading channels are given in Figure 4 and 5, consecutively. From Figure 4, it can be observed that the performance of LT-BCH(15,7,3) and (31,21,5) is comparable at low  $E_b/N_0$  region (0-6 dB). The performance of LT-BCH(31,21,5) is slightly better than that of LT-BCH(15,7,3) at very high  $E_b/N_0$  (18-20 dB). A similar result is observed from Figure 5, where LT-BCH(31,21,5) shows higher BER compared to LT-BCH(15,7,3) for all  $E_b/N_0$  values, most notably above 6 dB. This shows that LT code equipped with low coding rate, despite being able to correct more errors, do not necessarily perform well in rapidly changing fading channels. The codes with low coding rates are able to correct a large number of errors spread across the data. However, these codes may not be suitable to correct burst errors that are often introduced during deep fades.

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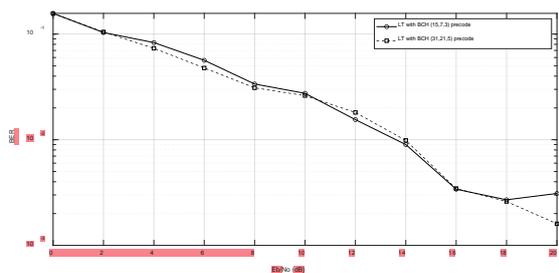


Fig. 4 Performance of LT with BCH (15,7,3) and BCH (31,21,5) precodes in Rayleigh fading channel

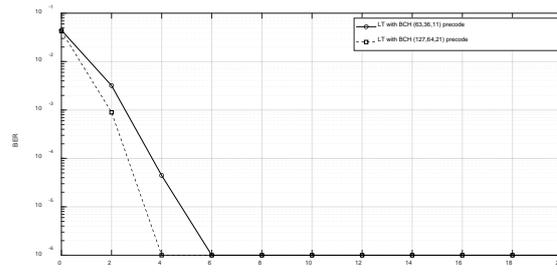


Fig. 7 Performance of LT with BCH (63,36,11) and BCH (127,64,21) precodes in Rician channel

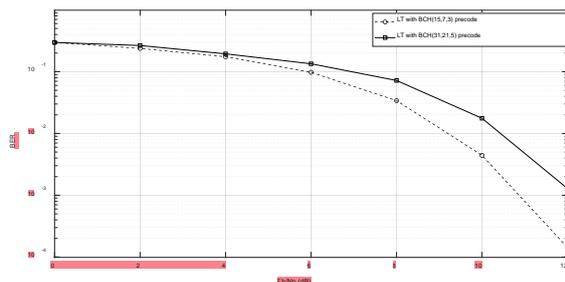


Fig. 5. Performance of LT with BCH (15,7,3) and BCH (31,21,5) precodes in Rician channel

#### IV. CONCLUSIONS

LT codes with different BCH precodes have been simulated and analyzed based on the BER versus  $E_b/N_0$  metric. A simulation has also been done to show that the performance of LT code with BCH precode is better compared to standalone BCH, consistently for  $E_b/N_0$  values ranging from 0 to 20 dB. It is shown that the BCH precodes capable of correcting more erroneous bits, namely BCH (63,36,11) and BCH (127,64,21) when combined with LT codes, will outperform LT codes with BCH (15,7,3) and (31,21,5) precodes. However, the LT-BCH with high code rates are shown to have good performance in fading channels. This error-correcting capability makes LT with BCH precodes a good candidate for WBAN applications, which necessitate low error tolerance.

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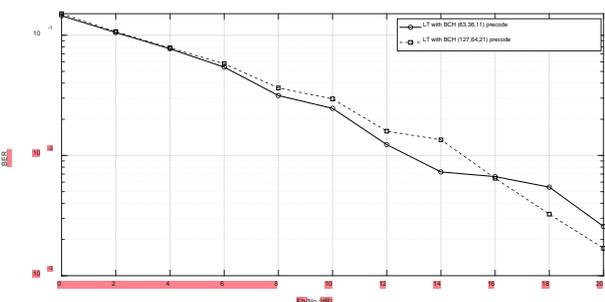


Fig. 6 Performance of LT with BCH (63,36,11) and BCH (127,64,21) precodes in Rayleigh channel

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