USER COOPERATION DIVERSITY FOR MULTI-USER CCMA

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ABSTRACT

In this paper, we introduce a user cooperation diversity scheme for uplink Collaborative Coded Multiple Access (CCMA) system. In this scheme, the cooperating users transmit their own codewords and that of their partners’ employing collaborative coding. The base-station receives two copies of the composite codeword signals via two different channels. Joint detection and decoding is employed at the receiver to recover the individual users’ codewords and their data based on the minimum distance criteria of collaborative coding. The bit error performance of the proposed technique is analysed in flat Rayleigh fading channels with AWGN, and shown to provide significant gain compared to CCMA with no cooperation and near to that of CCMA using dual receive diversity.

I. INTRODUCTION

In CCMA the multiple access function is achieved by employing collaborative codes allowing multiple users to transmit independently without subdivision in time, frequency or orthogonal codes. The CCMA technique potentially offers higher transmission rate than other multiple access techniques leading to higher capacity and more efficient system [1]. However, one of the main problems of this technique in wireless systems is the practical combining of signals to provide the unique decodability of the composite signals at the receiver. In [2] and [3] effective and practical approach to address this problem is proposed by the use of complex valued CCMA (CV-CCMA) and joint channel estimation and detection. Also, recently, cooperative communication has emerged as an interesting approach to improve the link performance of wireless networks by sharing the antennas and other resources among the mobile nodes (users) [6]-[9]. It becomes more useful particularly for the mobile users, which can not due to their size and power limitations, employ more than one antenna to communicate with other users or base-station. The cooperation concept was used much earlier in the case of improving the performance of node to node communication by using additional relay nodes e.g.[4],[5]. The paper by Sendonaris et.al [6] has considered user cooperation in multiuser communications and particularly for CDMA.

In this paper, we propose a cooperative scheme for achieving the diversity gain in the uplink of a multiuser system employing CCMA. Here, the users are proposed to work in pairs to transmit their own and each other’s information to the base-station with the use of collaborative codes. The reception is based on the joint detection of codewords similar to CV-CCMA. The communication protocol is designed as such to transmit the coded signals over two codeword periods from the two cooperating users to allow for the exchange of users’ data and provide two copies of the signals at the receiver from different channels. The paper is organized as follows. In section II, the cooperative CCMA system model is presented. The proposed cooperative CCMA implementation is described in section III. The bit error performance analysis and simulation results are presented in section IV and V. Finally the paper is concluded in VI.

II. COOPERATIVE CCMA SYSTEM MODEL

A multiuser communication system of an uplink CCMA with T users and a base-station receiver \( \{d\} \) is considered. The cooperation scenario between two users is shown in Fig. 1, where the users communicate between themselves and the base-station receiver. The cooperating users are denoted as user \( i \) with it’s partner \( u \) and vice versa. The data from \( i^{th} \) user \( b_i \) is first encoded with collaborative codes \( C_i = \{C_{i1}, C_{i2}, \ldots, C_{iN}, \ldots, C_{iN}\} \), where \( C_{id} \) is the \( i^{th} \) codeword of \( i^{th} \) user of length \( n \) bits and \( N_i \) is the number of codewords for the \( i^{th} \) user assumed equal for all users. The transmitted signal elements of each codeword is denoted by \( C_{id} = \{s_{i1}, s_{i2}, \ldots, s_{ij}, \ldots, s_{in}\} \) that use BPSK mapping. The channels are assumed flat Rayleigh fading and remain constant over the duration of the cooperating periods. The channels are modeled as samples of complex Gaussian random variable with variances \( \sigma_{iu}^2, \{i \neq u\}, \sigma_{id}^2 \).

For \( T=2 \), the cooperation is performed over two codeword
periods, to exchange users’ information and retransmit to the base-station. The received signals during the exchange period at the first and second user are given by

\[ r_{1j} = s_{1j}g_{21} + w_1, \]
\[ r_{2j} = s_{1j}g_{12} + w_2, \]
\[ 1 \leq j \leq n \]  

(1)

where, \( r_{1j} \) is the \( j^{th} \) received coded symbol at the \( 1^{st} \) user, \( s_{1j} \) is \( j^{th} \) transmitted coded symbol of the \( 2^{nd} \) user, \( g_{12}, g_{21} \) are the inter-user channels between the cooperating users with variances \( \sigma_{12}^2, \sigma_{21}^2 \), respectively and \( w_1 \) is AWGN with two sided power spectral densities \( N_0/2 \) for \( 1^{st} \) user.

The received signals at the base-station \( d \) from both users during the first and second period \( r_{dj}, r'_{dj} \), respectively are given by

\[ r_{dj} = s_{1j}g_{1d} + s_{2j}g_{2d} + w_d, \]
\[ r'_{dj} = s'_{1j}g_{2d} + s'_{2j}g_{1d} + w_d, \]
\[ 1 \leq j \leq n \]  

(2)

where, \( s_{1,j} \) and \( s'_{1,j} \) are the transmitted signals of user 1 from its own and partner’s node, \( g_{1d} \) and \( g_{2d} \) are the transmit channels of the users to the base-station with variances \( \sigma_{1d}^2 \) and \( \sigma_{2d}^2 \), respectively.

In a 2-user cooperative CCMA transmissions, there are \( L \) allowable codeword combinations \( \mathbf{A}_k = \{a_{k1}, a_{k2}, \ldots, a_{kn}\}, 1 \leq k \leq L \), consisting of the two users’ composite codewords over their corresponding complex channels. Each element \( a_{kj} \) is the \( j^{th} \) symbol of \( k^{th} \) allowed composite codeword is given by

\[ a_{kj} = s_{1j}g_{1d} + s_{2j}g_{2d}, \]
\[ 1 \leq k \leq L, 1 \leq j \leq n \]  

(3)

Similarly codeword combinations \( \mathbf{A}'_k = \{a'_{k1}, a'_{k2}, \ldots, a'_{kn}\} \) are defined for the second period and each element is given by

\[ a'_{kj} = s'_{1j}g_{2d} + s'_{2j}g_{1d}, \]
\[ 1 \leq k \leq L, 1 \leq j \leq n \]  

(4)

For a cooperative scheme to perform satisfactorily, the inter-user channel gains are desired to be higher or at least equal to that of the respective transmit channels of the users to the destination (base-station in this work) [5]. Assuming equal average signal power and noise variances of all users’ and base-station receivers, the relative signal to noise ratio (SNR) gain \( \{\beta_1\} \) and \( \{\beta_2\} \) of inter-user channels compared to the respective transmit channels of the users to the base-station can be expressed as

\[ \beta_1 = \frac{\sigma_{12}^2}{\sigma_{2d}^2}, \quad \beta_2 = \frac{\sigma_{21}^2}{\sigma_{2d}^2} \]  

(5)

### III. THE COOPERATION SCHEME IMPLEMENTATION

Based on the system model, a signalling method of the proposed scheme with two users spanned over two consecutive codeword periods is shown in Table 1. A single cycle of cooperative codewords transmission can also be written in a matrix form as

\[ \mathbf{S} = \begin{pmatrix} C_{11} & C'_{21} \\ C_{21} & C'_{11} \end{pmatrix} \]  

(6)

where the columns indicate the codeword time periods \( (t_1, t_2) \) and the rows indicate users’ codewords transmission. The signals in first column represent users’ own codewords whereas, the signals in the second column are the estimated codewords at the partners’ nodes.

#### Phase I: Codewords exchange

In the first period, the users’ transmit their signals as shown in (6). Due to the broadcast nature of the channels, the signals are simultaneously received both at the cooperating users and at the base-station receiver. At the same time, the received signals are independently processed at the users’ receivers. For handling these operations, we assume full duplex capabilities are available [5],[6]. The received signals at this period are given in (1). The detection of signals at each other user node is achieved by first obtaining the soft estimates of the signals, for example the first user this is given by

\[ \tilde{s}_{1j} = r_{2j}g_{12}^*; 1 \leq j < n \]  

(7)

where, * denotes complex conjugation operation. Then by taking the sign of the real part of the signal \( \tilde{s}_{1j} \) over the codeword length \( n \), the estimate of the first user’s transmitted signal \( s'_{1j} \) is obtained for transmission in second period

\[ s'_{1j} = \text{sgn}\{\text{Re}\{\tilde{s}_{1j}\}\}; 1 \leq j < n \]  

(8)
where $\text{sgn} \{ \cdot \}$ and $\Re \{ \cdot \}$ denote the signum function and the real part of a complex number, respectively.

**Phase II: Retransmission of detected codewords**

During this phase, the cooperating users simply forward the detected codewords of the partners to the base-station receiver $C_{it}^\text{r}$. It should be noted that this codeword may not be identical to the codewords transmitted by source users in the first phase due to detection errors.

**Joint detection and decoding at base-station receiver**

The receiver performs joint detection and maximum likelihood (ML) decoding of users’ codewords and provides the estimates of transmitted data signals of both users. The distance metrics from the received signals for each combination of codewords at two consecutive periods are denoted as $d_k$ and $d'_k$, respectively. The distance metrics are calculated by utilizing the estimates of users’ corresponding channels for each combination of codewords as follows

$$d_k = \sum_{j=1}^{2^n} r_{d_j} - \left( s_{1j}\hat{g}_{1d} + s_{2j}\hat{g}_{2d} \right)^2$$

$$d'_k = \sum_{j=1}^{2^n} r'_{d_j} - \left( s_{1j}\hat{g}_{1d} + s_{2j}\hat{g}_{1d} \right)^2 \quad \forall k, 1 \leq k \leq L$$

where, $\hat{g}_{1d}$ and $\hat{g}_{2d}$ are the channel estimates of the 1st and 2nd user, respectively. The sum of calculated distance metrics $d_k$ and $d'_k$ for each combination of codewords from the two phases are used to perform ML decoding such that the combination of codewords that minimizes the sum of distance metrics are selected as the transmitted codewords of the users

$$\{\hat{C}_1, \hat{C}_2\} = \arg \min_{C_1, C_2 \in \mathbf{W}} \left\{ d_k + d'_k \right\}$$

where, $\mathbf{W}$ is the set of codewords of all users. Finally, the data symbols of the users are obtained by using a lookup table decoding of the codewords to the symbols as used at the transmitters.

**IV. BER Performance Analysis**

The probability of bit error of the collaborative coded multiuser signals using BPSK mapping in flat slowly fading channels can be derived by doing some simple modifications to the tools developed for single user signals in [10],[11]. For this purpose, we derive error metric associated with each codeword combination of the transmitted signals. The absolute magnitude of distance between different composite codeword combinations are calculated and normalized with $n$ to give an error metric $z_m$ as follows

$$z_m = \frac{\left| \{C_{1x} + C_{2x}\} - \{C_{1y} + C_{2y}\} \right|_n}{1 < m < M; 1 < x \neq y < L}$$

(11)

where, $\{C_{1x}, C_{2x}\}$ and $\{C_{1y}, C_{2y}\}$ are any possible two composite codeword combinations of user 1 and 2, $M = \sum_{m=1}^{L-1} m$ is the total number of possible distances between codeword combinations. Assuming that all the codewords are equally likely to be transmitted, it is appropriate to find the average error metric so that the tools developed for single user signals can be used. Averaging $z_m$ over all $M$ possible distances between the codeword combinations, we obtain the average error metric $z$, that is used for the bit error performance approximation of the CCMA scheme.

$$z = \frac{\sum_{m=1}^{M} z_m}{M}$$

(12)

Using $z$, we can now calculate the probability of bit error of existing (non-cooperative) CCMA over fading channels both with and without diversity. For the ideal cooperation case i.e. where each user perfectly decodes it’s partner’s codewords, the performance of the proposed scheme becomes identical to that of CCMA scheme with dual space diversity reception. The BER performance conditioned on the transmit channels of the cooperating users can also be written as

$$P(z|\gamma_{1d},\gamma_{2d}) = Q\left( \sqrt{z(\gamma_{1d} + \gamma_{2d})} \right)$$

(13)

where, $Q(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-t^2/2} dt$ is the well known Gaussian error function, $\gamma_{1d}$ and $\gamma_{2d}$ are the instantaneous SNRs of the transmit channels of user 1 and 2, respectively. To obtain the average error probability $P(z)$ in fading channels, we have to calculate (13) over all the fading events of the users [9] and is written as

$$P(z) = \int_0^\infty \int_0^\infty P(z|\gamma_{1d},\gamma_{2d}) p(\gamma_{1d})p(\gamma_{2d}) \gamma_{1d} \gamma_{2d} \gamma_{1d} \gamma_{2d}$$

(14)

where $p(\gamma_{1d})$ and $p(\gamma_{2d})$ are the PDF of fading distributions of user 1 and 2, respectively. In [10] a unified approach to calculate the probability of error of linearly modulated single user digital signals in arbitrary fading channels is proposed. This approach using moment generating function (MGF) and alternate representation of $Q$ function originally proposed by Craig in [10], allows the expressions within indefinite integrals of fading events in (14) to be accurately approximated using set of definite integrals. Using this approach $P(z)$ can then be written as

$$P(z) = \frac{1}{\pi} \int_0^{\pi/2} \left( 1 + \frac{z\Gamma_{1d}}{s \sin^2 \theta} \right)^{-1} \left( 1 + \frac{z\Gamma_{2d}}{s \sin^2 \theta} \right)^{-1} d\theta$$

(15)

where, $\Gamma_{1d}$ and $\Gamma_{2d}$ are the ensemble average SNR of fading distributions of the user 1 and 2 with instantaneous SNR...
of $\gamma_1d$ and $\gamma_2d$, respectively. The upper bound on the $P(z)$ is obtained by knowing the fact that the integrands in (15) are maximized when $\sin^2 \theta = 1$. Thus probability of error bound of CCMA signals with dual receive diversity can be shown as

$$P(z) \leq \frac{1}{2} \left( \frac{1}{1 + z\Gamma_1d} \right) \left( \frac{1}{1 + z\Gamma_2d} \right)$$  \hspace{1cm} (16)$$

For the case of the CCMA without diversity, using the error metric of (12), the the probability of error $P(z)$ can be derived as follows

$$P(z) \leq \frac{1}{2} \left( \frac{1}{1 + z\Gamma_d} \right)$$  \hspace{1cm} (17)$$

where $\Gamma_d = 1/2(\Gamma_1d + \Gamma_2d)$ is the averaged SNR of users’ channels to the base-station receiver.

V. SIMULATION RESULTS AND COMPARISONS

In this section, we present the performance bounds and simulation results of the cooperative and non-cooperative (with and without receive diversity) CCMA schemes under different channel conditions. A simple 2-user CCMA system with BPSK mapping and two codewords per user each of length 3 is used. The modulated codewords of user 1 and user 2 are $C_1 = \{1, 1, 1\}, \{-1, -1, 1\}$ and $C_2 = \{1, -1, 1\}, \{-1, 1, 1\}$, respectively. It is assumed that all the users’ and the base-station receivers have perfect knowledge of their received channels.

In Figure 2, we plot the derived BER performance bounds of the non-cooperative CCMA using these codewords as given in equations (16) and (17). For the purpose of verification, the simulation results are also obtained and shown in Figure 2. It is noted that the derived BER bounds become tighter with the increase of diversity order. The performance of the cooperative CCMA with inter-user channel SNR gain of ($\beta_1 = \beta_2 = 20\,\mathrm{dB}$) is shown as expected to be within the range of the dual diversity and no diversity bounds. Also, the BER performance of a single user BPSK with dual diversity using maximum ratio combining (MRC) is shown for comparison.

Figure 3 shows the BER simulation results of the proposed 2-user cooperative and the non-cooperative CCMA with same channel settings. The ratios $\beta_1$ and $\beta_2$ described in (5) are used to quantify the degree of cooperation of the proposed scheme. The variances of all users transmit channels to the base-station are assumed to be equal to one ($\sigma_1^2 = \sigma_2^2 = 1$) and $\beta_1 = \beta_2$. Then as expected, as $\beta_1$ increases, the degree of cooperation increases and the proposed scheme shows rapid improvement in BER performance. Also it is noted from the figure that, even when all the channels have average equal variances i.e. $\beta_1 = 0\,\mathrm{dB}$, the scheme still offers several dB of $E_b/N_0$ gain compared to the non-cooperative scheme. When $\beta_1 = 20\,\mathrm{dB}$, at the BER of $10^{-3}$, the performance of cooperative CCMA is only around $0.5\,\mathrm{dB}$ worse to that of CCMA with dual receive diversity.

Figure 4 shows the BER performance of CCMA schemes for the case of non-identical average variances of each cooperating users’ transmit channels to the base-station receiver. The condition also termed as ‘channel asymmetry’, is defined by the ratio given below

$$\beta_d = \frac{\sigma_1^2}{\sigma_2^2}$$  \hspace{1cm} (18)$$

For the channel asymmetry ratio of $\beta_d = 10\,\mathrm{dB}$, when the
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Figure 4: BER performance of the 2-user cooperative and non-cooperative CCMA with channel asymmetry condition of $\beta_d = 10\,\text{dB}$ and inter-user SNR gains $\beta_1 = 0\,\text{dB}, \beta_2 = 10\,\text{dB}$

inter-user channels have relative SNR gain of $\beta_1 = 0\,\text{dB}$, $\beta_2 = 10\,\text{dB}$, the cooperative CCMA scheme offers significant improvement in error performance for both users compared to that with non-cooperative CCMA without diversity. This result is very beneficial for the mobile users, and particularly for the weaker users as their performances are now significantly less sensitive to the fading effect than that in the non-cooperative case.

VI. CONCLUSION

We proposed a new approach to improve the performance of multi-user CCMA system by employing user cooperation diversity in fading channel conditions. The probability of error performance of CCMA and cooperative CCMA are presented under different diversity and channel conditions. The proposed cooperative scheme is shown to provide significant gains approaching that of CCMA with dual receiver diversity as the ratio of inter-user channel gains increase.

REFERENCES


