

# A Comparative Study on Channel Coding Scheme for Underwater Acoustic Communication

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## Research Article

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# **A comparative study on Channel Coding Scheme for underwater acoustic communication**

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## **Abstract**

There are various challenges in underwater acoustic communication (UWA) however bit error rate (BER) is considered as the main challenge as it significantly affects the UWA communication. In this paper, different coding schemes such as Convolution, Turbo, LDPC, and Polar coding based on the t-distribution noise channel are investigated, and binary phase-shift keying (BPSK) modulation with a code rate of 1/2 has considered in the evaluation and analyses. The evaluation of these channel coding schemes is performed based on BER, computational complexity as well as latency. The results have shown the outperform of polar coding in UWA over other channel coding schemes as it has lower BER and lower computational complexity.

**Keywords:** Channel coding scheme; underwater acoustic; Convolutional; LDPC; Turbo; Polar; t-distribution.

## **1. Introduction**

Under water explorations, subsea resource extractions, pollution monitoring, national defence missions etc. are being critically analysed by underwater acoustic communications (UWAC) and networking technologies. The applications of UWAC have attracted increased interests as the oceans are explored as a sustainable source of food and energy [1], [2],[3]. Communications across shallow seawater channels are characterized by high multipath, high noise level, strong Doppler and other complex random transmission features. These complicate underwater communication (UWC) in terms of reliability and a low data rate compared with wireless communication [4].

Recent research focus on acoustic communications has sought to address issues such as reliability, latency, and bandwidth efficiency, where adaptation to the changing propagation conditions is the main focus [2]. In the systems' designs, the nature of the acoustic propagation forces trade-offs on the various issues depending

on the requirements. For instance, reliability is a trade-off for a high data rate while latency is traded for full reliability. Moreover, a low computational complexity is required to achieve a high-speed data rate system. Thus, in channel coding, computational complexity and reliability are compromised with respect to each other depending on the systems' design. Figure 1 demonstrates the trade-off between reliability, latency and computational complexity considered in channel coding techniques. These channel trade-offs and constraints are challenging; however, acoustic channel exhibit peculiar challenges and solutions. This paper considers a user requirement channel coding scheme for UWAC system of lengthy message transmission.

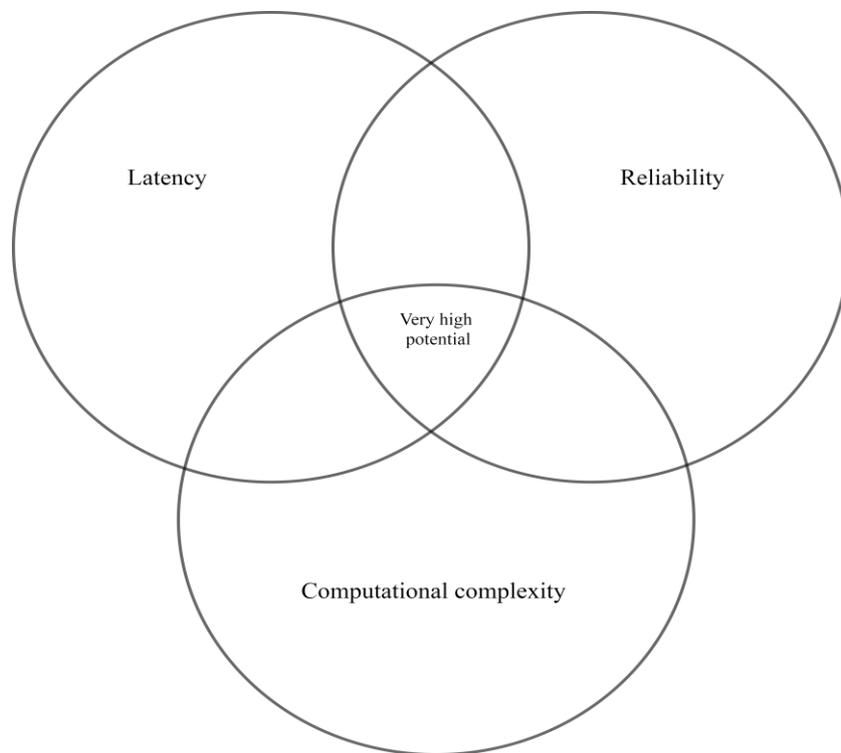


Figure 1: Requirements for the channel schemes for UWAC

In this work, different channel coding schemes, turbo, convolution, LDPC, and polar codes are considered and evaluated for application in the transmission of lengthy messages ( $256 < K \leq 1024$  bits) with respect to user requirement of complexity, BER and latency performance on the t-distribution of noise channel with Binary phase-shift Keying (BPSK) of code rate 1/2. Next, Section 2 presents the channel model in UWA while Section 3 describes the channel coding schemes. The results and analyses are given in Section 4 and finally, 5 concludes the research.

## 2. Channel model in UWA

Based on the analysis of the field data measurements in a shallow water, a noise model of the underwater acoustic channel is presented in [5]. The likelihood density function has been proposed for the noise amplitude distribution and the probability functions have been derived in [5],[6]. Hence, for binary signalling of the channel, an expression to the symbol error probability is presented. The noise data collected from a shallow water was also simulated to show the noise effects on the performance of binary signalling system of UWAC. In addition, t-distribution was used to show good fitting of the field measurement analysis of the amplitude of the noise distribution with average degree of freedom of about 3. Equation (1) expresses the symbol error probability of the binary UWA noise channel.

$$P_{BPSK} = 0.636 \sqrt{\frac{2E_b}{N_o}} \int_0^{\infty} \left[ 1 + \frac{2E_b}{N_o} (x+1)^2 \right]^{-2} dx \quad (1)$$

where  $x$  is a vector of  $M$  discrete amplitude levels of noise, and  $b_o/E_N$  is the energy per bit to noise power spectral density ratio. Some researchers have indicated that the noise distribution in shallow water follows the Gaussian distribution while others assume the noise distribution in UWA is non-white and non-Gaussian [7],[8].

## 3. Channel coding schemes

In channel coding, redundancies are added to some useful bits to secure the data in a noisy channel and to reduce transmission errors to the minimum regardless of its intricacies in communication systems. The main step of the channel coding procedures is partitioning the coding into several subsets. There are four common kinds of the channel coding schemes and these are convolutional codes (CC), turbo codes (TC), polar codes (PC) and low density parity check (LDPC) code [9]. Figure 2 depicts the digital communication system block diagram of the different channel coding schemes. The most important aspect of channel coding is its ability to provide the satisfaction for user requirements.

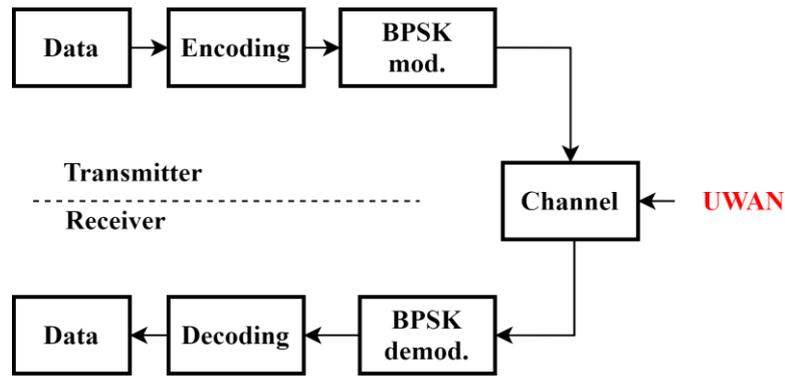


Figure 2: Digital communication system block diagram of the channel coding schemes

### 3.1 convolution code

Convolution code (CC) is a division of linear error-code broadly applicable to systems such as IS-95 based narrow band CDMA, GSM and WCDMA [10]. A set number of the shift registers is used to develop the convolutional encoder. Each of the input bits is made to enter the shift register with the encoder output obtained from the combination of the bits in the shift register. Three parameters, the output bits,  $v$ , input bits,  $u$  and the number of memory registers,  $m$  are used to define CC [11]. The code rate,  $R = u/v$  gives the coding efficiency with values of  $u$  and  $v$  ranging from 1 to 8 and 2 to 10, respectively. One CC defined as CC (7, 5) was used. Using trellis representation by employing four states following the CC order, Viterbi algorithm was utilized for the decoding.

The decoding could be soft or hard. In hard decoding, only binary values are used, but real values, generated by the output equalizer, are utilized in soft decoding. However, sequential decoding comes with a disadvantage of returning a random variable of the searched number of state metrics [12]. The increasing value of the look-ahead length of the feedback decoder not only increase the coding gain but also increases the complexity of the decoding implementation [13]. With the Viterbi algorithm, exponential decrease in the error probability with increasing number of code states,  $S$  and constraint length,  $u$  is its disadvantage. Some research works such as those presented in [14],[15] have utilized CC in underwater acoustic with  $u$ -order code implemented by several options. Figure 3 shows the best polynomial, which is arrived at by simulations, and trial and error method [16].



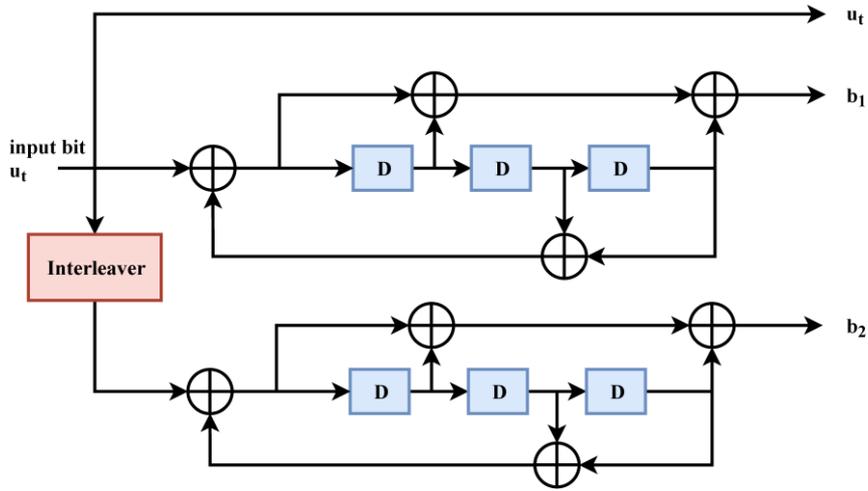


Figure 4: Turbo code structure [11]

Nevertheless, turbo coding is faced with a major challenge of characteristic delay linked with both the decoding algorithm and the interleaver [10]. The associated high implementational complexities could make the block lengths and code rates fail to satisfy the requirements of UWA [18]. Several submissions have been made on turbo codes and its use in UWA [5],[10],[19].

### 3.3 LDPC code

A class of linear error-correction code, Low-Density Parity Check (LDPC) matrix code, was in 1962, introduced by Gallager [20]. It is characterized by a sparsed parity check matrix  $H$ . WiMAX and DVB-S2 adopted LDPC code. LDPC code can be considered regular or irregular LDPC codes [21]. It is regular when  $H$  has equal number of ones in each column,  $w_c$  and the equal number of ones in each row,  $w_r$  [22]. An example of regular binary LDPC codes [21] is the original Gallager codes [20]. Although, it has generally very large size of  $H$  matrix, it has very low the density of the nonzero element [12]. LDPC code of length,  $n$  can be written as  $(n, w_c, w_r)$ . Thus, each information bit is characterized by  $w_c$  parity checks while each parity check bit is characterized by  $w_r$  information bits [12]. An algebraic construction can be used to represent the parity check matrix,  $H$  [21], and by Tanner graph [21]. In this case, the variable or bit nodes (VN or BN) in Tanner graph is equal to  $w_c$ , and the check nodes (CN) is equal to  $w_r$  connected by 1s in the  $H$  matrix. The representation of Tanner graph is shown in Figure 5. An example of  $H$  matrix algebra representation is given in equation (2) [21].

$$H = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 0 \end{bmatrix} \quad (2)$$

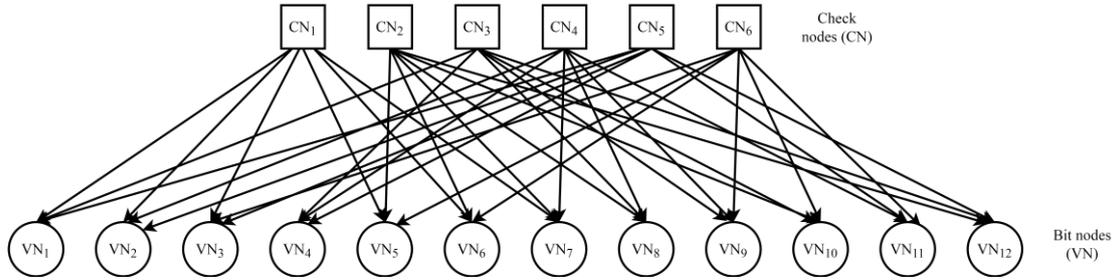


Figure 5. Tanner graph of the example  $H$  matrix

LDPC is a simple code which is characterised by linear time encoding and decoding with high efficiency and low complexity compared with turbo code. LDPC code is a high-performance coding scheme of RF communication, however, it is not used in the UWAC. This is because firstly, a long package (about 1000 bits) is needed whereas the UWA communication commonly adopts a short package since the channel is characterised by variable propagation delay and low communication rate [10]. Secondly, it requires more iterations which makes it more complex as compared to other simplified codes [23].

### 3.4 Polar code

In 2009, polar codes (PC) were invented by Erdal Arikan [24]. This class of linear error-correction code was introduced based on polarization technique, a new concept. PC became active research focus as soon as they were invented. This is owned to the fact that PC demonstrate promising outcome with increasing capacity. They have shown better performance over other coding techniques and hence, extended to cover a number of applications and generalizations as presented in [25]. PC offer very low complexity and explicit construction encoding and decoding. Furthermore, arbitrary design of the code rate of a PC is possible making it more flexible for applications to various scenarios, such as security coding on the physical layer [4]. PC can be defined as  $(N, K)$  with  $N$  and  $K$  denoting the encoded block and the information block lengths, respectively.  $N = 2^n$ , and  $n \geq 0$  where  $n$  is a natural integer [27]. The remaining  $N - K$

indices is called the frozen bit indices [27]. Channel polarization transform is used to construct the PC [26] with the polarization transform being the encoder, which is given by the kernel of equation (3) [24].

$$F = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \quad (3)$$

For larger input size, the transform is found the Kronecker product of this kernel with itself. This causes the PC to have lengths of powers of 2. For a code of length  $N$ , and  $n = \log_2(N)$ , the encoder is given by equation (4)

$$G = F^{\otimes n} \quad (4)$$

where  $F^{\otimes n}$  is the Kronecker product of  $F$  with itself for  $n$  times. The encoding is then carried out as in (4), which is shown in Figure 6 for a code of length 4. In this study, the technique of Successive Cancellation (SC) decoding is applied as the decoder for the PC due to the regular structure of the PC.

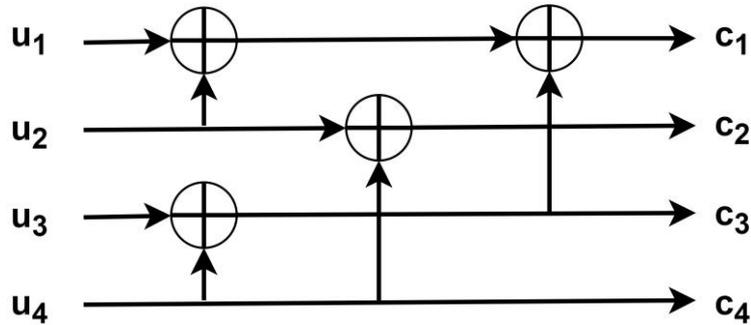


Figure 6. Polar encoder of length 4.

#### 4. Results and Analyses

This section presents the outcomes of UWA system simulation to evaluate the performance of channel coding schemes based on t-distribution of the noise channel. Table 1 shows the simulation parameters applied for the communication scheme. The analysis of UWA system is evaluated in three phases. Firstly, BER reduction of CC, TC, LDPC and PC is assessed and compared with the signal to noise ratio (SNR). Secondly, the computational complexity level was analysed and lastly, the decoding latency of the channel coding schemes is investigated and discussed. The results of the simulations were retrieved from simulation in MATLAB using the adopted BPSK with code rate 1/2.

Table 1. Simulation parameters for the baseline

Parameters	Values
Modulation constellation (M)	BPSK
Degree of freedom ( $d$ )	3
Channel	t-distribution noise
Code rate	1/2
Channel decoding algorithm	CC(Viterbi) TC(MAX-Log-MAP) LDPC( MSP) PC(SC)
Message length	256,512, and 1024

#### 4.1 BER performance

For UWAC system of message transmission, BER reduction is the first requirement of the channel coding. The reliability is then evaluated based on BER comparison of CC, Turbo, LDPC, and PC schemes for the UWAC. This is done for the transmission of different lengths of messages using the parameters as determined in Table 1. The simulation results for all the schemes are depicted in Figures 7 through 9. These results are compared with the uncoded schemes by theory and simulation for the length of message ( $256 \leq K \leq 1024$  bits) at code rate 1/2. Good performance for UWA based on TC, LDPC and PC are depicted in Figure 7 where the BER of all the schemes is less than  $10^{-4}$  for channels with low SNR (0 to 3dB), which notably outperforms the CC.

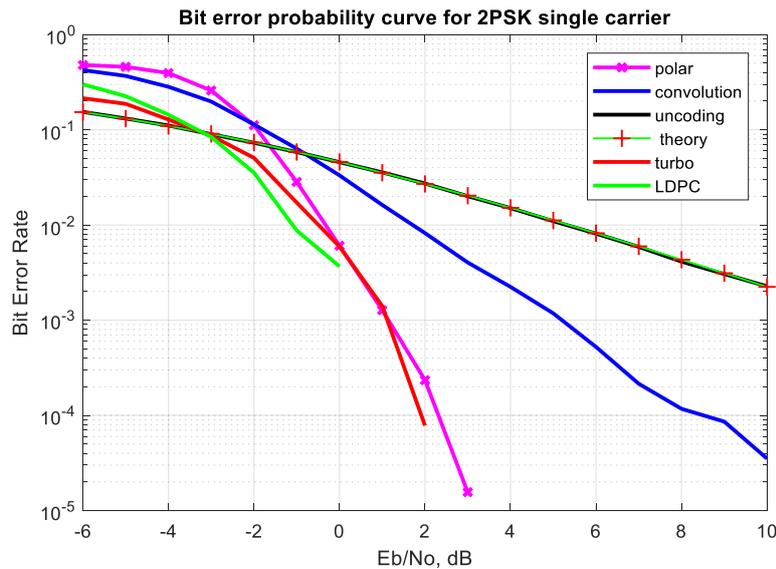


Figure 7: BER performance evaluation for different channel coding schemes ( $K = 256$  bits)

From Figures 8 and 9, it is clear that polar code scheme is more significant (BER performance is  $10^{-3}$  at SNR -1 dB) than TC, LDPC, and CC schemes for different message lengths ( $512 \leq K \leq 1024$  bits) at code rate of 1/2. The PC scheme has better reliability with an improvement of 1.5 dB channel gain compared with TC scheme at length  $[K = 512 \text{ and } 1024 \text{ bits}]$  because the SC decoder of polar code has an acceptable performance in short length messages however, it achieves better results in longer length messages. Also, Figures 8 and 9 reveal that BER of  $10^{-4}$  at message  $K = 512$  and 1024 bits is achievable using the TC. Since the message length is short and TC is characterized by random interleaving, the random position in the medium is not really very random. Furthermore, the decoding capability is limited by punctured TC to correct the errors emanating from the removal of some of the parity bits.

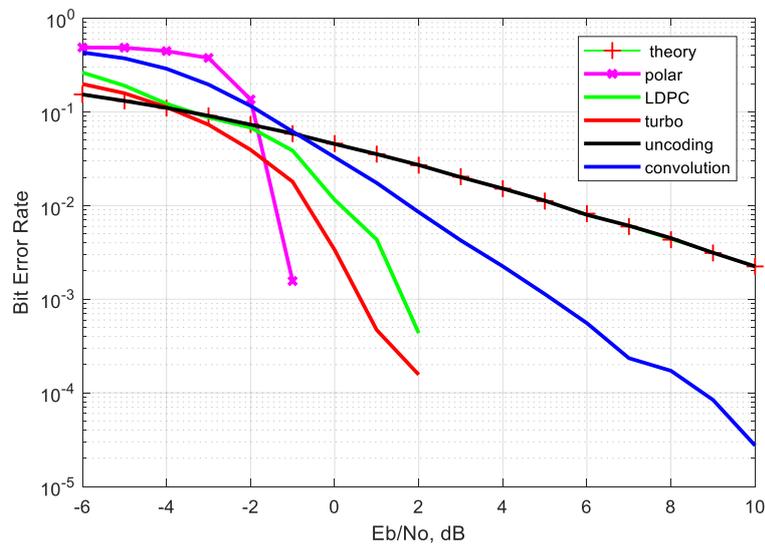


Figure 8: BER performance of different channel coding schemes for  $K = 512$  bits

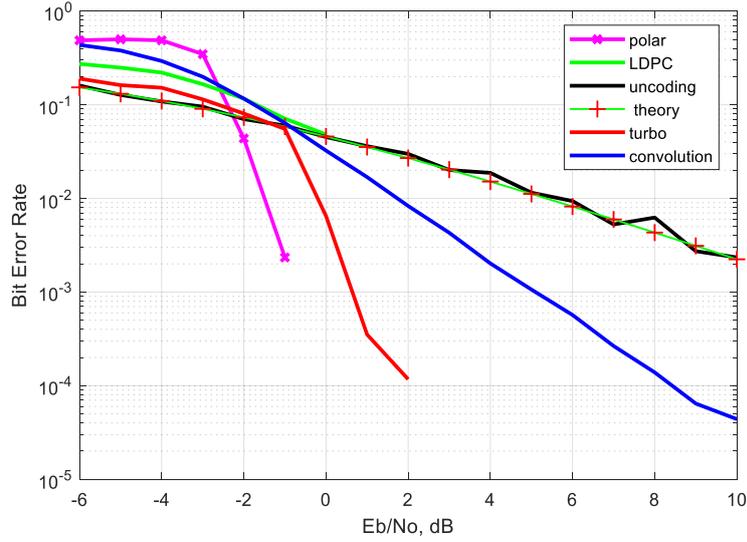


Figure 9: BER performance of different channel coding schemes for  $K = 1024$  bits

## 4.2 Complexity

The computational complexity is an essential performance metric to be evaluated in codes building and its applied especially in UWA. Therefore, in this paper, the complexity evaluation is analysed and discussed, which is important in examining the computational complexity in the encoding and decoding techniques. In this section, it is required to understand the complexity of the decoding algorithm used to evaluate and find the iteration number identical to providing fair comparison for different schemes. The decoding complexity can be evaluated through multiple mathematical operations such as addition, subtract, multiplication, division, and comparison. Based on code building, different result conclusions can be obtained.

The parameters related to the computational complexity of the PC scheme is calculated and compared with TC, LDPC and CC schemes. Table 2 presents the equations used in the determination of the number of operations for the various schemes. The parameters  $K$ ,  $R$  and  $N$  denote the information block length, the code rate and the encoded block length respectively [27] [24]. Additionally,  $m$  represents the memory length of the component for TC and CC [28],[29];  $d_c$  and  $d_v$  represent the average check degree and average variable degree respectively for LDPC scheme [30], while  $I_{max}$  stands for the maximum number of iterations.

Table 2. Computational complexity of polar code, turbo code and some of the previously channel code methods in literature

Method	Computational complexity
Polar [24]	$O(N \log_2(N))$
Turbo [27]	$I_{max} \times 16 \times K \times 2^m + I_{max} \times 8 \times K \times 2^m$
LDPC [30]	$I_{max} \times 2 \times N \times d_v + M \times (2 \times d_c - 1) + I_{max} \times M \times d_c$
Convolution [28]	$4 \cdot R \cdot N \cdot 2^m$

Table 3 shows the comparison of the computational complexity of each studied channel coding scheme with TC scheme. It can be seen that the computational complexity of PC scheme is kept lowest as compared with other coding schemes along with the variation of K parameter. This could be attributed that the PC scheme is constructed based on simple algorithm (Successive Cancellation). Therefore, it is implemented efficiently by the factor graph of the code that has a structure resembling the Fast Fourier Transform (FFT) [24]. On the other hand, the coding schemes of TC and LDPC show higher computational complexity compared with PC and CC schemes. This is because, they construct base on an iterative algorithm with high number of iterations leading to increase in the computational complexity. The comparison is clearly illustrated in Figure 10.

Table 3. comparison of the computational complexity of polar code and turbo code

Code Scheme	Parameters							Complexity	Complexity Ratio w.r.t. Turbo decoder (%)
	$K$	$m$	$d_c$	$d_v$	$N = (K/R)$	$R$	$I_{max}$		
Turbo	256	3	-	-	-	1/2	8	393216	100
LDPC		-	7.17	3.58	-		16	142663.68	36.28
CC		6	-	-	512		-	65536	16.66
Polar		-	-	-			-	4608	1.17
Turbo	512	3	-	-	-	1/2	8	786432	100
LDPC		-	7.17	3.58	-		16	285327.36	36.28
CC		6	-	-	1024		-	131072	16.66
Polar		-	-	-			-	10240	1.30
Turbo	1024	3	-	-	-	1/2	8	1572864	100
LDPC		-	7.17	3.58	-		16	570654.72	36.28
CC		6	-	-	2048		-	262144	16.66
Polar		-	-	-			-	22528	1.43

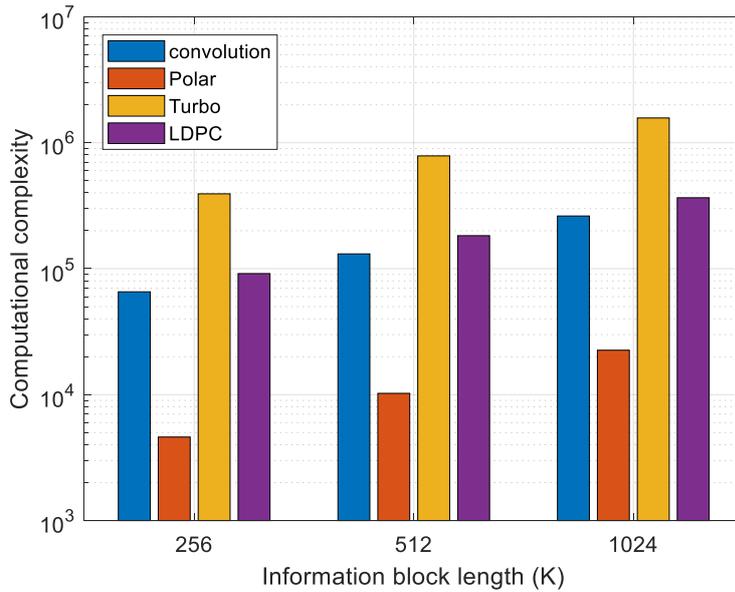


Figure 10. Computational complexity versus information block lengths, K for various techniques with coding rate of  $R = 1/2$ .

### 4.3 Latency

Latency is considered as the third requirement for the implementation of UWA communication channel coding schemes. It is defined as the time taken for the message bits transmitted over all communication blocks as displayed in Figure 2. In this section, the latency is evaluated and compared in terms of different channel decoding schemes such as polar, Turbo, LDPC and Convolution coding. The MATLAB functions *tic* and *toc* are used to calculate the decoding latency time with taking in consideration the type of processor used in the simulation. The simulation result shown in Figure 11 is the computational latency of the different channel coding schemes of UWA for transmitted message length of  $256 \leq k \leq 1024$  bits at code rate of  $1/2$ . The PC gives higher decoding computational latency compared with the other coding schemes as a result of the serial decoding by SC algorithm. It is time-consuming and could get worse with an increasing code length, N.

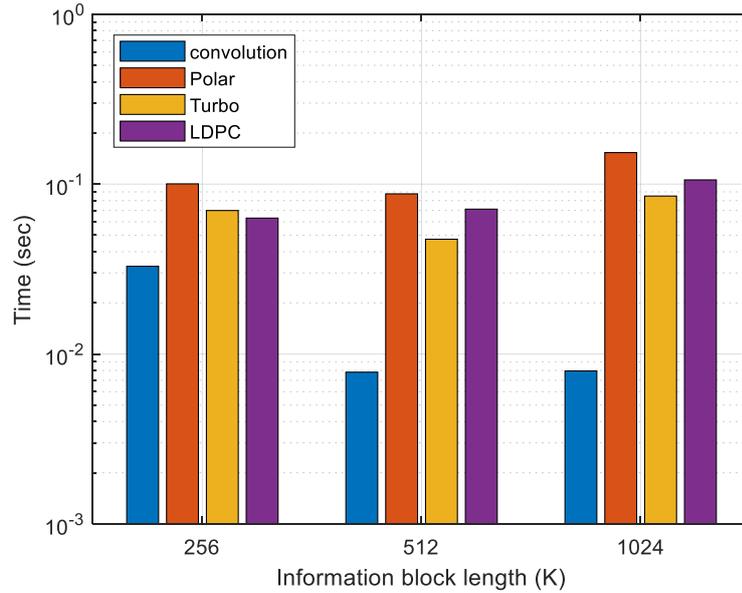


Figure 11. Decoding computational latency

Figure 11 also shows TC (MAX-Log-MAP) and LDPC (MSP) give have a higher decoding computational latency than CC (Viterbi) owing to the associated iterative algorithms. Higher decoding computational latency is given by the LDPC (MSP) compared with the TC (MAX-Log-MAP) since LDPC (MSP) requires more number of iterations ( $I_{max}=16$ ) than the TC ( $I_{max}= 8$ ). However, if the system can tolerate large time delay and complexity, TC will be considered one of the competing error correction codes.

## 5. Conclusion

In conclusion, different channel coding schemes of convolution, Turbo, LDPC, and Polar coding were analysed for UWA system based on the t-distribution noise channel with BPSK modulation. The evaluated results of the different coding schemes show that polar coding is the optimum channel coding scheme for UWA as it fulfils user requirements in terms of BER reduction and low computational complexity. Moreover, other requirements such as application type, quality, cost, and data transmission rate are often considered in the choice of channel coding techniques. For instance, the high-speed data rate requires low computational complexity, whereas an excellent BER reduction performance is needed for high-quality. Hence, there is always a trade-off between computational complexity and BER reduction

performance in the channel coding techniques. This must be kept firmly considered in the choice of channel coding technique for BER reduction.

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