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# A COMMUNICATION SYSTEM WITH P-LDPC FOR INTERNET OF UNDERWATER THINGS

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***Abstract*- The acoustic communications are extremely challenging in underwater environments due to harsh conditions of this kind of nature. That medium's harshness affects the transmission reliability which in turn crucially requires an adoption of robust channel codes based on cooperative approaches to attain a more reliable data communication. This study proposes a cooperative communication system based on a protograph low-density parity check (P-LDPC) code. The system is elaborated in an Internet of underwater things (IoUT) scenario in which a relay node is acting as a helper that provides side information to destination. Compression and channel coding are offered by the system to cope with requirements of IoT in terms of reliable communication and compressed data between nodes. Furthermore, an algorithm for joint source channel coding is presented based on a modified version of offset min-sum. Moreover, layered decoding is Implemented in order to minimize number of iterations for the P-LDPC code. The results prove that proposed design can achieve a bit error rate (BER) of $5 \times 10^{-6}$ at signal to noise ratio $SNR = 8$ dB for a coding rate of $1/3$ and block length of 1500 bits. In addition, the proposed system shows a coding gain of $3.6$ dB when compared with a non cooperative (no relay) approach. Besides, the proposed cooperative design can offer reduced computations versus the non cooperative system to achieve the same BER at a fixed SNR.**

***keywords:*** **IoUT, P-LDPC, Cooperative communication, BER, IoT, JSSC.**

## I. Introduction

The idea of the Internet of things (IoT) is conceived by the exponential growing number of Internet-connected physical devices. Recently, the IoT has witnessed a rapid development and allowed various applications in many fields such as smart homes [1], transport systems [2], emergency responding systems [3], automation in industry [4] and healthcare [5]. In addition, the domain of IoT has been extended to the underwater environment which is then termed as the Internet of underwater things (IoUT). The field of IoUT has attracted researchers to explore underwater events. It has become an area to investigate as it aims to connect technologies for sensing and interconnecting underwater objects forming a smart network [6]. Autonomous underwater vehicles (AUVs), smart sensors, developed underwater communication technologies and routing protocols are all playing crucial roles in enabling the IoUT. Applications of IoUT ranges from monitoring environments [7] (e.g., quality of water and submarine creatures), exploring resources [8] (e.g., oil and food), and preparing for disasters [9] (e.g., oil spilling and tsunami) to detecting submarine intrusion [10]. While the environment of underwater brings benefits to people, it also emerges challenges for IoUT evolution. Consequently, implementing land-based models and designs directly into IoUT is not straightforward. For instance, Underwater node's movement in the IoUT caused by underwater currents regularly affects network's coverage and the quality of transmitted data [11]. Additionally, underwater acoustic communication presents limitations in terms of data transmission efficiency due to factors like increased costs, limited bandwidth and data rate, increased bit error rates and slow transmission speeds [12]. However, some of these challenges can be mitigated by employing coding schemes that focus on error correction to mitigate the channel's severe conditions. Furthermore, realizing a relay would help cooperatively with a state-of-the-art channel code to safeguard the transmitted data, against errors occurring during transmission. Additionally, rather than relying on separate source-channel coding, a joint source channel coding technique is proposed to present data compression to obey the huge exchange of data in IoUT applications.

In literature, the benefits of applying cooperative transmission in acoustic networks have been addressed by several studies. In [13], a single-relay node was applied to perform amplify and forward cooperative communication to increase the spatial diversity at receiver. The study in [14] proposed a protocol that reduces energy consumption and decreases delay over acoustic cooperative communications. In [15], the transmission efficiency of acoustic underwater cooperative system was enhanced by proposing a dynamic scheme for transmitting minimized redundant blocks. In [16], the packet loss issue in IoUT was addressed by presenting a cooperative-solution for nodes selection based on k-mean algorithm. Furthermore, several studies discussed the channel coding adoption in underwater transmission. In [17], the research focused on examining Reem Solomon codes and convolutional codes in the UAC condition. The authors worked on creating a channel that can transmit text, images and low bit rate speech using an equalizer to minimize the impact of the channel. In [18], The authors combined space time coding schemes, with multiple-input-multiple-output (MIMO) systems to achieve higher UAC transmission rates. For this study they developed trellis and layered codes with an equalizer at the receiver. To demonstrate its effectiveness practical experiments were conducted on a channel in the Pacific Ocean where they successfully transmitted data at a rate of 48 kb/s within a 23 kHz bandwidth over a distance of 2 km. Another investigation explored LDPC codes, for communications using non binary sources [19].

This paper mainly deals with: (i) building an underwater communication system for IoUT scenario; (ii) adopting a capacity-approaching protograph-based low-density parity check (P-LDPC) error control coding scheme; (iii) deploying a cooperative approach through realizing a relay (sensor) that decodes and forwards data to destination for reliable communication (iv) implementing a layered joint source-channel decoder at receiver to extract original data transmitted over two different underwater channels. The rest of the study is structured as follows. Section II presents the system proposed scenario description and detailed design. Section III provides the impulse and frequency responses for the underwater channel models. Section IV shows the layered joint source channel decoding algorithm. The simulation results and discussion are outlined in section V. Finally, the conclusion is drawn in section VI.

## II. PROPOSED SYSTEM DESIGN

The general scenario considered in this paper is shown in Fig.1. The data transmission is split into two phases. In phase 1, the source transmits its data to the destination as well as to a sensor node via long and short underwater channels, respectively. The sensor can relay the data as well; hence it might be referred to as a relay in the rest of the paper. In phase

 

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2, the relay first decodes the received vector then re-encode it using P-LDPC before forwarding to the destination. The mission of the relay/ sensor is to act as a helper to deliver data to destination via alternative path using acoustic signals.

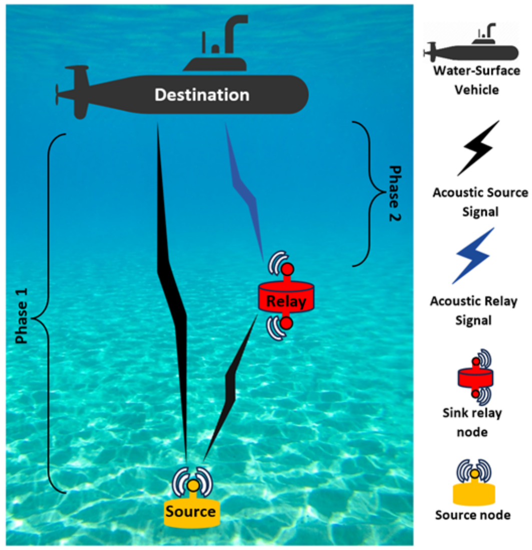


Figure 1: Data transmission in cooperative communication scenario

This study proposes the detailed system design as shown in Fig.2. The cooperative communication is achieved by involving a relay (or sensor) in between the source (or transmitter) and destination (or receiver) for the IoUT scenario. At the source, the information bits are encoded by attaching control bits using P-LDPC code for fighting distortion caused by harsh underwater channels. At this point, an inter-leaver is used for permuting the data to improve the system's protection capability against burst errors may occur. The encoded data are then mapped into M symbols as $b = [b(0), b(1), \cdots, b(\mathrm{M}{-}1)]^T$. Afterward, for the purpose of eliminating inter-symbol-interference (ISI) effect by channel, OFDM is performed by adopting inverse fast Fourier transform (iFFT) and inserting cyclic prefix (CP) and pilots. The CP length must essentially exceed the maximum channel delay [18]. Consequently, first N data symbols are copied as a CP into the original symbols to become as:

$$b = [\underbrace{b(M-N+1), \cdots, b(M-1)}_{CP}\underbrace{b(0), b(1), \cdots, b(M-1)}_{b}]^T \tag{1}$$

Then, the resultant vector is serialized to be transmitted via the underwater channel. The stages of interleaving, mapping and OFDM encoding at the source, and equivalently the deinterleaving, de-mapping and OFDM decoding at the destination, are applied in this paper but not explicitly appeared in Fig.2 for a clearer graph visualization. Moreover, at the source before transmission, the vector is fragmented into two parts: the systematic bits $(d_s)$ and the parity check bits $(d_p)$. The lengths of $d_s$ and $d_p$ are $k$ and $n-k$, respectively, where k is the length of source message bits and $n$ is the P-LDPC block length. For transmission, two phases are involved. In phase 1, the source transmits only $d_s$ chunk to the destination and $d_s + d_p$

 

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to the relay. Since the only systematic bits $(d_s)$ are transmitted to destination, a more effective usage of communication bandwidth can be achieved. In other words, by pruning the parity bits $(d_p)$ before transmission, an implicit compression, or source coding, is offered. On the other hand, this crucial missed portion of data is compensated at destination by the relay to help decode data. In phase 2, the relay first decodes the received vector that contains both systematic as well as parity bits. Then, it re-encodes the resultant data using a P-LDPC code before forwarding it to the destination. The relay is adopted in this proposed system as a cooperative communication to help perform compression or source coding as well as channel coding by providing the destination with necessary side information punctured at the source. Additionally, if an IoUT scenario is present with several source nodes transmitting correlated data, one of the source nodes can act as a relay node which provide side information (i.e.,$d_s + d_p$) to destination while keeping compressing data from remaining source nodes. Furthermore, if a huge number of sensors are deployed, they may be grouped as clusters in which each cluster includes a sensor that behaves as a relay. Finally, both the source and relay transmitted vectors are received to be jointly utilized by a decoder to extract information bits using an iterative algorithm outlined in section IV.

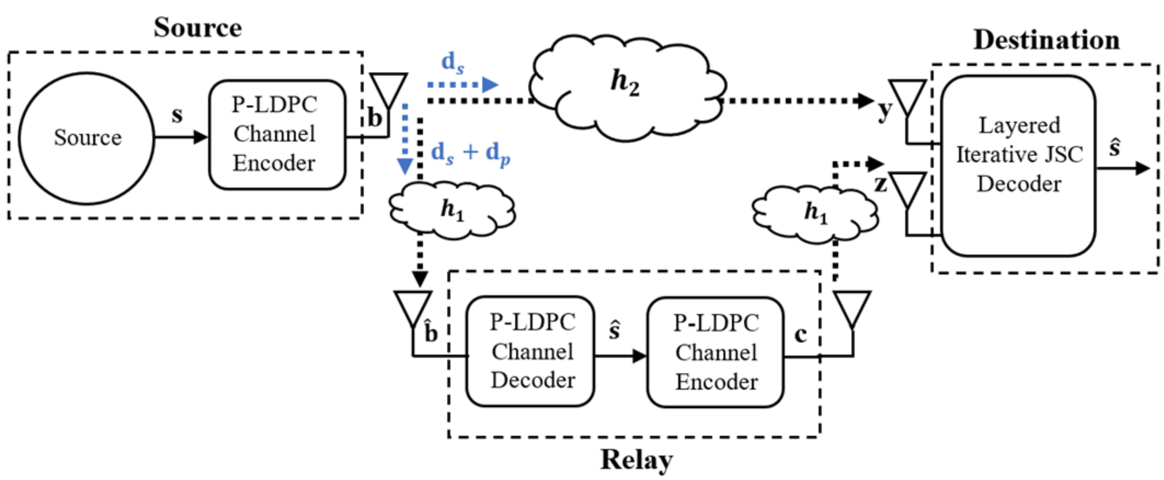


Figure 2: Proposed System Design

## III. UNDERWATER CHANNELS

The transfer function of a multi-path channel is defined in frequency-domain as:

$$H(f) = \sum_p H_p(f) e^{-2j\pi f \tau_p} \tag{2}$$

where $p$ is the path number, $H_p(f)$ is the transfer function of $p^{th}$ path and $\tau_p$ represents the propagation delay of the $p^{th}$ path. In addition, the impulse response of the channel is expressed in time-domain as [20]:

$$h(t) = \sum_p h_p(t - \tau_p) \tag{3}$$

In this study, two underwater acoustic channels are considered, namely $h_1$ and $h_2$. The source-destination $(S - D)$ direct path is defined by $h_2$ while $h_1$ characterizes the source-relay $(S - R)$ and relay-destination $(R - D)$ links. Both underwater

 

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channels are complex and baseband with a bandwidth of 8 kHz. The max spread of delay for $h_1$ is 3.5 ms whereas it is 6 ms for $h_2$. The multi-path components with their delays for both $h_1$ and $h_2$ are demonstrated in Fig.3 which shows the time-domain magnitude impulse responses of channels. Furthermore, the frequency-domain transfer functions of the adopted channels are depicted in Fig.4. Since the relay is assumed, as shown in Fig.2, to sit in between the source and destination in this IoUT, $h_1$ defines a short length channel for $S-R$ and $R-D$ paths whereas $h_2$ is selected as a longer channel for $S-D$ direct transmission. The root mean square ($RMS$) delay spreads for both $h_1$ and $h_2$ are equal to 0.64 ms and 1.1 ms, respectively, obtained using [21]:

$$\tau_{rms}=\sqrt{\frac{\sum_p\left((t_p-t_a)-\tau_m\right)^2a_p^2}{\sum_p a_p^2}} \tag{4}$$

where for each $p^{th}$ path, $a_p$ and $t_p$ represent the amplitude and the arrival time, respectively, $t_a$ is the $1^{st}$ path's arrival time, and $\tau_m$ denotes the average delay which is calculated as [21]:

$$\tau_m=\frac{\sum_p(t_p-t_a)a_p^2}{\sum_p a_p^2} \tag{5}$$

In order to mitigate the severe fading and ISI caused by underwater channels, the duration of CP extension is chosen to be 8 ms. As a result, the CP length becomes longer than the max delay spread of both $h_1$ and $h_2$ which in turn assists reconstruct data at the destination.

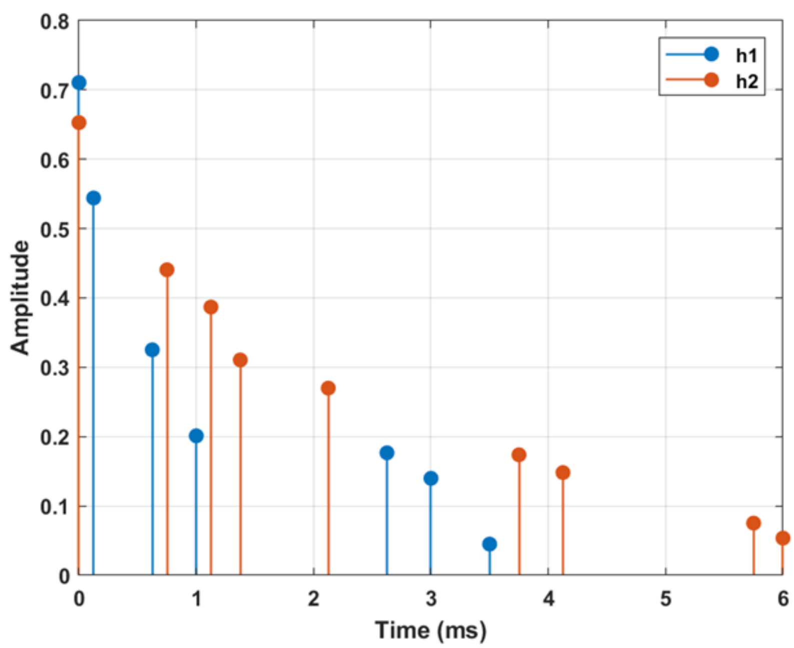


Figure 3: Underwater Channels Impulse Responses

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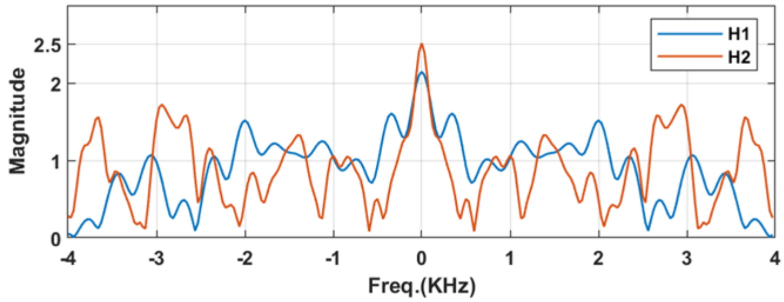


Figure 4: Underwater Channels Frequency Responses.

## IV. JOINT DECODER

The channel coding scheme used in this paper is the LDPC code based on protograph construction that is defined by the 3rd generation partnership project (3GPP) in the fifth-generation new radio 5G-NR standard [22]. The construction of the LDPC H matrix is achieved by selecting one of two base graphs (BG) matrices ($B_1$ or $B_2$). The size of $B_1$ is $46 \times 68$ whereas $B_2$ is dimensioned as $42 \times 52$. The H matrix is created through the replacement of each element in B by a matrix with size $Z_c \times Z_c$, where $Z_c$ is a lifting (or expansion) factor defined in the standard according to a set index. Detailed protograph construction and encoding phase are demonstrated with examples in [23]. For the decoding of P-LDPC used in this study, a modified layered version of the offset min-sum MS (OMS) algorithm [24] is applied with a correction-factor ($\alpha$) added directly to the log-likelihood ratio (LLR) outputs of the check nodes (CNs). First, the codeword $C = \{c_1 c_2 \cdots c_n\}$ is categorized by a $J \times n$ parity-check matrix of an LDPC code. The symbol vector passes through the channel to produce $r_i$ as an input to the P-LDPC decoder, $i \in [1, n]$. Then, the soft-in-soft-output (SISO) iterative decoding is performed based on LLRs exchanged between variable nodes (VNs) and CNs, and that message passing mechanism is prompted by the decoding algorithm defined in Algorithm 1. The set of VNs contributed in CN ($cn_j$) is established as $M(j) = \{i | \, h_{j,i} = 1\}$. Similarly, the set of CNs involved in VN ($vn_i$) is symbolized as $N(i) = \{j | \; h_{j,i} = 1\}$. Furthermore, $L_{ij}$ and $L_{ji}$ are two vectors that represent the LLR information sent from variable-node $vn_i$ to check-node $cn_j$ or oppositely from check-node $cn_j$ to variable-node $vn_i$, respectively.

The flooding and layering are the two mostly deployed mechanisms for scheduling VNs and CNs exchange of updates. In accordance with the 5G NR standard, the layering scheduling mechanism is implemented to improve performance and reduce complexity by minimizing the number of iterations required for decoding convergence. This is achieved through the grouping of rows in the H matrix into layers. For instance, the H matrix depicted in Eq.8 represents bundling two layers for $C_1 \& C_2$ codes associated with $H_1 \& H_2$ parity matrices, respectively. The decoding process follows an approach as described in Fig.5 where variable node updates are represented as LLRs [25]. During decoding, for $C_1$ is initialized with a channel LLR, followed by iterations using $LLR_{21}$. Similarly, this study considers the base graph 2 matrix ($B_2$) to consist of 42 layers/rows. This ensures that the decoding in the 5G standard is processed in a layered manner.

 

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**Algorithm 1: JSC Decoding**

1. Initialize $r_S = y$ from source after CP removal, de-mapping, de-interleaving
2. Initialize $r_R = z$ from relay after CP removal, de-mapping, de-interleaving
3. Buffer the last $(n - \mathrm{k})$ LLR values of $r_R$; that is $r_{RB} = r_R(\mathrm{k}+1)$ to $r_R(\mathrm{n})$
4. Concatenate $r_S$ with $r_{RB}$ to produce a new LLR vector $r_i$
5. *for* each $vn_i, i \in [1, n]$ do
6.     Assign $L_{ij}^0 = r_i$
7. *end for*
8. Set $k = 1$
9. Update $cn_j, j \in [1, J]$ as $L_{ji,MS}^k = \left(\prod_{i' \in M(j) \setminus i} sign\left(L_{i'j}^{k-1}\right)\right) \cdot \min_{i' \in M(j) \setminus i} \left|L_{i'j}^{k-1}\right|$
10. Approximate using $L_{ji}^k = max\{|L_{ji,MS}^k| - \alpha, 0\}$
11. Compute the $k^{th}$ output of $vn_i, i \in [1, n]$ as $L_i^k = L_i^0 + \sum_{j \in N(i)} L_{ji}^k$
12. Calculate $c_i^k = \left(1 - sign(L_i^k)\right)/2$
13. Perform $X^k = C^k H^T$
14. *if* $X^k = 0$, then
15.     set the output $\tilde{C} = C^k$ and finalize decoding
16. *end if*
17. Update $vn_i, i \in [1, n]$ as $L_{ij}^k = L_i^k - L_{ji}^k, j \in N(i)$
18. Increase $k$ by 1
19. *if* $k \leq Iter_{max} + 1$, then
20.     go back to line 9
21. *else* terminate
22. *end if*

Instead of being pending for all rows and columns calculations to output newer updates, this kind of scheduling allows for the updated LLR packets on each particular layer to be utilized within the same iteration to compute a new CN message [25]. Consequently, this paper considers the layered OMS decoding implementation. Furthermore, since the S-D link performs compression/ source coding and the S-R-D path involves channel coding, the destination is utilizing both sides of data receptions for message recovery using a joint source channel (JSC) decoder.

$$H = \begin{bmatrix} H_1 \\ H_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix} \begin{array}{l} \left.\vphantom{\begin{matrix}1\\0\end{matrix}}\right\} Layer\#1 \\ \left.\vphantom{\begin{matrix}1\\0\end{matrix}}\right\} Layer\#2 \end{array} \tag{6}$$

 

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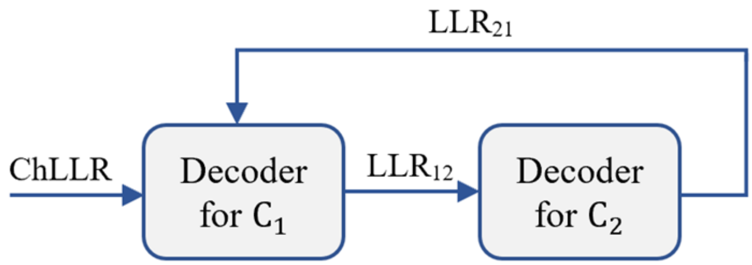


Figure 5: Example of a Layered Decoding Structure

## V. RESULTS AND DISCUSSIONS

The MATLAB simulations were adopted as a tool to evaluate the proposed system's performance in terms of bit error rate (BER) for different signal to noise ratios (SNRs). For the P-LDPC, the base graph 2 ($B_2$) with an expansion (or lifting) factor of$Z_c$=48 were selected. That gave$k \approx 500$ bits and $n \approx 1500$ bits as the information length and the block length, respectively with 1/3 coding rate. Moreover, the maximum of transmitted blocks was maintained $\leq 10000$ and the maximum number of iterations is 15 for the code to converge. In addition, the source, destination and relay underwater nodes were assumed to be semi-static which enables the system to experience a low mobility and minimized Doppler shifts. The P-LDPC-coded output of the source, b is almost 1.5k bits long which is sent as the whole via the S-R link. On the other hand, the parity part ($d_p$) which is approximately 1k bits long is punctured from b before being sent over the S-D path. That results in a compression of data in addition to channel control redundancy offered by the system.

To investigate the cooperative system's behavior, a non-cooperative system (i.e., no relay involved) is considered as reference of comparison. Fig. 6 shows BER performance of both systems for block length of 1.5k bits. The proposed cooperative system offers BER steadily decreases as the SNR rises to achieve$5 \times 10^{-6}$ of BER at SNR=8 dB. Furthermore, it is explicit that the proposed system outperforms the non-cooperative system for all values of SNRs. For instance, to attain a BER of $10^{-3}$, the cooperative system requires 5.4 dB compared with 9 dB for the non-cooperative system, and that results in a coding gain of 3.6 dB. That outperformance of the proposed design is attained because the relay node sits in between the source and destination which means shorter delay spread (i.e., via $h_1$) is experienced compared with the severer direct path (i.e., via $h_2$). This results in a better combat against errors via the S-R-D path and then as a consequence that data is utilized as a side information to support the S-D path at the joint decoder. Moreover, the block length of the cooperative system is doubled to examine its impact on the system's reliability. As shown in Fig.6, at n=3k bits, the system performs better than that at n=1.5k bits as the encoded blocks are longer which allow the system to involve more redundant control bits to fight channel's imperfection.

 

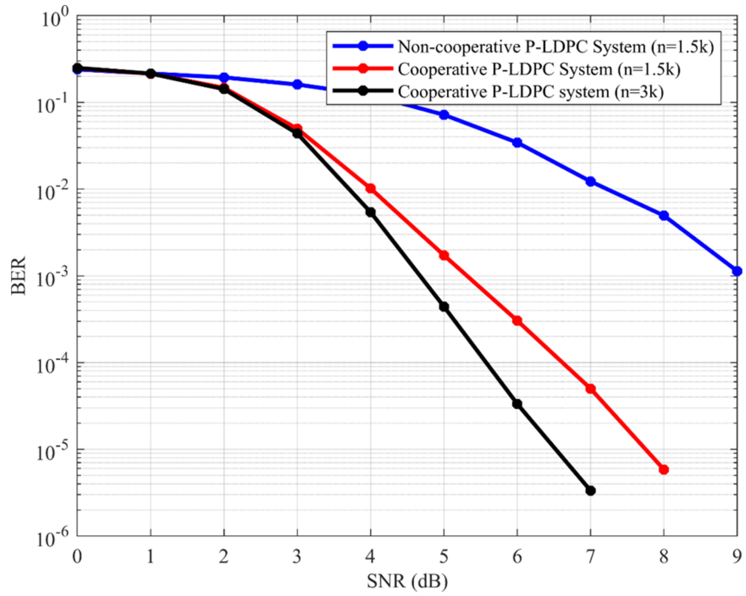


Figure 6: BER performance of the proposed system

In addition, Fig.7 depicts the computational complexity of the system in terms of the number of iterations required by the P-LDPC to achieve a BER level at a fixed SNR value at 8 dB. Generally, it is obvious that the cooperative system requires less computations than the non-cooperative approach to achieve the same BER. For example, it is essential for the non-cooperative system to run 7 to 8 iterations to approximately achieve the same BER level offered by the cooperative system iterated 4 times only. Similarly, 12 iterations offer a BER of 0.009 and 0.00001 for the non-cooperative and cooperative systems, respectively.

 

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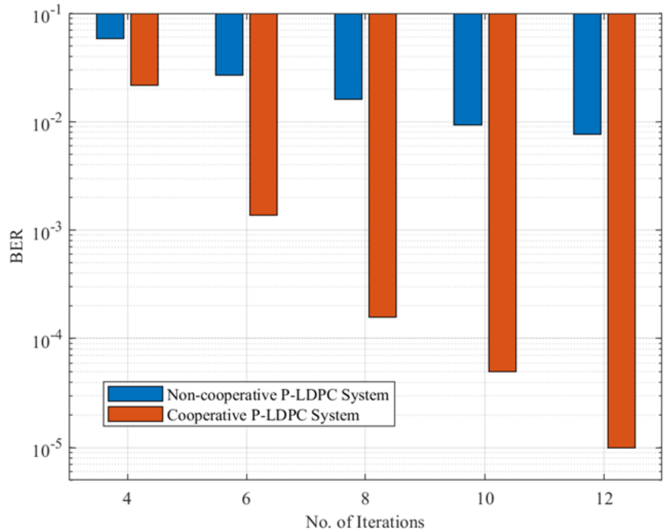


Figure 7: Computation Complexity for fixed SNR=8 dB

## VI. Conclusion

This study involves the implementation of a cooperative communication system based on P-LDPC codes applied at the source and relay in an IoUT scenario. The relay acts as a helper that aids the joint source channel decoder to reconstruct the information at the destination node. The system is beneficial in terms of providing both data compression as well as data channel protection for a reliable transmission. The simulation results proved the proposed design's functionality via offering a BER of $5\times10^{-6}$ at SNR=8 dB. Furthermore, a 3.6 dB coding gain at BER $=10^{-3}$ is achieved by the suggested cooperative design when compared with a non-cooperative approach. The design presented in this study contributes in meeting some of IoUT constraints such as (i) compressing data to cope with huge data exchanges among IoT nodes; and (ii) protecting data while transmitting among nodes in underwater harsh conditions to offer reliability; and (iii) possibly involving one relay in a cluster of many source nodes when they transmit correlated data. As future works, further investigation can be made. Firstly, the general information binary bits to be replaced with images to explore the proposed system's performance for image transmission. That in turn will prompt the privilege for investigating parallel hardware implementation using a field programmable gate array (FPGA) [26] to utilize parallelism that fits P-LDPC layered iterative structure. Additionally, once the node mobility is getting higher rather than the semi-static state assumed in this study, that leads to critical severity of channel effects due to Doppler shifts. In consequence, implementing adaptive algorithms [27] become crucial to compensate for that Doppler effect in such an acoustic underwater environment. Finally, deeper evaluation for the proposed system can be elaborated by applying two P-LDPC codes, one for channel coding and another for source coding. Then, those two codes are decoded at the receiver using two tanner graphs instead of a single one for further BER enhancement but with a possible complexity increase.

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**CONFLICTS OF INTEREST**

The author declares no conflict of interest.

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