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Enhancement of code division multiple access system performance using raptor codes

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ABSTRACT

Some kinds of communication systems work in very low signal-to-noise (LSNR) environments. For these systems to function reliably, specific techniques and methodologies have to be used to mitigate the degrading effects of the channel. The channel coding method is the key element in most LSNR communication systems, but emphasizing the code division multiple access (CDMA) is a new transmission technique in these channels. To enhance the CDMA scheme's system capacity and reach unprecedented ranges of LSNR values in wireless sensor network. This paper suggests combining CDMA with certain types of channel coding algorithms, such as the raptor codes. The raptor channel encoding technique has improved the CDMA system's performance when using binary phase-shift keying (BPSK) modulation in additive white gaussian noise (AWGN) channels. It has achieved a low bit error rate in range of 10-7 at Eb/No value of (-3) dB and about 10-6 at shannon's limit. The Raptor-coded CDMA scheme works well for channel signal to noise ration (SNR) values of greater than -9 dB, showing an improvement of about 7 dB compared with turbo/convolutional channel coding methods used with the CDMA system bit error rate (BER) and throughput. On the other hand, it has been shown that the convolutional encoder presents the weakest performance compared to both the turbo and raptor codes.

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1. INTRODUCTION

Wireless sensor networks (WSNs) have become an attractive research topic in recent years. It is considered one of the most promising technologies due to its distinctive properties like low cost, flexibility, and ease of development. WSNs are used in various applications, including medical monitoring, military operations, security, environmental monitoring, and industrial surveillance [1]. It consists of massive, small, cheap, and intelligent sensor nodes that can sense, process, and send the gathered information to the base station [2]. The massive growing preference for a wide range of wireless application, each with its own set of needs in terms of service quality, has led to the search for new technologies to enhance the capacity of digital communication systems. Wireless technology's current state is essential for significant improvement [3]. In the third and fourth generations of mobile communication systems, Code division multiple access (CDMA) supports multiusers with varying rates and quality of service (QoS) demands in the same bandwidth and time [4]. Because of its many benefits over other multiple access systems, direct sequence code division multiple access (DS-CDMA) has grown in prominence in recent decades [5]. In DS-CDMA technology, each user is assigned a unique code. The code assigned to the user is essential for modulating the signal since the overall system performance depends on it. Depending on the type of CDMA technique, different codes can be used. In a synchronous system, orthogonal codes like (orthogonal variable spreading factor (OVSF) codes and hadamard codes) have been used, while pseudo-random codes or Gold codes have been used [6], [7]. Channel coding can minimize multi-access interference (MAI) by decreasing the transmitted power at the expense of increasing the transmitted signal bandwidth through the redundant codes. Also, by employing efficient coding algorithms with error-correcting capabilities and high coding gain, system performance can be improved by minimizing the bit error rate [7], [8]. There are two types of channel codes: block codes and convolutional codes. The Viterbi algorithm is the most widely used decoding approach for convolutional codes. The convolutional codes have been used extensively to provide reliable channels with a low signal-to-noise ratio (LSNR) [9].

In the paper, Shah *et al.* [10] turbo code is an error correction algorithm that sends data over a channel with a very low bit error rate. This code comprises two-block convolutional codes concatenated in parallel and separated by a random interleaver [11], [12]. In the paper, MacKay [13] fountain code, also referred to as rateless code, is a new member of the channel coding family that can produce an infinite number of encoding symbols from a set of source symbols *k*. In the paper, MacKay [13] demonstrates the essential advantages of fountain codes related to efficiency, durability, and reliability over the AWGN channel and fading channels [14], [15]. The luby-transform (LT) codes are a practical class of fountain codes. LT codes have been used to increase the likelihood of the distribution for the rateless code [16]. These codes can recover the source information from any set of the output symbols whose size is near the ideal value [17] LT codes with direct time encoding and decoding outperform low-density parity-check (LDPC) codes in bursty channels [18]. Raptor codes, introduced by A. Shokrollahi, represent a first-class fountain code with linear encoded and decoded time. They are LT code extensions with high error ceilings in extremely noisy channels. These concerns are addressed by employing a pre-code linear block that encodes a specified source block of data before the LT encoder [16], [17].

The rateless codes may also be used in massive multiple-input-multiple-output (MIMO) systems and relay channels. The LT and raptor codes have found their way into standards and applications like 3GPP multimedia broadcast multicast services (MBMS) and digital video broadcasting (DVB) due to their great performance DVB [19], [20]. However, many communication systems, like ad-hoc, sensor, and ultrawideband networks, operating with LSNR per node despite the large degrees of freedom available [21]. Therefore, a performance enhancement technique for the DS-CDMA multi-user system through raptor coding is proposed in this work. This paper has shown that the raptor channel-coded with DS-CDMA system outperforms the Turbo/Convolutional channel-coded with DS-CDMA system in additive white gaussian noise (AWGN) channels with a low SNR(LSNR) environment. It presents the BER performance for multiuser raptor channel-coded DS-CDMA technique in LSNR channels. We have used a multi-user decorrelator and a traditional receiver in each case. This paper is structured as following. In section 2, relevant work is introduced. The concepts of the raptor code are revisited in section 3. In section 4, the proposed system model construction is discussed. Section 5 presents the simulation result, and finally, section 6 gives the main concluding remarks.

2. RELATED WORKS

Throughout the last few years, several academics have developed algorithms for simplifying improved Gaussian estimation methods to evaluate the efficiency of the CDMA technique in wireless communication systems. In addition, many works in the literature have analyzed the performance of errors of the multiuser DS-CDMA scheme in fading channel. Some authors employed various techniques to evaluate the error performance of such a system [22]. A study has been performed on channel-coded direct-sequence CDMA systems using maximum free distance for convolutional code [23]. This study introduced moderate convolutional code with distinct constrained lengths and varying code rates for the CDMA scheme. In the paper, Rajagopal *et al.* [24], the DS-CDMA technique proposes quadratic residue theory based on pseudo-noise (PN) sequences to design low density parity check codes (LDPC) codes. In that approach, an effective decoding algorithm known as the sum-product algorithm (SPA) is used to improve LDPC codes' performance spanning an Eb/No ratio range of 0 to 6 dB.

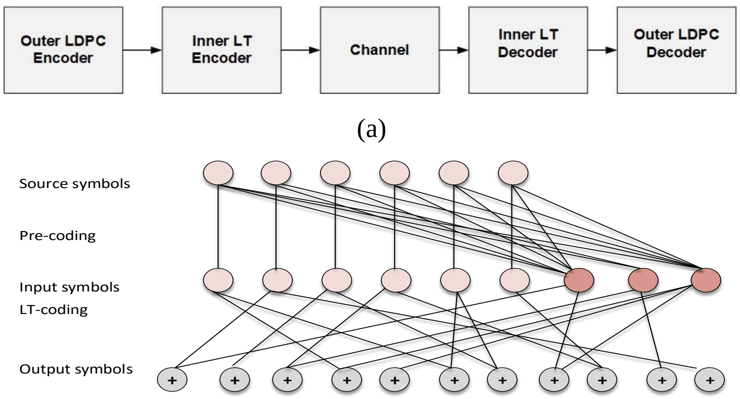
In the paper, Shojaeezand e*t al.* [25] LDPC coded CDMA receiver system. This approach uses the LDPC technique and the scrambling code in the CDMA approach to improve security and usability. The system's performing was verified by measuring the BER for different values of SNR with limits between 1 dB and 13 dB. In the paper, Tahir *et al.* [26], a design for a Polar-Coded CDMA system is proposed. This approach has proved that the performance of the BER of the polar channel-coded with DS-CDMA system outperform the convolutional DS-CDMA system by a wide margin (approximately 4 dB gain at Eb/No of 4 dB) based on the obtained simulation results.

In the paper, Xiao and Lee [27], the design of CDMA systems using MIMO-LDPC can achieve good error rate performance with short LDPC codes and fewer decoding iterations. It was shown that the MIMO-CDMA system outperforms the traditional CDMA system that uses only one transmission antenna with an improvement in SNR of about 2.5 dB [27].

In the paper, Marcu and Halunga [4] analyzed a multi-user CDMA system behavior using a minimum mean square error (MMSE) detector. In the presence of LDPC/Turbo coding and decoding techniques, the LDPC-Code DS-CDMA system performance is investigated when an optimal multi-user detector is used in the recovery of the information data, and the performance is improved with a BER = 10^{-3} for SNR = 4 dB in an AWGN channel. In the paper, Shah *et al.* [10], a convolutional code for the IS-95 standard CDMA system was proposed over a Rayleigh fading channel and a turbo-code for the CDMA 2000 system. Because of their recursive design, turbo codes provide better performance due to their constructional capabilities. The simulation was run in a Rayleigh fading environment, showing that the turbo code outperforms convolutional codes at low SNRs for IS-95 and CDMA 2000 systems. In the paper, Khoueiry and Soleymani [28] proposed a system that evaluated combining the LDPC technique and raptor codes in a rayleigh fading channel. In the paper, El-Gohary *et al.* [14], a raptor-coded OFDM system with binary phase-shift keying (BPSK) was implemented for improving the BER of the codeless OFDM system, which was verified to offer enhanced error performance for OFDM over AWGN channels. In the paper, Benzida and Kadochb [29] suggested a new scheme for a massive MIMO communication system. In this scheme, the receiver uses the raptor decoding symbols jointly with the MMSE technique, and this approach estimates the channel without using pilot symbols at the receiver.

3. RAPTOR CODE

Raptor code is considered a more advanced variant of the LT code with low computational cost and the potential to minimize channel effects [14]. It incorporates the benefits of block and Fountain codes to construct modern Fountain codes with linear encoded and decoded techniques. Figure 1 shows the raptor codes layout in Figure 1(a) structure and Figure 1(b) Tanner graphs. raptor code consists of a serial concatenation of the high rate LDPC encoder as an outer code and the LT encoder as the inner code, resulting in better performance than the single LT codes [17], [30]. Raptor codes are both theoretically and practically superior to LT codes. Generating an encoding symbol in raptor codes takes O(1) time. Furthermore, the raptor coding concept eliminates the need for all input symbols to be reconstructed as it is required in LT codes [29].



(a)

(b)

Figure 1. Raptor codes (a) structure and (b) tanner graph [31]

First, k input symbols are encoded into (n, k) blocks by error-correction block codes to create the intermediate symbol n. Then, these intermediate symbols are further coded with the LT codes. Every encoded symbol is created by randomly selecting the degreed through the degree distribution Ω(x), selecting the distinct d input symbols, and XORing them. Thus, the (k, C, Ω(x)) parameters can be used to specify a raptor code, where C represents the (n, k) of the error-correction block codes, also known as the precode, and Ω(x) represents the generated polynomial for the degree distribution of the LT code [31]. Raptor codes are distinguished from LT codes by their degree distribution and high-rate pre-code performance metrics. There are two types of raptor codes: systematic and non-systematic. We are primarily interested in the systematic case in which the source packets are included within the set of created encoded packets. Gaussian elimination can be used to find the inverse of the generating matrix in a systematic raptor decoding process, following the established relations between the intermediate packets and the data packets. This process is due to the decoding of the k source packet symbols. The source packets are protected by the pre-code, which corrects erasure packets that the LT code cannot recover. The LT code complexity is reduced to O(log k), which is superior to the typical LT complexity of O(k log k). As a result, this serial concatenates block code might have a low level of complexity while still providing a high level of protection [31]. However, the raptor technique could be achieving any coding rate (k/n), depending on the lengths of the produced codewords. Assuming that BPSK modulation with 0 to +1 and 1 to -1 mapping is employed, the received signal for an AWGN channel for the input data symbols $x_i = \pm 1$ is $y_i = x_i + n_i$, where $x_i = 1\text{-}2c_i$ represents the BPSK modulating signal, c_i is the encoded symbol, and n_i represents the Gaussian noise with mean equal to zero and variance of σ^2. For each received symbol y_i, the log-likelihood ratio (LLR) of the decoder can be calculated as follows [32], [33].

$$L(\text{cj}) \quad = ln\, \frac{p(c_j{=}0/y_j)}{p(c_j{=}1/y_j)} = \frac{2y_j}{\sigma^2} \tag{1}$$

The two-step sequential decoding method introduced in [34] decodes the inner system first, followe by the outer code. The sum-product algorithm (SPA) is used to decode a **tanner graph** that uses intermediate variable nodes (VNs), and the output symbol represents the check nodes (CNs) to an inner decoder. The Tanner graph of a raptor code ensemble can be drawn as shown in Figure 1(b). The LLR updates the linked j^{th} CN to i^{th} VN, which is referred to as L_{cjVi}, as well as the i^{th} variable node to j^{th} check node, indicating that L_{Vicj} is determined as [34].

$$L_{C_j\,V_i} = 2tanh^{-1}\left(\left(tanh\frac{L(C_j)}{2}\right)\prod\nolimits_{\iota\,\in N_c(j)-\{i\}} tanch\,\left(\frac{L_\iota C_j}{2}\right)\right) \tag{2}$$

$$L_{C_j\,V_i} = L(V_i) + \sum\nolimits_{j\in N_v(j)-\{j\}} L_{C_{\hat{j}}\,V_i} \tag{3}$$

$N_c(j)$ indicates the variable nodes connecting to the j^{th} check node. Moreover, $N_v(i)$ displays the check node collection associated with the i^{th} variable node. After the decoded process is completed, the final value of LLR is connected using (3), which represents the decision rule for every variable node (VN). It is used as the outer decoder's channel estimate. Because both the encoded and decoded processes of the raptor code are performed using the solus par agula (SPA) algorithm, then the code rate of the inner (R_i) and outer (R_o) codes are related by the overall code rate (R) [34].

$$R = R_i\ \ R_O \tag{4}$$

Where $R_o = k/k'$, and $R_i = k'/n$

Where k is the number of the bits per packet entered into the encoder, k' is the number of bits per block at the output of the inner stage of the coder, and n is the number of the bits per block at the output of the channel encoder. The channel is Eb/No for transmitting one codeword, and the noise variance is $\sigma^2 = N_o/2$ [35].

4. IMPLEMENTATION OF THE PROPOSED MODEL

Combining the CDMA transmission technique and raptor channel coding will create a reliable communication system for sending data in low SNR channels. Implementing and testing the proposed scheme needs to build a general model for the communication system under a fair environment to assess the effect of adding raptor coding into the CDMA transmission system. This approach requires specifying the system's parameters before starting the testing process through MATLAB simulation. This section will determine the properties of the proposed system as illustrated in the following two sub-sections.

4.1. Raptor coded DS-CDMA system

The block diagram of the proposed system, including the channel coding technique, is shown in Figure 2. In this paper, we have investigated the system based on raptor codes. The performance of this code depends mainly on the structure of the pre-code parity-check matrix, H, for the LDPC codes that represent the first layer of the raptor structure. It has been assumed that the structure of the parity-check matrix H has no girth of 4. Also, we have used a regular LDPC with dimensions of (4, 204) in H so that the number of ones per column is 4, and the number of ones per row is 204. These codes are characterized by a high code rate of 50/51 [33]. The second layer is the LT codes with weight distribution Ω(x) that is optimized for raptor code and is set as [36]:

$$\Omega(x) = 0.07969X + 0.49357X^2 + 0.166220X^3 + 0.0726X^4 + 0.082558 X^5 + 0.056058X^8 + 0.037229X^9 + 0.05590X^{19} + 0.025023X^{65} + 0.0003135X^{66} \quad (5)$$

At the transmitter side, each user source of information bits is encoded through a raptor encoder to produce the FEC-encoded codeword symbol sequence with the rate of R and bit interval of $1/R$. Then, these encoded bits are modulated by BPSK. Afterward, the modulated data streams are multiplexed by Walsh–Hadamard codes using a sequence of length M. The receiver can retrieve the desired signal by multiplying the received signal with the same Walsh code used during transmission. The de-mapped signal is passed to the LT ecoder, employing the belief propagation (BP) or SPA algorithm for decoding. After that, the log-likelihood ratio (LLR) output values from the LT decoder are entered to the LDPC stage, which represents the fixed-rate outer decoder. The raptor code uses the LLR information to estimate the original data. Furthermore, the bit error rate (BER) is then used to evaluate the coding scheme's reliability for the desired E_b/N_o ratio.

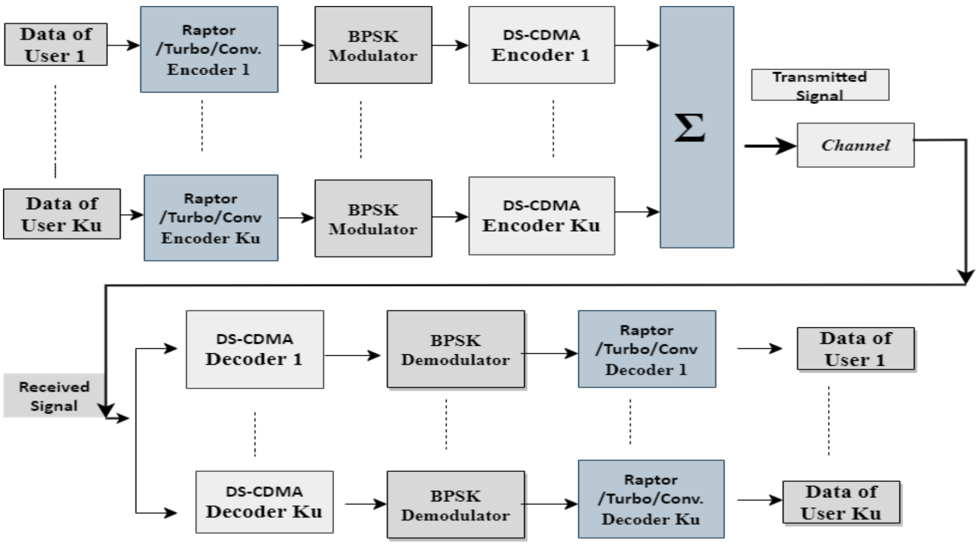


Figure 2. Block diagram for the system model

4.2. Turbo-coded DS-CDMA system

We have also considered the same communication system using Turbo and convolutional codes rather than raptor encoder, as shown in Figure 2. At the transmitting side, the information bits are encoding and block-interleaved. For the turbo code, the encoding stage comprises two recursive systematic convolutional (RSC) encoders concatenate in parallel at a rate of 1/2, as specified in [12]. The traditional 1/3 rate in turbo code is converted to 1/2 by puncturing the parity bits alternately. On the other hand, for designing a convolutional encoder, the encoding level consists of RSC encoders with a rate of 1/2. The encoded bits from Turbo/convolutional encoder for each user are modulated by (BPSK). Then, the modulated data are multiplied with the Walsh code sequence. The Turbo/convolutional coding with DS-CDMA system uses constraint length of seven and generator vectors with the size of {133, 171} for a code rate of ½ and size of {133, 145, 171} for a code rate of 1/3, and soft decision Viterbi decoding algorithm for the decoding process. The interference margin in the convolutional or raptor DS-CDMA technique is formulated as:

$$\frac{Pi}{Ps} = \left(\frac{W}{R}\right) - \left(\frac{Eb}{No}\right) \quad (6)$$

The ratio Pi/Ps in decibels is the interference margin ratio. The bandwidth extension factor is measured as W/R. Moreover, when the information bits are encoded with convolutional code or raptor code, the SNR outside the decoder is increase due to the coding gain (CG).

$$Coding\ gain = CG = R\ .\ d^{H}_{\min} \tag{7}$$

And therefore, the interference margin ratio is re-written as (8).

$$\frac{P_i}{P_S} = \left(\frac{W}{R}\right) + (CG) - \left(\frac{E_b}{N_o}\right) \tag{8}$$

This interference is determined by the number of user in the channel. As a result, the CDMA system has the benefit of handling a considerable number of users with ease of adding and/or removing them without having to reconfigure the system.

5. SIMULATION RESULTS

In this work, the performance characteristics of the proposed system consisting of the raptor channel encoder in conjunction with the CDMA multiple access techniques are examined and compared with other channel coding algorithms used with the same CDMA system. Specifically, the bit error rate versus signal to noise ratio is evaluated for four systems. In the first scheme, the CDMA technique is used solely without channel coding; in the second system, the convolutional channel encoder is used prior to the modulation and multiple access stages. In the third scheme, the turbo channel coder is utilized with the CDMA technique. Finally, in the last scheme, the raptor coding is used with the CDMA system to illustrate its unique advantages in reducing the BER for a very LSNR. The noise level is comparable to the signal power. Table 1 summarizes the parameters using in the simulation process and the resulting bit error rate values. In the simulation process, data are transmitted in packets with a block length of k = 1000, and the four schemes are analyzed under the same SNR and channel conditions. To make system simulation easier, we set the number of users in each raptor-CDMA cell to be four and have used Hadamard code with a length of 4 to different users. In addition, the raptor coded-CDMA system's performance will be investigated, we have used a DS/CDMA system with a spreading code of length equal to 8 and evaluated its performance before inserting the channel coding stages for comparison purposes.

Figure 3 shows the BER performance comparison of DS-CDMA with three distinct spread sequences under AWGN channels, and these spreading sequences include PN, Gold, and Walsh-Hadamard . The results indicate that the best performance is obtained when the DS-CDMA system utilizes Walsh-Hadamard spreading codes. This is because Walsh-Hadamard sequences have more vital crosscorrelation properties (equal to 0) than PN and Gold sequences. This indicates that multiple access interference resulting from various users is prevented if no multi-path exists. However, the orthogonally of Walsh code sequences is lost in a multi-path environment, and the performance is therefore degrade

Figure 4 shows the simulated BER performance of a single-user raptor coded with DS-CDMA system and a Turbo/Convolutional coded DS-CDMA system with a typical source block length of k = 1000, the code rate of R = 1/3, and a spreading code with a length equal to 4. Compared to the Turbo and convolutional coded with CDMA systems, the raptor coded DS-CDMA system has an improved signal-to-noise ratio of about 6 dB for a BER = 10^{-6}. According to the results of simulation presented in Figure 5, the receiver in the Raptor-coded CDMA scheme using a spreading factor of the length of 4 outperforms the conventional DS-CDMA receiver that uses a higher spreading factor with a length of 8. Besides, the Raptor-coded system improves the Eb/No ratio of about 7 dB compared with the convolutional coded DS-CDMA schemes for a BER = 0.008, the message block length k = 1000, and a code rate R = 1/2 for each system.

From these test results (Table 1, Figure 4, and Figure 5), we can observe the consistency of the theoretical prediction after comparison with the practical results, indicating that the raptor code greatly improves the tradithinal CDMA performance transmission scheme under the same conditions. On the other hand, it has been shown that the convolutional-encoder presents the weakest performance compared to both the turbo and raptor codes. Furthermore, it has been shown that the turbo-CDMA system can reach the Shannon limit with acceptable efficiency, but its performance is collapsed after this point. It was evident that the Raptor-encoded CDMA scheme provides superior performance under low E_b/N_o conditions, and therefore it is highly recommended to be used in such channels.

Figure 6 presents the BER performance comparison of single-user raptor coded DS-CDMA system for k = 1000 with different code rates of 1/3, 1/2, and 5/7, respectively, using a spreading factor with a length of 4. The results show that the raptor-coded DS-CDMA systems' performance is superior at a code rate of 1/3 compared to other code rate values. In contrast, the traditional DS-CDMA receiver cannot work in this range due to its significant bit error rate. As a result, we conclude that using the raptor code with DS-CDMA is very effective in low SNR circumstances and can provide reliable communication compared with the results in reference [10], [23].

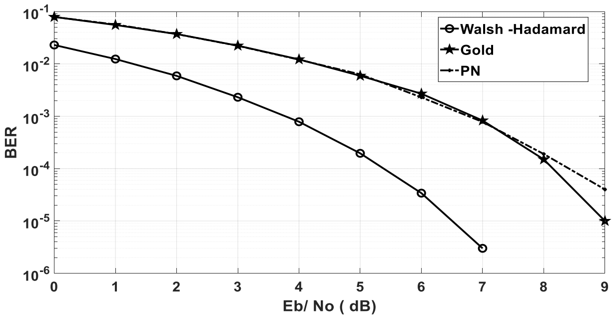


Figure 3. The Performance of DS-CDMA in AWGN channel

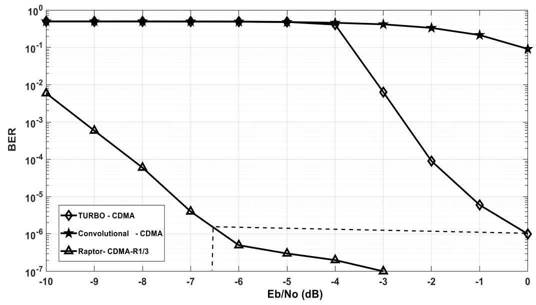


Figure 4. Raptor coding with DS-CDMA system BER comparison with turbo/convolutional with CDMA schemes (rate 1/8) with k = 1000 and coding rate = 1/3

Table 1. Simulation parameters and performance results

Parameters	DS/CDMA	DS/CDMA with convolutional channel coding	DS/CDMA with turbo channel coding	DS/CDMA with raptor channel coding
Input bits (k)	1000	1000	1000	1000
Code Rate (R)	1/8	1/3, 1/2	1/3	1/3, 1/2 ,5/7
Throughput	1/8	1/12 , 1/8	1/12	1/12,1/8, 5/28
Walsh code length	8	4	4	4
BER at Eb/No= -3dB	0.0226	0.4152, 0.432	0.0063	1e-08,2e-06, 2.0e-04
BER at Eb/No=-6dB	0.0777	0.4881, 0.321	0.488	5e-07,4e-04,0.0858
BER at Eb/No= -9dB	0.158	0.7974, 0.6832	0.4947	5.8800e-04, 0.0399, 0.4001

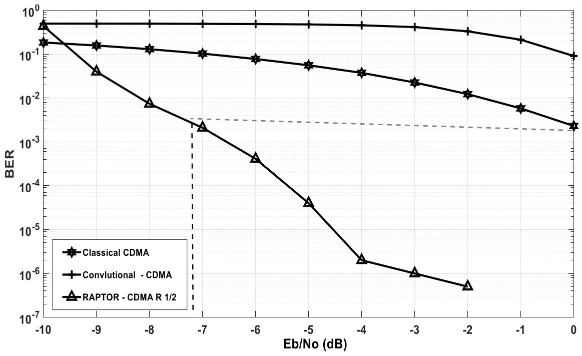


Figure 5. Raptor coded DS-CDMA system BER comparison with convolutional and conventional CDMA with k =1000 and coding rate equal to 1/2

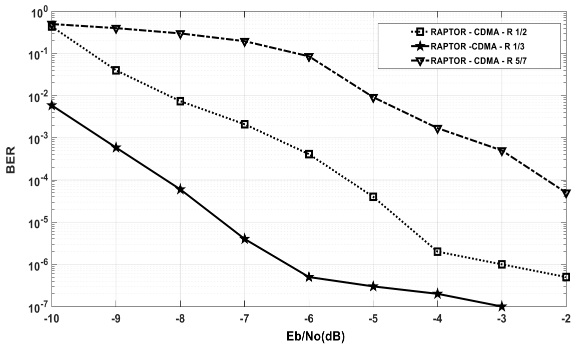


Figure 6. Raptor code DS-CDMA BER comparisons with k=1000 and varied code rate values

6. CONCLUSION

This paper has studied and compared the performance of turbo-coded and convolutional-coded with DS-CDMA schemes with a Raptor-coded with DS-CDMA scheme for multi-user communication systems over AWGN channels. A high code rate and girth test selection are developed to design a regular LDPC parity check matrix *H* for the outer encoder of raptor code. This work showed that the raptor code BER performance with the DS-CDMA system, including BPSK over AWGN channels, is superior to other schemes. The simulation results concluded that the raptor code DS-CDMA with a short length of raptor codes and Walsh code length of 4 and a lower number of decoding iterations could achieve better performance than conventional DS-CDMA with Walsh code length of 8. The performance analysis of raptor CDMA and Turbo/convolutional coded multiuser DS-CDMA systems having code rates of 1/3, 1/2, and 5/7 is analyzed. Simulation results showed that the Raptor-coded CDMA system is better than the conventional

CDMA transmission system under the same channel conditions. When used with the CDMA system, it also outperforms other channel coding schemes like the Turbo and convolutional codes. Thus, the Raptor-coded CDMA system is a promising candidate to work reliably under severe noise and low power conditions.

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