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Effect of repetition coding on the BER performance of interleave-division multiple access systems

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Abstract: This paper investigates the bit error rate (BER) performance of interleave-division multiple access (IDMA) schemes to show the effect of repetition coding on the system performance. The considered system is tested in the presence of repetition coding by varying system parameters such as number of simultaneous users, data length, spread length, iteration number, and code rate over additive white Gaussian noise channels. In addition, the performance of the considered system is also illustrated in Rayleigh flat fading channels for a more realistic scenario. Our simulation results show that the BER performance of IDMA systems with repetition coding can achieve significant performance gains over existing uncoded IDMA schemes.

Key words: Interleave-division multiple access, repetition coding, interleaving

1. Introduction

In the last decades, multiple access techniques have had a crucial role in wireless and mobile communications. There are three widely known multiple access methods, namely frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA) [1]. These techniques were improved to overcome the disadvantages of previous ones. CDMA is the most important improvement for third-generation wireless cellular communication systems. This multiple access model has gained popularity due to some advantages such as robustness against multipath fading, dynamic channel sharing, asynchronous transmission, and mitigation of cross-cell interference [2]. In contrast to these advantages, CDMA has some negative points, such as multiple access interference (MAI) and intersymbol interference (ISI). The performance of CDMA-based wireless communication systems suffers from these negative effects [3].

To combat the disadvantages of conventional CDMA in second- and third-generation cellular mobile communications, interleave-division multiple access (IDMA) is proposed as a new spread spectrum technique [3,4]. IDMA has all the advantages of CDMA and this multiple access technique can be seen as an improved version of CDMA. In addition, the effects of ISI and MAI are avoided with the use of multiuser detection (MUD) [5] in the receiver structure of IDMA. In CDMA, user-specific spreading sequences are employed for user separation. The IDMA system differs from the CDMA system in the sense that the chip-interleaving process is used for user separation. In the context of IDMA systems, it is assumed that this interleaving process is employed randomly and independently [4,6]. The authors in [7] also presented chip-interleaved CDMA to combat ISI and MAI. The spreading process is carried out before interleaving in the transmitter part of IDMA.

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This spreading process can be the same for all users [2,4]. When only spreading is employed before interleaving, this type of IDMA is called uncoded IDMA. If any forward error correction (FEC) coding techniques are used before the spreading process, it is called coded IDMA [3]. In coded IDMA, the system performance varies according to the types of FEC coding. Liu and Ping et al. [3,4] examined various FEC coding techniques including turbo-Hadamard coding [8], concatenated zigzag Hadamard codes [9], and zigzag codes [10] in IDMA. In [11], low-density parity check (LDPC) codes were successfully applied to IDMA systems.

Recently, some works on IDMA techniques were presented in [12–16]. Similar to [1], orthogonal frequency division multiplexing interleave division multiple access (OFDM-IDMA) systems were examined in [12–14]. In [12], a revised signal to noise ratio (SNR) updating expression was derived for OFDM-IDMA systems in Rayleigh fading channels. A novel user grouping technique for grouped OFDM-IDMA systems was considered in [13]. The authors in [13] aimed to maximize the system capacity by adaptively distributing users according to their channel conditions. Peng et al. [14] proposed an improved detection algorithm to avoid the effect of carrier frequency offsets (CFOs) in uplink OFDM-IDMA. They employed the proposed algorithm where the principle is based on iterative estimation and mitigating the combined interference from multiple users and CFOs at the receiver. The work in [15] presents integration of multiple-input multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM) and IDMA systems. In [16], a new element signal estimator (ESE) scheme was introduced based on the two-dimensional received signals.

In this paper, the effect of repetition coding on the bit error rate (BER) performance of IDMA systems is investigated. The simulation results are obtained by varying number of simultaneous users, code rate, data length, spreading length, and number of iterations over additive white Gaussian noise (AWGN) and Rayleigh fading channels. Moreover, convolutional coding is also utilized to compare uncoded and repetition coded IDMA. As a result, the performance of IDMA systems has been improved with the use of repetition coding as expected.

The rest of this paper is organized as follows: in Section 2, general IDMA principles are described with transmitter and receivers structures. Section 3 explains the interleaving process and repetition coding. Finally, the performance evaluations and conclusions are presented in Sections 4 and 5, respectively.

2. Transmitter and receiver structures of IDMA system

The structure of a transmitter and a receiver for an IDMA system with K simultaneous users is demonstrated in Figure 1. The upper and lower parts of this figure shows transmitter and receiver sections, respectively. The receiver structure of the system, which uses a chip-by-chip (CBC) algorithm, operates the iterative processing. The information bits of user k are denoted by d_k. The input data stream d_k is encoded by a low-rate code C. When the system is considered without FEC coding, only a spreading process is applied. However, d_k is encoded by a concatenation of repetition encoder and spreader in this study. Then $c_k \equiv [c_k(1), ..., c_k(j), ..., c_k(J)]^T$ is generated, where J is the frame length and T represents the transpose. The resulting coded bits c_k are interleaved by a chip-level interleaver π_k. After the chip-level interleaving process, $x_k \equiv [x_k(1), ..., x_k(j), ..., x_k(J)]^T$ are produced. We call the elements in c_k and x_k ‘chips’ by following the convention of CDMA. The key principle of this spread spectrum technique is that the interleavers should be different for different users [3,4]. The spreading sequence is constructed by +1 and –1, and the numbers of +1 and –1 should be balanced in $[+1,\ -1,\ +1,\ -1, ...,\ +1]$. After the interleaving process in the transmitter, x_k is transmitted over multiple access channels [3,4,6].

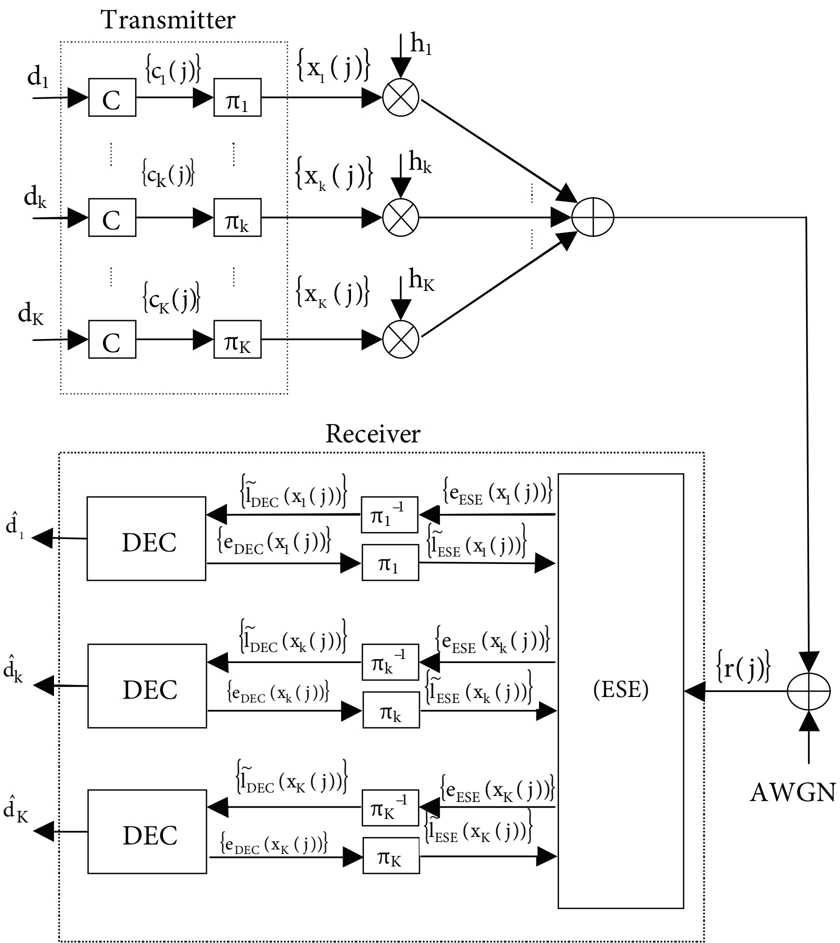

Figure 1. Transmitter and receiver structure of IDMA system with K simultaneous users [2].

The MUD receiver includes an ESE and a bank of K single-user a posteriori probability (APP) decoders (DECs) [3,4]. The interleaved information sequences are transmitted over AWGN or Rayleigh fading channels. Thus, the signal from K users at the receiver is expressed by

$$r(j) = \sum_{k=1}^{K} h_k x_k(j) + n(j), \quad j = 1, 2, \ldots, J, \tag{1}$$

where $n(j)$ are samples of an AWGN process with zero-mean and variance $\sigma^2 = N_0/2$, and h_k is the fading coefficient related to user k. $x_k(j)$ is the jth chip transmitted by user k. Real h_k is considered and it is assumed that these coefficients are known a priori at the receiver [3,4]. In this study, we consider two channel conditions, stated as follows:

- In the first case, fading effect is neglected because only the AWGN channel is considered as a destructive effect $(h_k = 1)$.

- In the second case, fading effect is included by assuming Rayleigh fading (h_k is the Rayleigh fading coefficient).

The CBC algorithm is employed at the receiver side and the IDMA system performs turbo-type iterative MUD. We assume binary phase shift keying (BPSK) signaling, $(x_k(j) \in \{+1, -1\}, \forall k, j)$. The outputs of ESE and DECs are extrinsic log-likelihood ratios (LLRs) about $x_k(j)$ by [3,4]:

$$e(x_k(j)) \equiv \log\left(\frac{\Pr(x_k(j)=+1)}{\Pr(x_k(j)=-1)}\right), \forall k, j. \quad (2)$$

These LLR values are separated by subscripts, i.e. $e_{ESE}(x_k(j))$ and $e_{DEC}(x_k(j))$, which depends on the generation process in the ESE or DECs. As illustrated in Figure 1, the deinterleaved version of $e_{ESE}(x_k(j))$ and the interleaved version of $e_{DEC}(x_k(j))$ are denoted as $\tilde{l}_{DEC}(x_k(j))$ and $\tilde{l}_{ESE}(x_k(j))$, respectively. For specific user k, Eq. (1) can be rewritten as [4]:

$$r(j) = h_k x_k(j) + \zeta_k(j), \quad (3)$$

where

$$\zeta_k(j) = \sum_{k \neq k'} h_{k'} x_{k'}(j) + n(j) \equiv r(j) - h_k x_k(j). \quad (4)$$

$\zeta_k(j)$ indicates a distortion with related to $x_k(j)$ [2].

2.1. Chip-by-chip detection algorithm for a single path

The DEC function can be calculated with the help of Eq. (2) and shown as:

$$e_{DEC}(x_k(j)) \equiv \log(\Pr(x_k(j)) = +1) - \log(\Pr(x_k(j)) = -1), \ \forall j. \quad (5)$$

Step 1: First, set $e_{DEC}(x_k(j))$=0, $\forall k, j$. It is assumed that the LLR of DECs is not received when the iterative processing starts. The mean value and variance of x_k are expressed as $E(x_k(j)) = \tanh(e_{DEC}(x_k(j))/2)$ and $Var(x_k(j)) = 1 - (E(x_k(j)))^2$, respectively. The signal from K simultaneous users at the ESE, $r(j)$, has mean value and variance given as [3,4]:

$$E(r(j)) = \sum_k h_k E(x_k(j)), \quad (6)$$

$$Var(r(j)) = \sum_k |h_k|^2 Var(x_k(j)) + \sigma^2. \quad (7)$$

The mean and variance of $\zeta_k(j)$, which indicates a distortion in relation with $r(j)$, can be calculated as [4]:

$$E(\zeta_k(j)) = E(r(j)) - h_k E(x_k(j)) = \sum_{k \neq k'} h_{k'} E(x_{k'}(j)), \quad (8)$$

$$Var(\zeta_k(j)) = Var(r(j)) - |h_k|^2 Var(x_k(j)) = \sum_{k' \neq k} |h_{k'}|^2 Var(x_{k'}(j)) + \sigma^2. \quad (9)$$

Step 2: The LLR expression can be written as [4]:

$$e_{ESE}(x_k(j)) = 2h_k . \frac{r(j) - E(\zeta_k(j))}{Var(\zeta_k(j))}. \quad (10)$$

Then APP decoding is applied in DECs. The mean values and variances are updated for every single chip. After that, the same process will be repeated for the next iteration. During the final iteration, the DECs produce hard decisions $(\hat{d}_k)$ on information bits $d_k(j)$ [3,4].

3. Repetition coding and interleaving

3.1. Repetition coding

The main purpose of the channel coding is to reduce the propagation errors in wireless communications. Therefore, it is called error control coding. In channel coding, the control bits that only check errors are added to the end of the information sequence in communication systems. These control bits do not contain any information and they are called redundancy bits in the information sequence. One of the simplest error control codings is repetition coding, in which all information bits are transmitted more than once [17].

The repetition coding technique can significantly reduce the probability of error. However, as a trade-off the required bandwidth increases n times due to every single information bit being transmitted n times. This process is evaluated as the disadvantage of the repetition coding [17]. Furthermore, the code rate of this technique is $1/n$ because of sending every single information bit n times.

In this paper, the repetition coding is applied to IDMA systems as explained below:

- The information sequence of user k is encoded with repetition code in the low-rate C block and IDMA transmitter processing steps are executed as explained in the previous section.
- In the turbo-type MUD receiver, which uses the CBC algorithm, the repetition decoding process is performed in a bank of K single-user APP DECs.

In this study, repetition coding is employed due to its advantages such as low complexity for decoding, simple implementation, and short simulation time with respect to some other FEC coding techniques, i.e. the LDPC and turbo codes. Although LDPC and turbo codes can yield better performance, they have high complexity for APP decoding and some difficulties on implementation. Another disadvantage of using LDPC and turbo codes is that it takes a more longer time compared to repetition coded systems.

3.2. Interleaving

The order of symbols of an N-length input sequence is varied by an interleaver. Therefore, a unique output sequence is produced and the generated sequence possesses a minimal relationship when compared to the input sequence. The interleaver performs this operation by using a predetermined special function (π). In other words, this operation disperses the input sequence to uncorrelate the neighboring bits and the relationship between the input and generated sequences is minimized [18]. The operational steps of an interleaver are demonstrated in Figure 2. We assume that N-length input and output sequences of an interleaver can be written as $\lambda = (\lambda_0, \lambda_1, ..., \lambda_{N-1})$ and $v = (v_0, v_1, ..., v_{N-1})$, respectively. On one hand, the $\mathbf{v}$ sequence is the changed form of the λ sequence. As can be seen from Figure 2, the $\boldsymbol{\lambda}$ sequence turns into the $\mathbf{v}$ sequence $(\lambda_i \Leftrightarrow v_i)$, $i \in N$. There are two different interleaver types, called the 'random interleaver' and 'algebraic interleaver' based on generation techniques. The performance of random interleavers can be improved with larger data sequences. From the other point of view, algebraic interleavers present significant performance improvement while the data sequence is small [18].

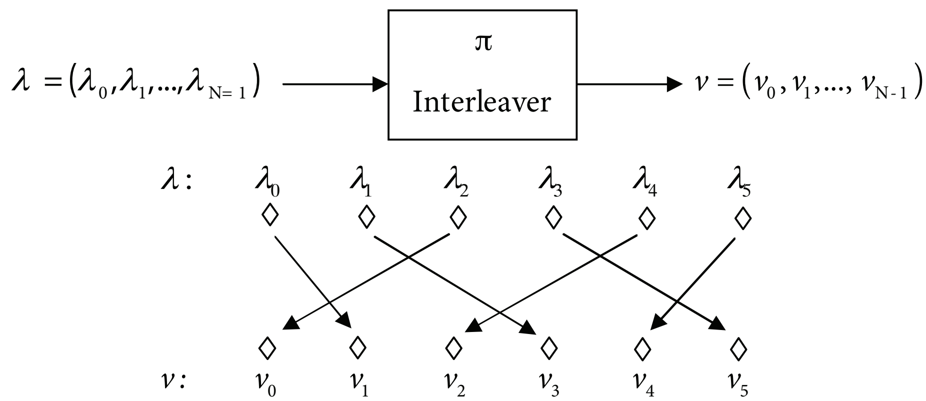

Figure 2. Illustration of chip-level interleaving $\pi = (2, 0, 4, 1, 5, 3)$ [19].

Every single k user is appointed to different interleaver indices in an IDMA system. An interleaver block has a great impact on the performance of IDMA systems as mentioned before. The chip-level interleaving process is carried out with traditional IDMA technology [3]. In IDMA systems, it is assumed that chip-level interleaver indices of the k user are known on the receiver side and these are used in the turbo-type MUD-based CBC receiver. In the CBC algorithm, the generated LLRs are interleaved before being transmitted to the ESE as feedback information. Similarly, the LLRs generated by ESE are deinterleaved before being sent to the APP DECs. Therefore, different interleaver approaches were proposed in [19–23] to improve the BER performance of IDMA systems.

4. BER performance analysis

In this section, simulation results are presented to show the effect of repetition coding on the BER performance of IDMA systems. It should be emphasized that the results presented in this work are only based on computer simulations. As will be seen, we discuss three different scenarios in the simulation studies. Let N_{info} be the data length, S denote the spread length that contains a balanced number of +1 and −1, and It be the number of iterations. In addition, K and R denote the number of simultaneous users in the IDMA and coding rate, respectively. BPSK modulation is used in the considered system. We assume a single path AWGN or Rayleigh fading transmission medium in the simulation. Figures 3–7 show the BER performance of different scenarios in IDMA in terms of different parameters.

In Figure 3, we consider an uncoded IDMA system with $N_{info} = 128$, $S = 16$, $It = 20$, $R = 1/3$, and different numbers of simultaneous users. As can be seen from Figure 3, the BER performance of IDMA systems is increased when repetition coding is used with $K = 4$, 16, and 28. It is shown that about 8.6 dB is needed for $BER = 10^{-4}$ when $K = 16$. However, similar performance with $R = 1/3$ is provided at $E_b/N_0 \approx 5.2$ dB. Therefore, we can say that less E_b/N_0 is needed to achieve the same BER performance when repetition coding is used. In Figure 4, we consider an uncoded and $R = 1/4$ low-rate repetition coded IDMA system with $N_{info} = 64$, $S = 32$, $It = 15$ for different numbers of simultaneous users. It can be seen that the BER performance of $R = 1/4$ low-rate repetition coded IDMA outperforms the BER performance of uncoded IDMA when $K = 6, K = 12$, and $K = 20$. In this simulation result, the BER case of 10^{-3} for $K = 20$ users is observed at $E_b/N_0 \approx 7.5$ dB, and the same BER performance can be achieved at $E_b/N_0 \approx 2.2$ dB in the $R = 1/4$ low-rate repetition coded IDMA.

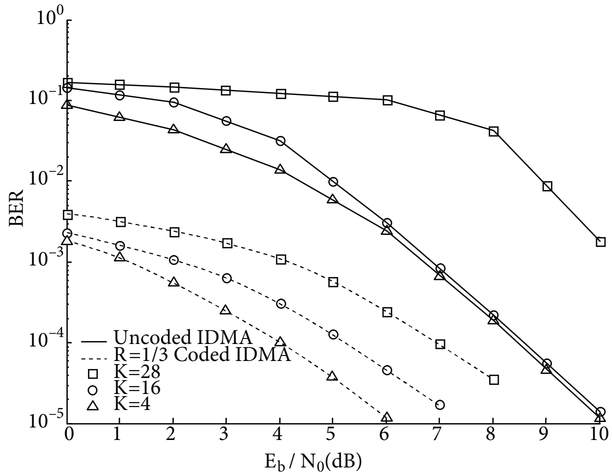

Figure 3. Comparison of uncoded IDMA with $R = 1/3$ repetition coded IDMA for $N_{info} = 128, S = 16, It = 20$ and different numbers of simultaneous users.

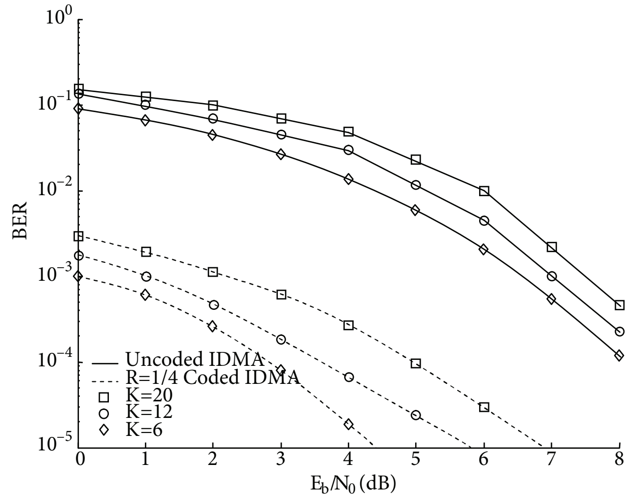

Figure 4. Comparison of uncoded IDMA with $R = 1/4$ repetition coded IDMA for $N_{info} = 64, S = 32, It = 15$ and different numbers of simultaneous users.

In Figure 5, a comparison of uncoded IDMA with $R = 1/5$ repetition coded IDMA is illustrated for cases of $N_{info} = 256, S = 32, It = 30$, and different numbers of simultaneous users. With $K = 10$ users, the overall BER performance of the uncoded IDMA is 10^{-5} at $E_b/N_0 \approx 9.7\,dB$. On the other hand, the BER level of 10^{-5} is obtained at $E_b/N_0 \approx 6.1\ dB$ for the $R = 1/5$ repetition coded IDMA system with the same number of users.

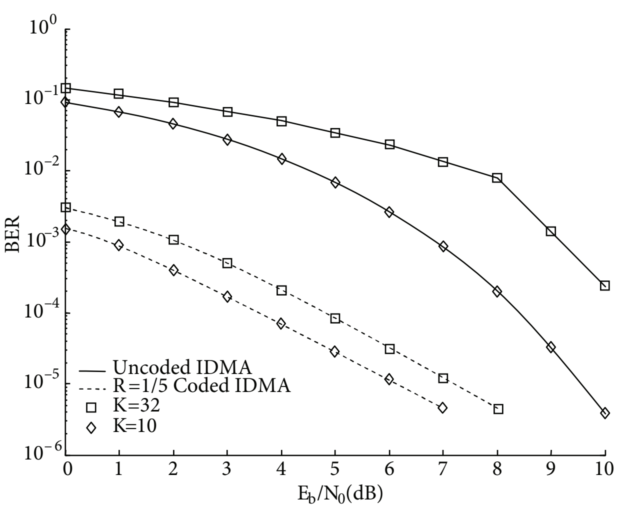

Figure 5. Comparison of uncoded IDMA with $R = 1/5$ repetition coded IDMA for $N_{info} = 256, S = 32, It = 30$ and different numbers of simultaneous users.

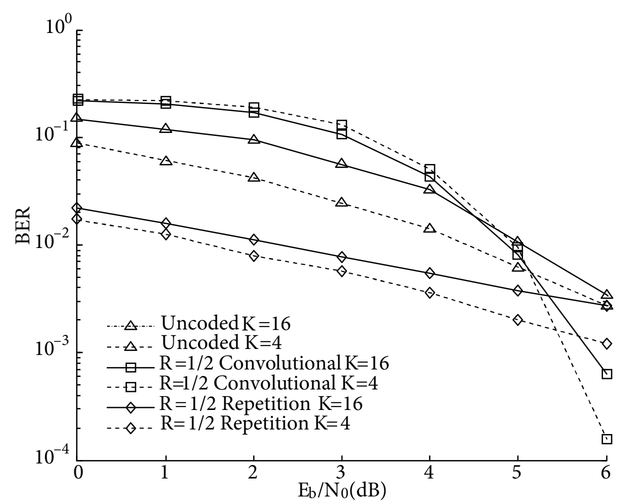

Figure 6. Comparison of uncoded, $R = 1/2$ repetition coded, and $R = 1/2(23, 35)_8$ convolutional coded IDMA for $N_{info} = 256$, $S = 16, It = 20$ and different numbers of simultaneous users.

Figure 6 shows the BER performance, which depends on uncoded and coded cases over an AWGN channel. We consider a sixteen-state (23,35) convolutional code in octal form with code rate $R = 1/2$ and repetition coded IDMA with code rate $R = 1/2$. In this simulation result, the system parameters are set as follows:

$N_{info} = 256, S = 16, It = 20$, for $K = 4$ and $K = 16$. As can be seen from Figure 6, the performance of IDMA improves rapidly within the SNR range of 4 dB to 6 dB with $R = 1/2(23,35)_8$ convolutional code. It is also worth noting that the best performance is provided with the use of $R = 1/2$ repetition coding in the SNR range of less than 5 dB.

The simulation results mentioned previously are considered over AWGN channels. The AWGN channel model is practically unrealistic, so we also consider an IDMA system subject to a Rayleigh flat fading channel, which includes the statistical characteristics of real wireless environments. This is also shown in Figure 7, where we set the number of simultaneous users at $K = 4$ and $K = 8$, respectively. We also consider uncoded and $R = 1/3$ low-rate repetition coded IDMA systems with $N_{info} = 128$, $S = 16$, $It = 20$. Again, we can observe the positive effect of repetition coding on the system performance, similar to the previous results. Furthermore, similar behavior observed in Figure 6 can be expected for Figure 7 because the convolutional coded IDMA will yield better performance at high SNR range when compared to the uncoded and repetition coded IDMA. It should also be noted that the BER performance degrades over Rayleigh fading channels since the system is under worse channel conditions with respect to the AWGN channel.

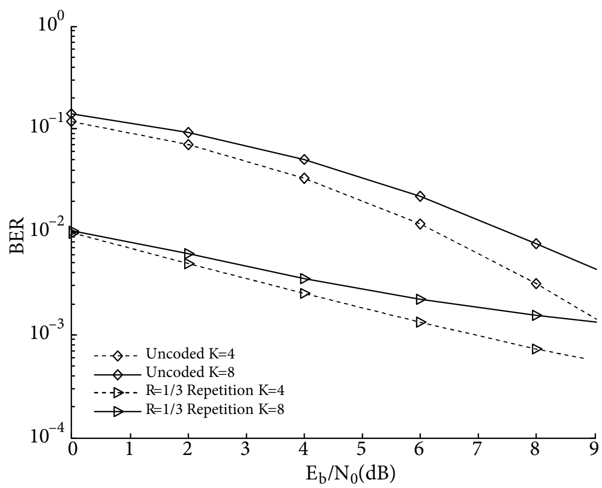

Figure 7. Comparison of uncoded IDMA and $R = 1/3$ repetition coded IDMA over Rayleigh flat fading channels for $N_{info} = 128, S = 16,\ It = 20$ and different numbers of simultaneous users.

All of the simulation results show that repetition coding has a positive effect aiding to improve the BER performance of the IDMA. However, a tradeoff occurred between BER performance and the bandwidth. The bandwidth of the IDMA system increases when the repetition coding is used.

5. Conclusion

In this study, we explained the interleaver process and repetition coding and investigated the effect of repetition coding technique on the system performance of IDMA by considering different scenarios over AWGN and Rayleigh channels. For the purpose of comprehensive comparison, convolutional coding was also employed alongside uncoded and repetition coded IDMA. From the study and simulation results, it can be shown that the achievable BER performance of the IDMA is significantly improved by using the repetition coding under both AWGN and Rayleigh channel conditions. A trade-off between the system performance and bandwidth showed that as the number of coding rates increases, the system performance improves, but on the other hand, the bandwidth starts to rise.

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