Turbo-coded CDMA-based Two-way Relaying

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Abstract— In this contribution, we have studied the performance of a Turbo-Coded (TC) Code Division Multiple Access (CDMA) based two-way relaying scheme. More explicitly, we employ a seven-user CDMA model, where two of the CDMA users are communicating with each other with the aid of an additional relay node, while the other five CDMA users are interferers. More explicitly, two CDMA users exchange their information frames within two timeslots. Note that the conventional one-way relaying system can only transmit one information frame within two timeslots because the relay node is half-duplex, where it cannot listen and transmit simultaneously. We found that our proposed TC-CDMA two-way relaying scheme is capable of attaining over 4 dB of SNR gain at a Bit Error Rate (BER) of 10^{-6} when compared to a conventional non-cooperative TC-CDMA system. We also found that there is about two dB of SNR loss at a BER of 10^{-6}, due to the error propagation from the relay node. The proposed scheme exploits the benefits of TC and CDMA schemes in order to assist the two-way relaying system to operate with a reduced transmit power. The reduction of the transmit power can also be exploited for increasing the coverage area of a cellular cell. Hence, the TC-CDMA two-way relaying scheme is a good candidate for future generation mobile systems.

1. INTRODUCTION

We proposed a Turbo-coded Code-Division Multiple Access (CDMA) based two-way relaying scheme for cooperative communications with the aid of a relay node. More specifically, Turbo Codes (TCs) [1] are power-efficient channel coding schemes that can perform near channel capacity, while CDMA [2] is an attractive multiple access scheme that allows multiple users to access the same frequency band at the same time. Both TC and CDMA schemes have been adopted in the current 3G mobile standard. By contrast, cooperative communications [3–5] is a new paradigm where each mobile unit collaborates with one partner or a few partners for the sake of reliably transmitting its own information and of its partners jointly. More specifically, source nodes can transmit their signals to their destination nodes via relay nodes. Cooperative communications can increase the capacity, transmission reliability, energy efficiency and coverage area of the overall system. Due to these advantages, cooperative communication schemes based on relaying have been considered in the recent LTE-Advance standard [6].

In this contribution, we studied the performance of the TC-CDMA scheme under the two-way relaying system [7] based on the Decode-And-Forward (DAF) protocol. More explicitly, we employ a seven-user CDMA model, where two of the CDMA users are communicating with each other with the aid of an additional relay node, while the other five CDMA users are interferers. In a conventional one-way relaying schemes [5, 8], two timeslots are required for the transmission of one information frame from the source node to the destination node, via a half-duplex relay node. Four timeslots would be required for the transmission of two information frames according to the conventional one-way relaying technique. In our system, only two timeslots are required for two CDMA users to exchange two information frames. This is because in a CDMA system, each user is equipped with a unique spreading code for enabling an effective multiuser detection at the destination node or relay node. Hence, time-orthogonality is not required to separate the two user signals. Our proposed TC-CDMA two-way relaying scheme is capable of attaining over 4 dB of SNR gain at a Bit Error Rate (BER) of 10^{-6} when compared to a conventional non-cooperative TC-CDMA system. We also found that there is about two dB of SNR loss at a BER of 10^{-6}, due to the error propagation from the relay node. The proposed scheme exploits the benefits of TC and CDMA schemes in order to assist the two-way relaying system to operate with a reduced transmit power. The reduction of the transmit power can also be exploited for increasing the coverage area of a cellular cell.

The paper is organised as follows. The system model is described in Section 2 while the performance of the proposed scheme is evaluated in Section 3. Our conclusion is offered in Section 4.

2. SYSTEM MODEL

We assume that each user unit is equipped with a single-antenna and the channel is constant during a symbol period. The received signal vector of a CDMA system supporting K users using P-chip

CDMA sequences can be represented by [9]:

$$\mathbf{y} = \mathbf{C}\widetilde{\mathbf{H}}\mathbf{x} + \mathbf{n}, \tag{1}$$

where the received signal $\mathbf{y}$ is a $(P \times 1)$-dimensional vector, the spreading code matrix $\mathbf{C}$ is $(P \times K)$-dimensional, the channel matrix $\widetilde{\mathbf{H}}$ is $(K \times K)$-dimensional, the user signal $\mathbf{x} = [x_1\, x_2\, \ldots\, x_K]^T$ is a $(K \times 1)$-dimensional vector and the noise vector $\mathbf{n}$ is $(P \times 1)$-dimensional. We consider a frequency-flat uncorrelated Rayleigh fading channel, which can be conveniently represented by the following diagonal matrix:

$$\widetilde{H} = \begin{bmatrix} \sqrt{G_{u_1 d}} h_{u_1 d} & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & \sqrt{G_{u_K d}} h_{u_K d} \end{bmatrix},$$

where $G_{u_k d}$ and $h_{u_k d}$ are the corresponding reduced-pathloss-induced geometrical gains [8] and the Rayleigh fading coefficient between the kth user node and the destination node, respectively. When considering a free-space path loss model, the geometrical gain between the kth user node and the destination node is given by [8]:

$$G_{u_k d} = \left(\frac{d_{u_k u_l}}{d_{u_k d}}\right)^2, \tag{2}$$

where $d_{u_k u_l}$ is the distance between the kth and lth users, who are the two users that want to exchange their information frames, while $d_{u_k d}$ is the distance between the kth user and the destination node (in our two-way relaying scheme, this is the relay node because the lth user node is the destination node for the kth user and vice versa). Equation (1) can be more conveniently rewritten as:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{3}$$

where $\mathbf{H} = \mathbf{C}\widetilde{\mathbf{H}}$. Minimum Mean-Square Error (MMSE) based multiuser detection is considered and the MMSE weight matrix is given by:

$$\mathbf{W} = \mathbf{H}\left(\mathbf{H}\mathbf{H}^H + N_0 \mathbf{I}_P\right)^{-1}, \tag{4}$$

where $\mathbf{I}_P$ is a $(P \times P)$-element matrix having ones on its diagonal, $N_0/2$ is the noise variance per dimension and $\mathbf{H}^H$ is the Hermitian transpose of $\mathbf{H}$. The MMSE-detected signal is given by:

$$\mathbf{z} = \mathbf{W}^H\mathbf{y} = \left(\mathbf{H}^H\mathbf{H} + N_0\mathbf{I}_P\right)^{-1}\mathbf{H}^H\mathbf{H}\mathbf{x} + \left(\mathbf{H}^H\mathbf{H} + N_0\mathbf{I}_P\right)^{-1}\mathbf{H}^H\mathbf{n} = \mathbf{A}\mathbf{x} + \mathbf{v}, \tag{5}$$

where $\mathbf{z}$ is a $(K \times 1)$-dimensional vector, $\mathbf{A} = (\mathbf{H}^H\mathbf{H} + N_0\mathbf{I}_P)^{-1}\mathbf{H}^H\mathbf{H}$ is the $(K \times K)$-dimensional equivalent channel matrix and $\mathbf{v} = (\mathbf{H}^H\mathbf{H} + N_0\mathbf{I}_P)^{-1}\mathbf{H}^H\mathbf{n}$ is the $(K \times 1)$-dimensional equivalent noise vector. More specifically, Equation (5) can be written as:

$$\begin{bmatrix} z_1 \\ \vdots \\ z_K \end{bmatrix} = \begin{bmatrix} a_{11} & \ldots & a_{1K} \\ \vdots & \ddots & \vdots \\ a_{K1} & \ldots & a_{KK} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_K \end{bmatrix} + \begin{bmatrix} v_1 \\ \vdots \\ v_K \end{bmatrix}, \tag{6}$$

where it can be shown that the noise variance for the kth noise v_k is given by the multiplication of the kth diagonal element of $\mathbf{W}^H\mathbf{W}$ and N_0, i.e., $N_{0,k} = \mathrm{diag}_k\{\mathbf{W}^H\mathbf{W}\}N_0$. Hence, the kth MMSE signal can be written as:

$$z_k = a_{kk}x_k + \sum_{i \neq k}^{\text{all}\, i} a_{ik}x_i + v_k = a_{kk}x_k + w_k + v_k, \tag{7}$$

where $w_k = \sum_{i \neq k}^{\text{all}\, i} a_{ik}x_i$ is the interference term which equals zero when orthogonal spreading sequence is employed. Note that $\mathbf{A}$ is a diagonal matrix if orthogonal spreading code is used. We employ the m-sequence spreading code [9], where the off-diagonal elements in $\mathbf{A}$ is very small when the number of users supported is not greater than the number of chips, i.e., $K \leq P$. Hence, we

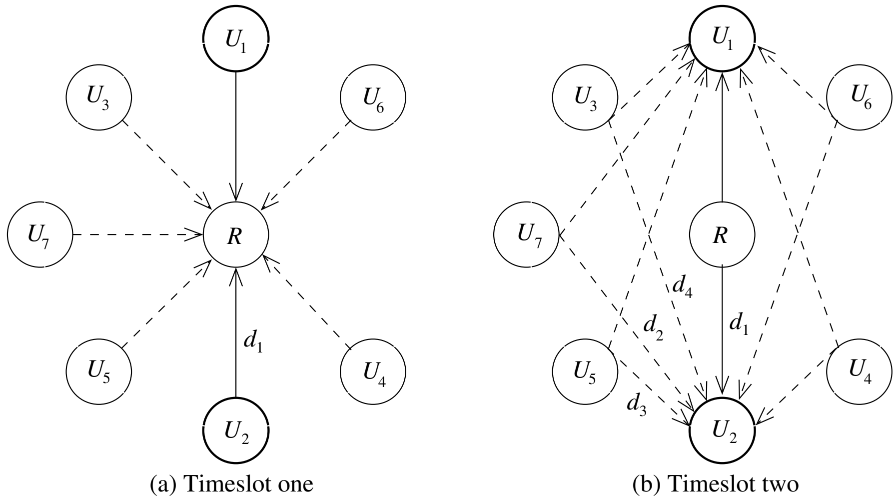


Figure 1: Two-way relaying transmission for users U_1 and U_2, in the presence of five interfering users, with the aid of a relay node, in the **circular model (m1)**. The corresponding normalized distances (and geometrical gains) are given by: $d_1 = 0.5\,(G_1 = 4)$, $d_2 = 0.7071\,(G_2 = 2)$, $d_3 = 0.3827\,(G_3 = 6.8283)$ and $d_4 = 0.9239\,(G_4 = 1.1716)$.

ignore the w_k term in Equation (7), when computing the probability of receiving z_k given that x_k was transmitted as:

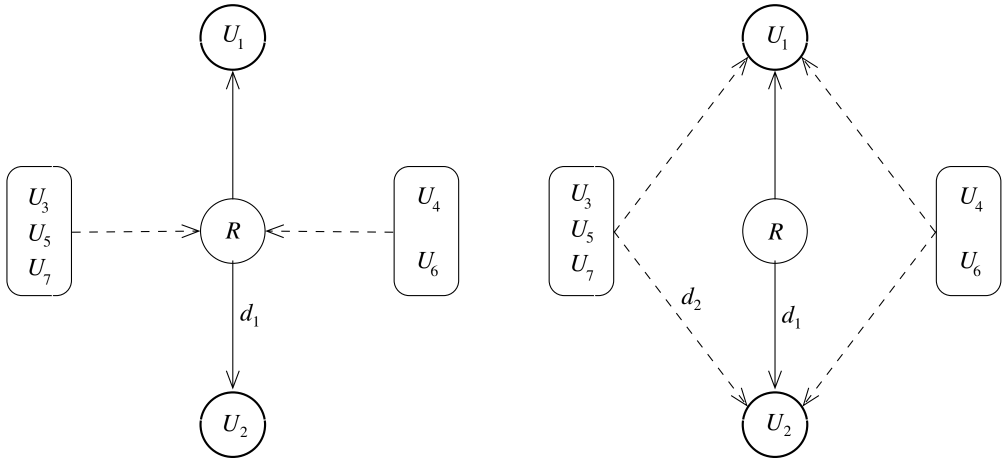
$$P(z_k|x_k) = \frac{1}{\pi N_{0,k}} \exp\left(-\frac{|z_k - a_{kk}x_k|^2}{N_{0,k}}\right). \tag{8}$$

The probability $P(z_k|x_k)$ is computed for each symbol in a transmission frame and then fed to the Turbo decoder for computing the information bit sequence. A more complicated interference-cancelation technique can be employed to remove the w_k term in Equation (7) but we opted for a lower complexity detection, which can still provide a good performance despite ignoring the presence of the inference term w_k in the calculation of Equation (8).

2.1. Network Topology

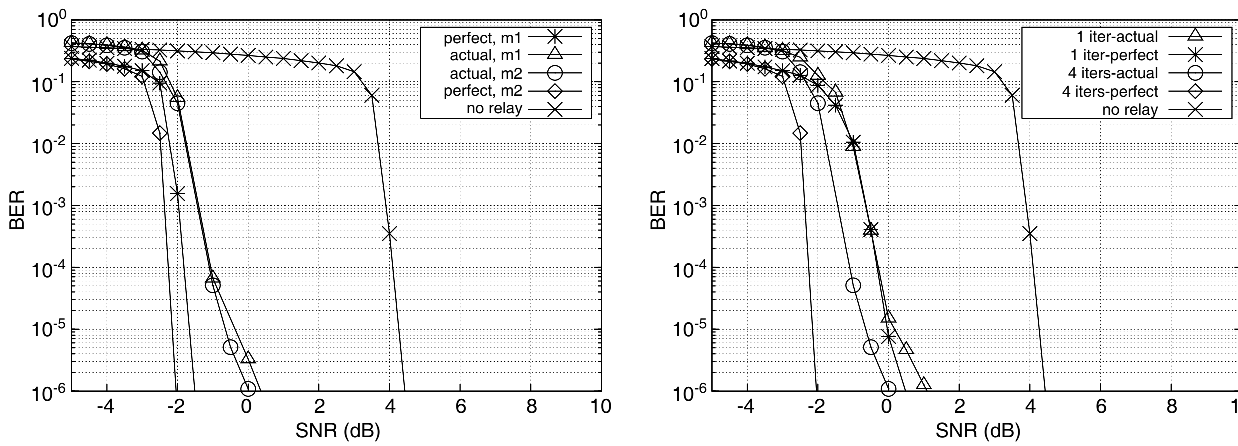
Figure 1 shows the network topology of the circular model (m1) where seven CDMA users are located in a circular arrangement and a relay node is located in the center. Seven-chip m-sequences are considered in our system to support seven users. The Relay Node (R) helps the first user (U_1) and the second user (U_2) to exchanging their information frames, in the presence of five interfering CDMA users (U_3, U_4, U_5, U_6 and U_7). During the first timeslot, U_1 and U_2 transmit their information frames to R, where R detects the two information frames. Then, R re-encodes and broadcasts the two information frames to U_1 and U_2 during the second timeslot. The detection of the wanted information frame at U_1 (or U_2) is also interfered by the other five CDMA users. By contrast, Figure 2 depicts the network topology of the triangular model (m2) where the five interfering CDMA users are located at the two sides in the network topology. Again the detection of the wanted signals at R, U_1 and U_2 are in the presence of the five interfering users. Assuming that the distance between U_1 and U_2 is normalized to unity, the various normalized distances can be calculated according to the trigonometry rules. The normalized distances and the corresponding geometrical gains are shown in the captions of Figures 1 and 2.

At each user node, a half-rate Turbo encoder and a four-level Phase-Shift Keying (4PSK) modulation is employed. At the relay node R, the two decoded information sequences $\mathbf{b}_1$ (from U_1) and $\mathbf{b}_2$ (from U_2) are modulo-two added to produce a new information sequence $\mathbf{b}_0 = \mathbf{b}_1 \oplus \mathbf{b}_2$. Then $\mathbf{b}_0$ is encoded by the same half-rate Turbo encoder into a coded sequence $\mathbf{c}_0$. The same 4PSK modulation is employed to map $\mathbf{c}_0$ into 4PSK sequence $\mathbf{x}_0$, which is then spread by either the spreading sequence of U_1 (or U_2), before it is broadcast to both users. A frame length of $N = 12000$ 4PSK symbols is used. In this study, we add the two user-frames at the information bit level. However, it is also possible to add the two user-frames at the chip-level after the two 4PSK sequences are properly spread by each corresponding CDMA codes. We found that these two approaches give similar performance in our two-way relaying scheme. On one hand, the complexity in using the information bit level addition is lower because only one encoder, one 4PSK mapper and one spreader



(a) Timeslot one (b) Timeslot two

Figure 2: Two-way relaying transmission for users U_1 and U_2, in the presence of five interfering users, with the aid of a relay node, in the **triangular model (m2)**. The corresponding normalized distances (and geometrical gains) are given by: $d_1 = 0.5\,(G_1 = 4)$ and $d_2 = 0.7071\,(G_2 = 2)$.



(a) (b)

Figure 3: BER versus transmit SNR performance of the Turbo-coded CDMA-based two-way relaying system. MMSE detection is used in conjunction with $P = 7$-chip m-sequences in a $K = 7$-user CDMA system. A frame length of 12000 symbols is employed. (a) Performance comparison between the m1 and m2 models. (b) Effect of employing one and four Turbo decoding iterations.

is required. One the other hand, if our scheme is extended to multiple-way relaying system, then all user frames have to be added at the chip-level.

3. PERFORMANCE EVALUATION

The received Signal to Noise power Ratio (SNR) of our relay model is given by [8]:

$$\mathrm{SNR}_r = \mathrm{SNR}_t + 10\log_{10} G, \tag{9}$$

where $\mathrm{SNR}_t = 10\log_{10}(1/N_0)$ is the *transmit* SNR and G is the corresponding geometrical gain. The SNR per information bit is given by:

$$E_b/N_0 = \mathrm{SNR}_t - 10\log_{10}(R\log_2(M)), \tag{10}$$

where R is the coding rate and $\log_2(M)$ is the number of bits per modulated symbol. In our case we have $R\log_2(M) = 0.5\log_2(M) = 1$, hence $E_b/N_0 = \mathrm{SNR}_t$.

The BER versus transmit SNR performance of the Turbo-coded CDMA-based two-way relaying schemes are shown in Figure 3. More specifically, as shown in Figure 3(a), a 7-user CDMA system without using a relay node would require approximately 4.3 dB in order to achieve a BER of 10^{-6}.

However, the relay-aided scheme in the m2 model can achieve the same BER at -2 dB if a perfect relay is assumed. A perfect relay is an idealistic relay where it is capable of detecting all wanted signals without error. However, the scheme using an actual relay in the m2 model is 2 dB away from this upper bound performance. Nonetheless, the relay aided scheme in the m2 model is still approximately 4.3 dB better than that of the non-relay aided scheme. On the other hand, the relay-aided schemes in the m1 model perform approximately 0.5 dB worse than that of their counterparts in the m2 model. This is because in the m1 model, as shown in Figure 1, there exists two strong interferers for either U_1 or U_2 where the normalized distance is given by $d_3 = 0.3827$. By contrast, in the m2 model of Figure 2, all interferers have the same distance d_2 away from U_1 or U_2, where $d_2 > d_3$. A longer distance would inflict a stronger path loss (or a smaller geometrical gain), making the interfering signals to be weaker.

Figure 3(b) shows the effect of the number of Turbo decoding iterations based on the m2 model. The performance of the perfect-relay aided scheme becomes approximately 2.5 dB worse, at a BER of 10^{-6}, when the number of Turbo decoding iterations is reduced from four to one. However, increasing the number of Turbo iterations from one to four, for the scheme employing the actual relay, only provides a gain of approximately one dB, at a BER of 10^{-6}. Hence, the iteration gain at the destination node is limited by the error propagation effects from the relay node.

4. CONCLUSION

Turbo-coded CDMA-based two-way relaying scheme has been studied. It was found that the orthogonality of the spreading code of each CDMA user can be beneficially utilized for enabling a two-way relaying based cooperative communication system, without the need for time/frequency orthogonality as in the conventional one-way relaying system. The proposed two-way relaying scheme is capable of attaining 4.3 dB of SNR gain at a BER of 10^{-6}, when compared to a non-relaying scheme. The proposed scheme can be extended to multiple-way relay scheme with the aid of a relay node that can perform multiuser detection. Powerful channel coding schemes, such as Turbo codes, should be used in order to minimize the detection error at the relay node and consequently to reduce the effects of error-propagation to the destination node.

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