BER Performance of Cooperative Transmission for the Uplink of TDD-CDMA Systems

Khuong Ho Van and Hyung Yun Kong

In time division duplex (TDD) code division multiple access (CDMA) systems, chip-synchronous transmission in the uplink is obtainable, thus leading to free multiple access interference in flat Rayleigh fading channels plus additive white Gaussian noise. This motivates us to develop a novel cooperative transmission strategy that allows single-antenna devices to benefit from spatial diversity using orthogonal signature sequences. The proposed cooperation is applicable to many digital modulation methods and achieves the fullest diversity level, low implementation complexity, and a full data rate. Closed-form bit-error-rate expressions were also derived and compared to simulation results in order to evaluate its validity. A variety of numerical results demonstrated the cooperation's superiority over single transmission under the same transmit power constraint.

Keywords: Cooperative transmission, STBC, Rayleigh fading, additive white Gaussian noise, TDD-CDMA, multiple access interference, MPSK.

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I. Introduction

Time division duplex (TDD) code division multiple access (CDMA) has been researched and experimented intensively and extensively to become a standard for the 4th-generation mobile communications system [1] due to its advantages such as design simplicity, efficient bandwidth utilization, and high performance. Moreover, a very interesting characteristic of TDD-CDMA is feasibility of chip-synchronous transmission in the uplink. The regular TDD slots allow a mobile device to precisely detect changes in the propagation delay and to adjust its transmission time such that its signal may arrive synchronously with other users in the same cell. As a result, the orthogonal spreading codes assigned to each mobile can completely remove multiple access interference (MAI) in flat Rayleigh fading channels plus additive white Gaussian noise.

In wireless networks, signal fading arising from multi-path propagation is a particularly severe channel impairment that can be mitigated through the use of diversity [2], which amounts to transmitting the same information over multiple channels that fade independently of each other. Some popular diversity techniques are time diversity and frequency diversity, where the same information is transmitted at different time instants or in different frequency bands, as well as antenna diversity in which one exploits the fact that fading is independent between different points in space. A simple way to make antenna diversity possible is to deploy multiple antennas at both the transmitter and receiver [3]. However, when wireless agents may not be able to support such multiple antennas due to size or other constraints [4], the conventional space-time coding cannot be used for transmit diversity. To overcome this restriction, a new technique, called cooperative transmission [4]-[11], was born that allows single-antenna mobiles to gain some benefits of spatial diversity. These advantages are practically achievable by using a collection of distributed antennas belonging to multiple users as a virtual antenna array. Thanks to cooperation with some partners by relaying information to each other, redundant messages are generated and delivered over multiple independent paths in the network, and this redundancy enables the receivers to essentially average channel fluctuations. Since the inter-user channel is noisy and faded, the relayed information is not perfect. Hence, one has to carefully study the possible signaling strategies that can most exploit the benefits of cooperative transmission. Aiming at that goal, we propose a cooperative scheme where two collaborative users share the same spreading code to exchange information together along with their own codes, which are used by the base station (BS) to distinguish one user from one another in a multiple access environment. Even though this waste of spreading code seems unreasonable, the group transmission mode [1] (a few users served in a time slot) in TDD-CDMA systems makes the redundancy of spreading codes available for use in a cooperation process, thus taking the greatest advantage of redundancy to obtain high performance, is very appropriate. In addition, the proposed cooperative transmission strategy can exploit the Alamouti code [12], which is the simplest space time block code (STBC) and has been adopted in the 3G WCDMA standard [13] to attain both full diversity and full rate, as well as to reduce the implementation complexity of the receiver. In the cooperation process, each user doesn't perform hard detection on the signal of its partner as in [5], but rather it simply estimates (by performing the despreading of the received signal) and forwards the resultant signal to the destination. This not only reduces the processing time at each user but also avoids the wrong decisions that can adversely affect the overall performance at the destination.

In this paper, besides proposing a new cooperative transmission strategy, we designed the detector and derived the closed-form bit-error rate (BER) expressions for each cooperative user under the transmit power constraint and the slow and flat Rayleigh fading channel plus Gaussian noise. The rest of the paper is organized as follows. The cooperative scheme and signal analysis are presented in detail in section II. Theoretical performance evaluations for both cooperation and non-cooperation cases, and the numerical results as well as simulation results are described and analyzed in sections III and IV, respectively. Finally, the paper is concluded in section V with many useful comments.

II. Cooperative Transmission

As discussed above, a TDD-CDMA system makes chip-synchronous transmission in the uplink possible, and as a result the orthogonality of spreading codes is remained for each user's signal to be completely distinguishable at the receiver. Therefore, the performance analysis of multi-user systems can be done in a similar fashion to the case of two users. For this reason, we only investigate cooperative transmission consisting of two mobile devices communicating with a base station in a cellular system, as shown in Fig. 1, during each time slot with the assumption that the devices can receive and send data simultaneously in the uplink. The basic idea is to construct a system such that signals transmitted by each user arrive at the base station through two independent fading paths while maintaining the same average power as a comparable non-cooperative system.

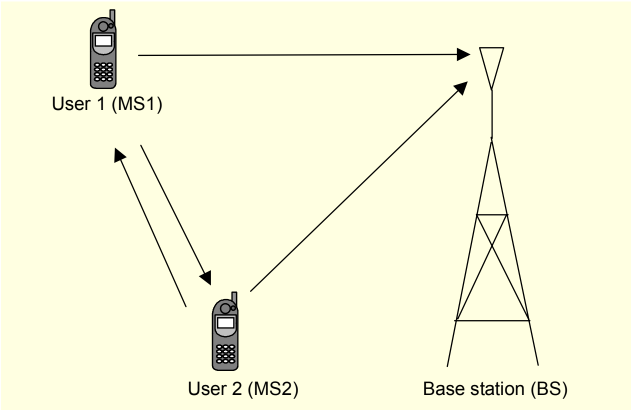

Fig. 1. Cooperative transmission scheme.

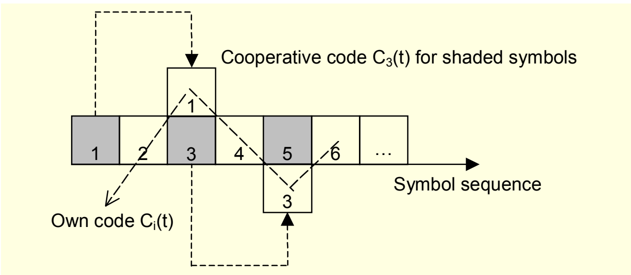

Fig. 2. Transmit symbol distribution in a time slot.

Figure 2 illustrates the chronological order for transmitting the data of each user in a time slot for whom two different spreading codes are allocated: an own code $C_i(t)$ for discriminating between active users and a cooperative code $C_3(t)$ for common usage. All original symbols (represented on the straight line, 1, 2, 3, 4, 5, 6…) are spread by the cooperative code in succession to the own code. For example, a symbol sequence numbered 1-2-3-4… will be spread by a spreading code sequence C_3-C_i-C_3-C_i… However, the repeated symbols (denoted by arrows, 1, 3…) always utilize the own code for spreading. Assuming that the echo cancellation at each mobile is perfect, each user only receives the signal from its partner; thus one spreading code is sufficient to share information for a pair of users. Figure 2 also indicates a structural reiteration of transmitted signals such that sending two symbols simultaneously (a new one and the replica of the symbol in the previous interval) is interleaved equally with transmitting only a new symbol. Such a repeat facilitates the signal processing at each side. Moreover, source data is sent continuously over the channel, and therefore the system obtains the full rate regardless of the cooperation in progress. This is one of the advantages of the proposed cooperative scheme because most cooperation is paid for the loss of data rate [4]-[11]. For example, the cooperative scheme in [5] takes three symbol periods to transmit only two data symbols, as shown in Table 2 in the Appendix; that is, the user can solely obtain 2/3 of the maximum possible transmission rate (MPTR). In contrast, our proposed scheme can send (K-1) symbols in a TDD time-slot of K symbol periods, as shown in Table 1. Therefore, the MPTR each user attains is (K-1)/K. For large values of K, the ratio (K-1)/K reaches 1, so our scheme offers the full rate.

Table 1. Summary of transmit and receive signals.

Symbol periods	User 1 (MS1)	
	Transmit	Receive
1	$\beta_{11}a_{11}C_3$	$y_{11}(t)$
2	$-\beta_{12}a_{12}^*C_1+p_{12}\bar{y}_{11}^*C_2$	$y_{12}(t)$
3	$\beta_{13}a_{11}C_1-p_{13}\bar{y}_{12}^*C_2+\beta_{11}a_{13}C_3$	$y_{13}(t)$
4	$-\beta_{12}a_{14}^*C_1+p_{12}\bar{y}_{13}^*C_2$	$y_{14}(t)$
5	$\beta_{13}a_{13}C_1-p_{13}\bar{y}_{14}^*C_2+\beta_{11}a_{15}C_3$	$y_{15}(t)$
6	$-\beta_{12}a_{16}^*C_1+p_{12}\bar{y}_{15}^*C_2$	$y_{16}(t)$
…	…	…

Symbol periods	User 2 (MS2)	
	Transmit	Receive
1	$\beta_{21}a_{21}C_3$	$y_{21}(t)$
2	$-\beta_{22}a_{22}^*C_2+p_{22}\bar{y}_{21}^*C_1$	$y_{22}(t)$
3	$\beta_{23}a_{21}C_2-p_{23}\bar{y}_{22}^*C_1+\beta_{21}a_{23}C_3$	$y_{23}(t)$
4	$-\beta_{22}a_{24}^*C_2+p_{22}\bar{y}_{23}^*C_1$	$y_{24}(t)$
5	$\beta_{23}a_{23}C_2-p_{23}\bar{y}_{24}^*C_1+\beta_{21}a_{25}C_3$	$y_{25}(t)$
6	$-\beta_{22}a_{26}^*C_2+p_{22}\bar{y}_{25}^*C_1$	$y_{26}(t)$
…	…	…

Base station (BS)	
Symbol periods	Receive
1	
2	$y_{BS2}(t)$
3	$y_{BS3}(t)$
4	$y_{BS4}(t)$
5	$y_{BS5}(t)$
6	$y_{BS6}(t)$
7	$y_{BS7}(t)$
…	…

The new cooperative transmission strategy is illustrated in Table 1. It is applicable to many digital modulation methods but we limit the theoretical analysis to M-ary phase-shift keying (MPSK)-modulation for simplicity. The notations in Table 1 stand for the following quantities.

- a_{ij}: user i's j-th modulated symbol. Without loss of generality, its amplitude is assumed to be 1, which is equally likely.
- $C_i(t)$: user i's spreading code given by

$$C_i(t)=\sum_{n=1}^{N}c_i(n)p(t-nT_C),$$

where $c_i(n)$ denotes the n-th chip of the i-th code, $p(t)$ is a unit-amplitude rectangular pulse with time duration equal to the chip duration, and N is the code length.

- β_{ij}: amplification factor for user i's own signal.
- p_{ij}: amplification factor for the estimated signal of the partner of user i.

  The parameters $\{\beta_{ij}, p_{ij}\}$ control how much power is allocated to a user's own symbols versus the symbols of the partner, while maintaining an average power constraint of P_i for user i.
- $y_{ij}(t)$: signal of user i's partner received during symbol period j.
- $y_{BSi}(t)$: received signal at the base station in symbol period i.

Moreover, there are the other channel parameters used throughout this paper such as α_{12}, α_{13}, α_{23} being the path gains of the channels between mobile stations MS1 and MS2, MS1 and the BS, and MS2 and the BS, respectively, which reflect the fading level from the transmit antenna to the receive antenna. We assume slow and flat Rayleigh fading; hence, they are modeled as independent samples of zero-mean complex Gaussian random variables (ZMCGRVs) with variances $\sigma_{12}^2,\sigma_{13}^2,\sigma_{23}^2$ and are constant during the two-symbol transmission of any given user, but change independently to the next. Because of slow fading, accurate channel estimation is possible at the receiver [5]. Thus, we will assume perfect channel-state information at all the respective receivers but not at the transmitters. For the inter-user channel, it is also assumed to be reciprocal (the channel characteristics are similar for both directions). The alternative parameters $n_{1ij}(t)$, $n_{0k}(t)$ (i = 1,2; j = 1,2; k = 2,3), are noise samples corrupting the inter-user channel and MS-BS channel that are modeled as independent ZMCGRVs with variances σ_1^2,σ_2^2, correspondingly. Finally, Gaussian noise and Rayleigh fading are considered to be statistically independent.

For convenience of exposition, we use complex equivalent base-band models to express all signals. Now, consider the first three symbol periods and assume that each user priorly knows the spreading codes of its partner, $C_i(t)$ and $C_3(t)$, while the base station is only interested in the users' own codes, $C_i(t)$. Due to having two signature sequences, each user must be equipped with two chip-matched filters separately, each for one code.

The cooperation process works as follows. During the first symbol period, users send their own data spread by their cooperative spreading code $C_3(t)$. The received signal at user i (i =1,2) is hence given by

$$y_{11}(t) = \alpha_{12}\beta_{21}a_{21}C_3(t) + n_{111}(t), \quad (1a)$$

$$y_{21}(t) = \alpha_{12}\beta_{11}a_{11}C_3(t) + n_{112}(t). \quad (1b)$$

At the end of this period, each user obtains the information of its partner by chip-matched filtering the received signal with the cooperative code. This filter's output is the partner's estimated signal distorted by fade and noise of the form

$$\bar{y}_{11} = \frac{1}{NT_C}\int_0^{NT_C} y_{11}(t)C_3(t)dt = \alpha_{12}\beta_{21}a_{21} + \bar{n}_{111}, \quad (2a)$$

$$\bar{y}_{21} = \frac{1}{NT_C}\int_0^{NT_C} y_{21}(t)C_3(t)dt = \alpha_{12}\beta_{11}a_{11} + \bar{n}_{112}. \quad (2b)$$

Without loss of generality, chip duration can be considered to be 1 time unit (T_C = 1). Thus, $\bar{n}_{1ij}$ are ZMCGRVs with variance σ_1^2/N, hereafter, i=1,2; j=1,2.

In the second period, each user amplifies the information $\bar{y}_{i1}$ received in the previous interval with the gain p_{ij} and sends it along with its own spread data. Therefore, during the second period, user i receives

$$y_{12}(t) = \alpha_{12}\left\{-\beta_{22}a_{22}^*C_2(t) + p_{22}\bar{y}_{21}^*C_1(t)\right\} + n_{121}(t), \quad (3a)$$

$$y_{22}(t) = \alpha_{12}\left\{-\beta_{12}a_{12}^*C_1(t) + p_{12}\bar{y}_{11}^*C_2(t)\right\} + n_{122}(t), \quad (3b)$$

where $\bar{y}_{21}, \bar{y}_{11}$ are the partner's noised signals in the first period; (.)* denotes a complex conjugate.

The despread signals produced at the end of the second period corresponding to the above are given by

$$\bar{y}_{12} = \frac{1}{NT_C}\int_0^{NT_C} y_{12}(t)C_2(t)dt = -\alpha_{12}\beta_{22}a_{22}^* + \bar{n}_{121}, \quad (4a)$$

$$\bar{y}_{22} = \frac{1}{NT_C}\int_0^{NT_C} y_{22}(t)C_1(t)dt = -\alpha_{12}\beta_{12}a_{12}^* + \bar{n}_{122}. \quad (4b)$$

In the third period, user i constructs a following signal based on three information sources: current symbol a_{i3}, repeated symbol a_{i1}, and the partner's estimated information $\bar{y}_{i2}$ in the previous period

$$\beta_{i3}a_{i1}C_i(t) - p_{i3}\bar{y}_{i2}^*C_{i'}(t) + \beta_{i1}a_{i3}C_3(t),$$

where i' stands for the index of the partner of user i; for example, if i=1 and a cooperative pair are user 1 and user 2, then i'=2.

Moreover, in the last two periods the base station starts to receive and process the signals from the mobiles. Those received signals are given by

$$y_{BS2}(t) = \alpha_{13}\left\{-\beta_{12}a_{12}^*C_1(t) + p_{12}\bar{y}_{11}^*C_2(t)\right\} + \alpha_{23}\left\{-\beta_{22}a_{22}^*C_2(t) + p_{22}\bar{y}_{21}^*C_1(t)\right\} + n_{02}(t), \quad (5)$$

$$y_{BS3}(t) = \alpha_{13}\left\{\beta_{13}a_{11}C_1(t) - p_{13}\bar{y}_{12}^*C_2(t) + \beta_{11}a_{13}C_3(t)\right\} + \alpha_{23}\left\{\beta_{23}a_{21}C_2(t) - p_{23}\bar{y}_{22}^*C_1(t) + \beta_{21}a_{23}C_3(t)\right\} + n_{03}(t), \quad (6)$$

where $\bar{y}_{12}, \bar{y}_{22}$ are expressed in (4).

Now, the BS carries out decoding separately the signals for MS1 and MS2 during the second and third symbol-periods by user-specific spreading codes.

1. For User 1

At the BS, the MS1's estimated signals at the output of the chip-matched filter corresponding to the third and second periods are respectively given by

$$\begin{aligned} r_{11} &= \frac{1}{NT_C}\int_0^{NT_C} y_{BS3}(t)C_1(t)dt \\ &= \alpha_{13}\beta_{13}a_{11} - \alpha_{23}p_{23}\bar{y}_{22}^* + \bar{n}_{031} \\ &= \alpha_{13}\beta_{13}a_{11} + \alpha_{23}p_{23}\alpha_{12}^*\beta_{12}a_{12} - \alpha_{23}p_{23}\bar{n}_{122}^* + \bar{n}_{031}, \end{aligned} \quad (7)$$

$$\begin{aligned} r_{12} &= \frac{1}{NT_C}\int_0^{NT_C} y_{BS2}(t)C_1(t)dt \\ &= -\alpha_{13}\beta_{12}a_{12}^* + \alpha_{23}p_{22}\bar{y}_{21}^* + \bar{n}_{021} \\ &= -\alpha_{13}\beta_{12}a_{12}^* + \alpha_{23}p_{22}\alpha_{12}^*\beta_{11}a_{11}^* + \alpha_{23}p_{22}\bar{n}_{112}^* + \bar{n}_{021}, \end{aligned} \quad (8)$$

where $\bar{n}_{0ij}$ are ZMCGRVs with variance σ_2^2/N, hereafter, i=2,3; j=1,2. The last expressions in (7) and (8) are derived by replacing $\bar{y}_{21}, \bar{y}_{22}$ with those in (2b) and (4b).

We choose

$$\beta_{13} = \beta_{12}, \quad p_{23}\beta_{12} = p_{22}\beta_{11}. \quad (9)$$

Then, (7) and (8) can be rewritten as

$$r_{11} = \gamma_{11} a_{11} + \gamma_{12} a_{12} - \alpha_{23} p_{23} \bar{n}^*_{122} + \bar{n}_{031}, \quad (10)$$

$$r_{12} = -\gamma_{11} a^*_{12} + \gamma_{12} a^*_{11} + \alpha_{23} p_{22} \bar{n}^*_{112} + \bar{n}_{021}, \quad (11)$$

where

$$\gamma_{11} = \alpha_{13}\beta_{13}, \quad \gamma_{12} = \alpha_{23} p_{23} \alpha^*_{12} \beta_{12}. \quad (12)$$

Equations (10) and (11) are analytical expressions at the receiver for 2-transmit antenna and 1-receive antenna space diversity using the Alamouti STBC 2 x 2 [12]. Therefore, applying the simple detection technique in [12] will generate the estimated values of a_{11} and a_{12}

$$\bar{a}_{11} = r_{11}\gamma^*_{11} + r^*_{12}\gamma_{12}, \quad (13)$$

$$\bar{a}_{12} = r_{11}\gamma^*_{12} - r^*_{12}\gamma_{11}. \quad (14)$$

Compared to the receiver in [5] (see the Appendix), it is obvious that the receiver in the proposed scheme is much simpler in hardware implementation because it applies a unique detector that is greatly different from [5], where two detectors are switched to recover two consecutive symbols. Moreover, the partial cooperation (only one cooperative symbol) and hard decision at each partner's side in [5] didn't exploit the potential of the cooperation at its most, and as a result the overall performance is not much improved. In contrast, our cooperative transmission strategy exposes the total cooperation and avoids the hard estimate to reduce the probability of error and the processing time.

Substituting r_{11} and r_{12} in (10) and (11) into (13) and (14), we have

$$\bar{a}_{11} = \left(|\gamma_{11}|^2 + |\gamma_{12}|^2\right) a_{11} + n_{11}, \quad (15)$$

$$\bar{a}_{12} = \left(|\gamma_{11}|^2 + |\gamma_{12}|^2\right) a_{12} + n_{12}, \quad (16)$$

where

$$n_{11} = \left(-\alpha_{23} p_{23} \bar{n}^*_{122} + \bar{n}_{031}\right)\gamma^*_{11} + \left(\alpha_{23} p_{22} \bar{n}^*_{112} + \bar{n}_{021}\right)^* \gamma_{12}, \quad (17)$$

$$n_{12} = \left(-\alpha_{23} p_{23} \bar{n}^*_{122} + \bar{n}_{031}\right)\gamma^*_{12} - \left(\alpha_{23} p_{22} \bar{n}^*_{112} + \bar{n}_{021}\right)^* \gamma_{11}. \quad (18)$$

Equations (15) and (16) show that the proposed cooperative transmission strategy provides exactly the performance as the 2-level receive maximum ratio combining.

2. For User 2

Similarly, processing the received signals at the base station for user 2, we obtain

$$r_{21} = \frac{1}{NT_C} \int_0^{NT_C} y_{BS3}(t) C_2(t) dt = \alpha_{13} p_{13} \alpha^*_{12} \beta_{22} a_{22} + \alpha_{23} \beta_{23} a_{21} - \alpha_{13} p_{13} \bar{n}^*_{121} + \bar{n}_{032} \quad (19)$$

$$r_{22} = \frac{1}{NT_C} \int_0^{NT_C} y_{BS2}(t) C_2(t) dt = \alpha_{13} p_{12} \alpha^*_{12} \beta_{21} a^*_{21} - \alpha_{23} \beta_{22} a^*_{22} + \alpha_{13} p_{12} \bar{n}^*_{111} + \bar{n}_{022}. \quad (20)$$

Choose $\beta_{23} = \beta_{22}, p_{13}\beta_{22} = p_{12}\beta_{21}$. (21)

Let $\gamma_{21} = \alpha_{23}\beta_{23}, \ \gamma_{22} = \alpha_{13} p_{13} \alpha^*_{12} \beta_{22}$. (22)

Then, (19) and (20) are of the following form :

$$r_{21} = \gamma_{21} a_{21} + \gamma_{22} a_{22} - \alpha_{13} p_{13} \bar{n}^*_{121} + \bar{n}_{032}, \quad (23)$$

$$r_{22} = -\gamma_{21} a^*_{22} + \gamma_{22} a^*_{21} + \alpha_{13} p_{12} \bar{n}^*_{111} + \bar{n}_{022}, \quad (24)$$

and user 2's estimated symbols are given by

$$\bar{a}_{21} = r_{21}\gamma^*_{21} + r^*_{22}\gamma_{22} = \left(|\gamma_{21}|^2 + |\gamma_{22}|^2\right) a_{21} + n_{21}, \quad (25)$$

$$\bar{a}_{22} = r_{21}\gamma^*_{22} - r^*_{22}\gamma_{21} = \left(|\gamma_{21}|^2 + |\gamma_{22}|^2\right) a_{22} + n_{22}, \quad (26)$$

where

$$n_{21} = \left(-\alpha_{13} p_{13} \bar{n}^*_{121} + \bar{n}_{032}\right)\gamma^*_{21} + \left(\alpha_{13} p_{12} \bar{n}^*_{111} + \bar{n}_{022}\right)^* \gamma_{22}, \quad (27)$$

$$n_{22} = \left(-\alpha_{13} p_{13} \bar{n}^*_{121} + \bar{n}_{032}\right)\gamma^*_{22} - \left(\alpha_{13} p_{12} \bar{n}^*_{111} + \bar{n}_{022}\right)^* \gamma_{21}. \quad (28)$$

By carefully observing the signals in Table 1 and the intuitive data distribution shown in Fig. 2, we can find that all mobile devices in the network iterate the signal processing procedure every two-symbol period since, except the first symbol, each user transmits the signals of the identical structure in such periods. This iteration is represented by either the shaded or un-shaded region in Table 1. It is also noted that the BS only pays attention to the received signal after the first symbol period. As a consequence, the signal analysis for the next two-symbol periods is similar to that in the 2nd and 3rd periods: each mobile gets the information of its partner at the end of "odd" periods and "even" periods by despreading the received signals with the cooperative code $C_3(t)$ and partner's code, respectively; and at the BS's side, it also detects the signals for each user by the user-specific spreading codes $C_i(t)$.

3. Selection of Amplification Factors

The amplification factors β_{ij} and p_{ij} are chosen to satisfy the long-term power constraint. Due to the repeating property in the signaling format of each user, the power constraint condition for user 1 (see the transmitted signals of user 1 in Table 1) is given by

$$E\left\{\frac{\beta_{12}^2|a_{12}|^2+p_{12}^2|\bar{y}_{11}|^2+\beta_{13}^2|a_{11}|^2+p_{13}^2|\bar{y}_{12}|^2+\beta_{11}^2|a_{13}|^2}{2}\right\}=P_1,$$

and for user 2,

$$E\left\{\frac{\beta_{22}^2|a_{22}|^2+p_{22}^2|\bar{y}_{21}|^2+\beta_{23}^2|a_{21}|^2+p_{23}^2|\bar{y}_{22}|^2+\beta_{21}^2|a_{23}|^2}{2}\right\}=P_2,$$

where P_1, P_2 denotes the average limited powers of users 1 and 2 over two consecutive symbol periods, correspondingly; $E\{.\}$ is an expectation operator. The values $E\{|\bar{y}_{ij}|^2\}$ can be calculated from (2) and (4):

$$E\left\{|\bar{y}_{11}|^2\right\}=\beta_{21}^2\sigma_{12}^2+\sigma_1^2/N, \quad E\left\{|\bar{y}_{12}|^2\right\}=\beta_{22}^2\sigma_{12}^2+\sigma_1^2/N,$$

$$E\left\{|\bar{y}_{21}|^2\right\}=\beta_{11}^2\sigma_{12}^2+\sigma_1^2/N, \quad E\left\{|\bar{y}_{22}|^2\right\}=\beta_{12}^2\sigma_{12}^2+\sigma_1^2/N.$$

Here $|a_{ij}|^2 = 1$ as assumed before. Thus,

$$\beta_{11}^2+\beta_{12}^2+\beta_{13}^2+p_{12}^2\left(\beta_{21}^2\sigma_{12}^2+\frac{\sigma_1^2}{N}\right)+p_{13}^2\left(\beta_{22}^2\sigma_{12}^2+\frac{\sigma_1^2}{N}\right)=2P_1,$$

$$\beta_{21}^2+\beta_{22}^2+\beta_{23}^2+p_{22}^2\left(\beta_{11}^2\sigma_{12}^2+\frac{\sigma_1^2}{N}\right)+p_{23}^2\left(\beta_{12}^2\sigma_{12}^2+\frac{\sigma_1^2}{N}\right)=2P_2.$$

Using the equalities in (9) and (21), we have

$$\beta_{11}^2+2\beta_{12}^2+2p_{12}^2\beta_{21}^2\sigma_{12}^2+\left(p_{12}^2+p_{13}^2\right)\frac{\sigma_1^2}{N}=2P_1, \qquad (29)$$

$$\beta_{21}^2+2\beta_{22}^2+2p_{22}^2\beta_{11}^2\sigma_{12}^2+\left(p_{22}^2+p_{23}^2\right)\frac{\sigma_1^2}{N}=2P_2. \qquad (30)$$

III. BER Performance

1. Cooperation

Only user 1 is analyzed in the sequel, and establishment of the expressions for user 2 is followed in an identical manner because of the symmetry.

For simplicity in deriving the probability of error, we consider the case where both users have the same transmit power (P_1=P_2=P) and choose all β_{ij} and p_{ij} to be equal ($\beta_{ij}=\beta$, $p_{ij}=p$). Thus, (29) and (30) can be rewritten as

$$p^2=\frac{2P-3\beta^2}{2\left(\beta^2\sigma_{12}^2+\frac{\sigma_1^2}{N}\right)}, \qquad (31)$$

which requires $\beta^2 \le 2P/3$. The equality of the above expression holds when users stop cooperation. If we let $\beta^2 = \delta P$ where $0 < \delta \le 2/3$ represents the power sharing level for cooperation, then (31) has the following form,

$$p^2=\frac{(2-3\delta)P}{2\left(\delta P\sigma_{12}^2+\frac{\sigma_1^2}{N}\right)}. \qquad (32)$$

BER expression for user 1

Equations (15) and (16) can be expressed in a more compact form:

$$\bar{a}_{11}=\lambda a_{11}+n_{11}, \qquad (33)$$

$$\bar{a}_{12}=\lambda a_{12}+n_{12}, \qquad (34)$$

where

$$\lambda=|\gamma_{11}|^2+|\gamma_{12}|^2=\beta^2|\alpha_{13}|^2+\beta^2p^2|\alpha_{12}|^2|\alpha_{23}|^2. \qquad (35)$$

The last equality is deduced from the substitution of γ_{11} and γ_{12} in (12).

From (17) and (18) and the fact that all random variables n_{ijk} are mutually independent of each other, conditioned on the channel realizations, n_{11} and n_{12} are also independent ZMCGRVs with the same variance,

$$\begin{aligned}\varsigma^2&=\left(|\alpha_{23}|^2p^2\frac{\sigma_1^2}{N}+\frac{\sigma_2^2}{N}\right)\beta^2|\alpha_{13}|^2\\&+\left(|\alpha_{23}|^2p^2\frac{\sigma_1^2}{N}+\frac{\sigma_2^2}{N}\right)p^2\beta^2|\alpha_{12}|^2|\alpha_{23}|^2\\&=\left(|\alpha_{23}|^2p^2\frac{\sigma_1^2}{N}+\frac{\sigma_2^2}{N}\right)\lambda.\end{aligned} \qquad (36)$$

Since α_{ij} are ZMCGRVs with variances σ_{ij}^2, $x=|\alpha_{13}|^2$, $y=|\alpha_{12}|^2$ and $z=|\alpha_{23}|^2$ have exponential distributions with mean value σ_{ij}^2; that is, the pdf's of x, y, z are respectively given by

$$f_x(x)=\lambda_x e^{-\lambda_x x}, \quad f_y(y)=\lambda_y e^{-\lambda_y y}, \quad f_z(z)=\lambda_z e^{-\lambda_z z},$$

where

$$\lambda_x=1/\sigma_{13}^2, \quad \lambda_y=1/\sigma_{12}^2, \quad \lambda_z=1/\sigma_{23}^2,$$

and $x, y, z \ge 0$.

Rewrite (35) and (36) as follows:

$$\lambda=\beta^2x+\beta^2p^2zy=x_1+y_1,$$

$$\varsigma^2=A\lambda,$$

where $A=zp^2\sigma_1^2/N+\sigma_2^2/N$. It is natural that x_1 and y_1

are also independent exponential random variables with parameters $\lambda_1=\lambda_x/\beta^2=1/(\beta^2\sigma_{13}^2)$ and $\lambda_2=\lambda_y/(\beta^2p^2z)=1/(z\beta^2p^2\sigma_{12}^2)$, correspondingly.

The pdf of λ, given z, can be computed by using convolution theorem

$$f_{\lambda|z}(\lambda)=\int_{-\infty}^{\infty}f_{x_1}(x_1)f_{y_1}(\lambda-x_1)dx_1$$
$$=\int_0^{\lambda}\lambda_1e^{-\lambda_1x_1}\lambda_2e^{-\lambda_2(\lambda-x_1)}dx_1=\frac{\lambda_1\lambda_2}{\lambda_1-\lambda_2}\left[e^{-\lambda_2\lambda}-e^{-\lambda_1\lambda}\right],$$

with $\lambda\geq 0$.

From (33), (34), and (36), we find that a_{11} and a_{12} are attenuated and corrupted by the same fading and noisy level, so their probability of error is equal. As a result, the symbol error rate (SER) of a_{11} is sufficient to evaluate the performance of user 1.

Equation (33) gives the SER conditioned on the instantaneous received SNR, $\gamma_r=\lambda^2/\varsigma^2=\lambda/A$, as follows (refer to p. 268 of [2]):

$$P_{eM}=1-\int_{-\pi/M}^{\pi/M}p_{\theta_r}(\theta_r)d\theta_r,$$

where

$$p_{\theta_r}(\theta_r)=\frac{1}{2\pi}e^{-\gamma_r\sin^2\theta_r}\int_0^{\infty}Ve^{-\left(V-\sqrt{2\gamma_r}\cos\theta_r\right)^2/2}dV$$

and $M=2^k$ denotes the number of possible phases of the carrier in MPSK modulation.

It is easy to deduce the conditional pdf of γ_r, given z, from $f_{\lambda|z}(\lambda)$:

$$f_{\gamma_r|z}(\gamma_r)=\frac{A\lambda_1\lambda_2}{\lambda_1-\lambda_2}\left[e^{-A\lambda_2\gamma_r}-e^{-A\lambda_1\gamma_r}\right].$$

Now, the average SER is found by averaging the P_{eM} over γ_r.

$$P_{eAVG}=\int_0^{\infty}P_{eM}f_{\gamma_r}(\gamma_r)d\gamma_r. \tag{37}$$

It is impossible to deduce an explicit expression for P_{eAVG} except the case of $M=2$. However, (37) can be calculated by approximating the integrals as sums [14].

The equivalent bit error probability for MPSK modulation can be asymptotic as follows when a Gray-code is used in the mapping process [2]:

$$BER\approx\frac{P_{eAVG}}{k}.$$

Special case: *M*=2

For coherent binary phase shift keying (BPSK) modulation ($M=2$), the symbol a_{11} is detected by

$$\hat{a}_{11}=sign\left(\mathrm{Re}\{\lambda a_{11}+n_{11}\}\right)=sign\left(\lambda a_{11}+N_1\right),$$

where *sign*(.) denotes a signum function, Re{.} the real part of a complex number, and $N_1=\mathrm{Re}\{n_{11}\}$ a ZMCGRV with variance $\varsigma^2/2=\lambda A/2$.

Therefore, it is straightforward to derive P_{e2} directly as

$$P_{e2}=P(N_1>\lambda|\lambda)=\int_{\lambda}^{\infty}\frac{1}{\sqrt{2\pi(\varsigma^2/2)}}\exp\left(-\frac{N_1^2}{2\pi(\varsigma^2/2)}\right)dN_1$$
$$=Q\left(\sqrt{\frac{\lambda^2}{\varsigma^2/2}}\right)=Q\left(\sqrt{2\gamma_r}\right),$$

where

$$Q(x)=\int_x^{\infty}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{y^2}{2}\right)dy.$$

Finally, by averaging P_{e2} over the parameters γ_r and z, we obtain the average BER,

$$P_{e2AVG}=\int_0^{\infty}\left[\int_0^{\infty}P_{e2}f_{\gamma_r|z}(\gamma_r)d\gamma_r\right]f_z(z)dz,$$

where the integral inside the square bracket can be reduced as

$$\int_0^{\infty}P_{e2}f_{\gamma_r|z}(\gamma_r)d\gamma_r$$
$$=\int_0^{\infty}Q\left(\sqrt{2\gamma_r}\right)\frac{A\lambda_1\lambda_2}{\lambda_1-\lambda_2}\left[e^{-A\lambda_2\gamma_r}-e^{-A\lambda_1\gamma_r}\right]d\gamma_r$$
$$=\frac{\lambda_1}{2(\lambda_1-\lambda_2)}\left[1-\sqrt{\frac{1}{1+A\lambda_2}}\right]-\frac{\lambda_2}{2(\lambda_1-\lambda_2)}\left[1-\sqrt{\frac{1}{1+A\lambda_1}}\right].$$

With $\lambda_1=1/\left(\beta^2\sigma_{13}^2\right)$ and $\lambda_2=1/\left(z\beta^2p^2\sigma_{12}^2\right)$, we obtain

$$P_{e2AVG}=\int_0^{\infty}\frac{\lambda_ze^{-\lambda_zz}}{2\left(1/\left(\beta^2\sigma_{13}^2\right)-1/\left(z\beta^2p^2\sigma_{12}^2\right)\right)}\cdot\left(\frac{1}{\beta^2\sigma_{13}^2}\left[1-\sqrt{\frac{1}{1+\frac{p^2\sigma_1^2z+\sigma_2^2}{z\beta^2p^2\sigma_{12}^2N}}}\right]-\frac{1}{z\beta^2p^2\sigma_{12}^2}\left[1-\sqrt{\frac{1}{1+\frac{p^2\sigma_1^2z+\sigma_2^2}{\beta^2\sigma_{13}^2N}}}\right]\right)dz. \tag{38}$$

This is a closed-form analytical expression for the probability of an error of user 1. The single-variable z integral in (38) can be approximated as a sum [14].

2. Non-cooperation

In the case of non-cooperation, the signal received at the BS is the superposition of the signals from two users attenuated by fade and distorted by noise, which is given by

$$y_{BS}(t) = \alpha_{13}\beta_1 a_1 C_1(t) + \alpha_{23}\beta_2 a_2 C_2(t) + n(t),$$

where a_i and β_i are the symbol and amplification factor of user i, respectively; $n(t)$ is the ZMCGRV with variance σ_2^2. Assume that each user's power is equal and restricted to the same level P as the case of cooperation ($\beta_1^2 = \beta_2^2 = P$) and that the receiver performs the coherent demodulation.

For user i, the signal after the chip-matched filter is given by

$$r_i = \frac{1}{NT_C}\int_0^{NT_C} y_{BS}(t) C_i(t) dt = \alpha_{i3}\beta_i a_i + \bar{n}_i,$$

where $\bar{n}_i$ are ZMCGRVs with variance σ_2^2 / N.

The SER of user i, given the channel realization, is of the following form,

$$P_{neM} = 1 - \int_{-\pi/M}^{\pi/M} p_{\theta_r}(\theta_r) d\theta_r,$$

where

$$p_{\theta_r}(\theta_r) = \frac{1}{2\pi} e^{-\gamma_s \sin^2\theta_r} \int_0^\infty V e^{-\left(V - \sqrt{2\gamma_s}\cos\theta_r\right)^2/2} dV,$$

and $\gamma_s = \frac{|\alpha_{i3}|^2 \beta_i^2}{\sigma_2^2 / N} = \frac{NP|\alpha_{i3}|^2}{\sigma_2^2}$ is exponentially distributed with the mean value of $NP\sigma_{i3}^2 / \sigma_2^2$.

Finally, the average SER is found by averaging the P_{neM} over γ_s:

$$P_{neAVG} = \int_0^\infty P_{neM} f_{\gamma_S}(\gamma_s) d\gamma_s. \quad (39)$$

Special case: M=2

For coherent BPSK modulation (M = 2), the symbol a_i is detected by

$$\hat{a}_i = \text{sign}\left(\text{Re}\{\alpha_{i3}^* r_i\}\right) = \text{sign}\left(|\alpha_{i3}|^2 \beta_i a_i + \bar{N}_i\right),$$

where $\bar{N}_i = \text{Re}\{\alpha_{i3}^* \bar{n}_i\}$ is ZMCGRV with variance $\left(|\alpha_{i3}|^2 \sigma_2^2 / N\right)/2$ conditioned on the channel realization. Thus, we can derive P_{ne2} directly as

$$P_{ne2} = \int_{|\alpha_{i3}|^2 \beta_i}^\infty \frac{1}{\sqrt{2\pi \frac{\sigma_2^2 |\alpha_{i3}|^2}{2N}}} \exp\left(-\frac{x^2}{2\frac{\sigma_2^2|\alpha_{i3}|^2}{2N}}\right) dx = Q\left(\sqrt{\frac{2NP|\alpha_{i3}|^2}{\sigma_2^2}}\right).$$

Because $g = 2NP|\alpha_{i3}|^2 / \sigma_2^2$ is exponentially distributed with the mean value of $\chi_i = 2NP\sigma_{i3}^2 / \sigma_2^2$, the average BER in the case of non-cooperation has the following form

$$\begin{aligned} P_{neAVGi} &= \int_0^\infty P_{ne2} f_g(g) dg = \int_0^\infty Q\left(\sqrt{g}\right)\frac{1}{\chi_i}\exp\left(-\frac{g}{\chi_i}\right)dg \\ &= \frac{1}{2}\left[1 - \sqrt{\frac{\chi_i}{2+\chi_i}}\right] = \frac{1}{2}\left[1 - \sqrt{\frac{NP\sigma_{i3}^2/\sigma_2^2}{1 + NP\sigma_{i3}^2/\sigma_2^2}}\right]. \end{aligned} \quad (40)$$

IV. Numerical Results

The signal-to-noise ratios of inter-user channel (MS1-MS2), MS1-BS channel, and MS2-BS channel are denoted as SNR1, SNR2, and SNR3, respectively, and are defined by

$$\text{SNR}1 = \frac{\sigma_{12}^2 P}{\sigma_1^2} \quad \text{SNR}2 = \frac{\sigma_{13}^2 P}{\sigma_2^2} \quad \text{SNR}3 = \frac{\sigma_{23}^2 P}{\sigma_2^2}.$$

In the results presented below, we adopt P=1, $\sigma_1^2 = \sigma_2^2 = 1$, and the system of two active users. All spreading codes are Walsh-Hadamard codes of length 64.

1. BPSK Modulation

First of all, we compare the analytical formulas in (38) and (40) with the simulation results. Figure 3 shows the BER performance of the TDD-CDMA system uplink with and without cooperation under the same transmit power constraint, δ = 0.53, the identical quality of channels from MS to BS (SNR2 = SNR3), and the inter-user channel of SNR1 = 1 dB. Therefore, it is certain that the performances of users are similar. It is easily realized that there is no difference between analysis

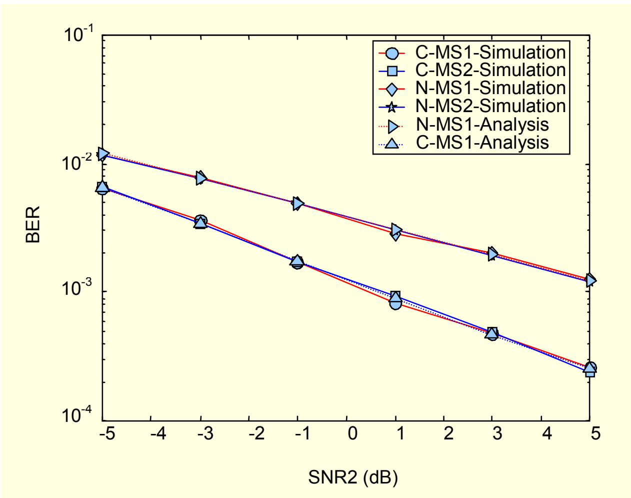

Fig. 3. BER performance for cooperative (C) and non-cooperative (N) cases with δ= 0.53. SNR1=1 dB, SNR2=SNR3.

and simulation. Furthermore, the proposed cooperative transmission significantly outperforms the non-cooperative scheme with a gain in SNR of over 4 dB, and this value keeps increasing when the quality of the MS-BS channel is improved further even though the inter-user channel is severely noisy (SNR1 = 1 dB is small). As a result, the partnership brings benefit to both participants.

Since the analysis agrees with simulation, we will use the analytical formulas in (38) and (40) to evaluate the potentials of the cooperative scheme in enhancing the BER performance in comparison to the non-cooperative scheme, as well as to that in [5] in the sequel.

A. Symmetric Case

In this section, we consider the symmetric scenario when both users have channels of similar quality to the destination. Our goal is to study the performance of the cooperative scheme for various qualities of the inter-user channel. For symmetric networks, both cooperative users suffer the same error probability. Therefore, the graphs only show the performance of user 1.

Figure 4 reveals that for any quality of the inter-user channel, cooperation always attains a considerable improvement over non-cooperation. Moreover, the BER enhancement increases proportionally to the increase in SNR1 and approaches a constant BER curve as SNR1 becomes very large. This curve is the BER lower bound of the cooperative scheme when the inter-user channel is perfect.

The cooperation performance via the variation of the power sharing level δ is shown in Fig. 5 with the unchanged SNR1 = 2 dB. It is found that δ dramatically affects the cooperation performance. This is evident because the nature of cooperation

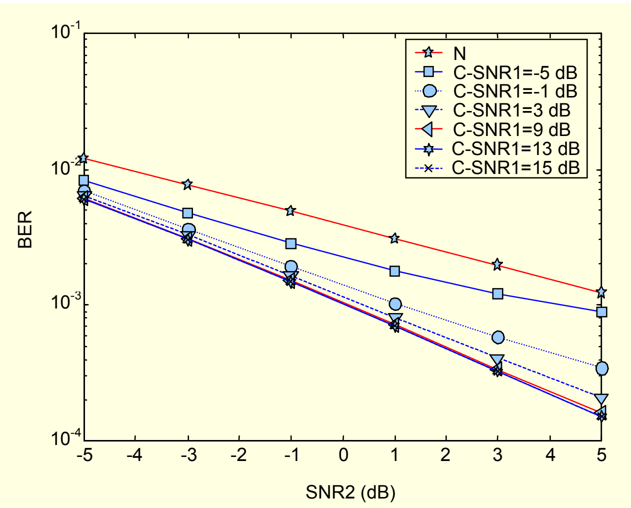

Fig. 4. BER performance for cooperative (C) and non-cooperative (N) cases with δ = 0.53. SNR2=SNR3.

is to take advantage of the partner's propagation path as the second independent diversity path to achieve the fullest spatial diversity. If one of two paths is seriously attenuated, the performance must be reduced. In the cooperative transmission, the signal attenuation can arise from the channel characteristics as well as from the power allocation to transmit each user's own data and its partner's data, which is controlled by the coefficients β and p. Therefore, the change of δ that leads to the changes of β and p certainly causes the significant fluctuation on overall performance. However, the values of δ greater than 0.2 are enough to guarantee that the cooperation is dominant over a single transmission (non-cooperation). Figure 5 also shows that there exits an optimum value of δ that minimizes the probability of error. This value slightly changes with respect to the quality of the MS-BS channel and is approximately 0.5.

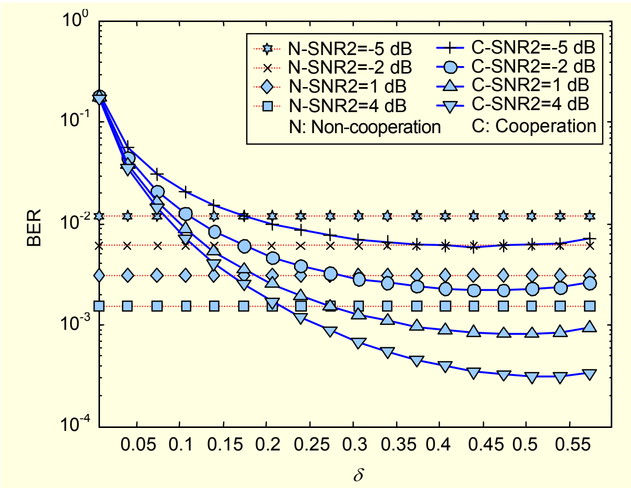

Fig. 5. BER performance as a function of δ. SNR1=2 dB, SNR2 =SNR3.

B. Asymmetric Case

The asymmetric scenario happens when one of the users has a better channel to the BS than the other user. We consider this case by assigning the mean SNR for user 1 to be 5 dB higher than that of user 2; that is, SNR3 = SNR2–5 dB.

Figure 6 demonstrates that under any circumstance of the inter-user channel, the cooperation brings an improvement of about 4 dB for both users compared to a single transmission. Thus, the cooperation proves beneficial not only for users with similar channel qualities to the destination, but also in the case when the users have significantly different channel qualities. As a consequence, any user has a motivation to cooperate with the other even though its propagation path's quality is dramatically better than that of the partner. Moreover, the cooperation performance can be enhanced further when the channels' condition is improved. This is represented by the fact that the slopes of cooperative BER curves increase significantly in accordance to the quality of user channel to the destination.

Similar to Fig. 5, factor δ plays an important role in enhancing the cooperation performance when the symmetry of the user channels to the BS is not guaranteed, as shown in Fig. 7. In general, the cooperation dramatically outperforms a single transmission when $\delta > 0.2$ and the optimum value of δ for the lowest BER slightly fluctuates around 0.5, which is almost independent of the channels' quality.

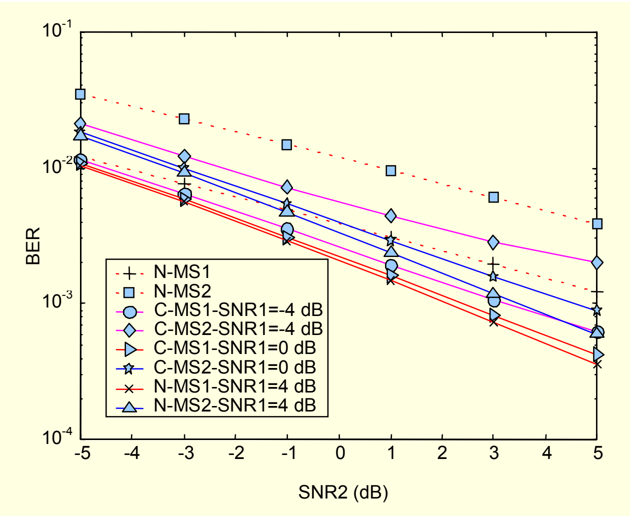

Fig. 6. BER performance for cooperative (C) and non-cooperative (N) cases with δ= 0.53. SNR3=SNR2–5 dB.

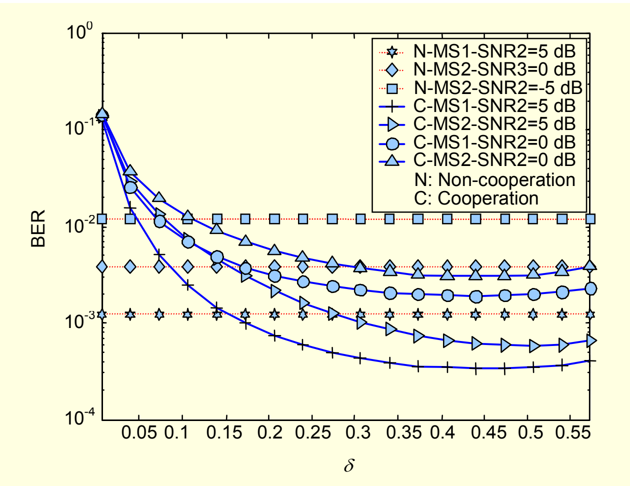

Fig. 7. Cooperation performance via δ. SNR1=4 dB, SNR3 =SNR2–5 dB.

C. Performance Comparison

The benefits that the cooperative users obtain have been proved analytically in the previous two sections. Now we turn to comparing the proposed scheme with the existing cooperative scheme in [5] in terms of BER performance. Remember that the closed-form expressions for the probability of error of the two proposed detectors in [5] were not established, but instead [5] derived the BER formulas in terms of instantaneous parameters of channel characteristics such as path gains for the suboptimal detector, as shown in (A2), (A4), and (A5), and no BER expression for the optimal detector. Therefore, the comparison can only be carried out by computer simulations. Moreover, the absence of the explicit expression for P_{e12} according to channel statistics, for instance σ_{12}^2 as shown in (A4), prevents us from performing a simulation for the optimal detectors, and as a consequence only the suboptimal detector is used for comparison.

For fair comparison, the average power of each user is set to 1, and β_{ij} are equal. In the symmetric scenario (SNR2 = SNR3) as shown in Fig. 8, it is observed that the proposed cooperative scheme considerably outperforms that in [5] with an SNR gain of over 3 dB under any inter-user channel quality change, and this improvement keeps increasing when the inter-user channel signal-to-noise ratio becomes larger. This is because the novel scheme achieves full cooperation and limits the hard decision at the partner's side that can adversely affect the overall performance of the receiver, which is the case in [5]. In fact, the probability of error for the suboptimal detector is simply the average BER of the non-cooperative and cooperative periods. Therefore, this measure only decreases to a certain degree when the cooperation exposes its benefits, which occurs under the better enhanced conditions of the inter-user channel. Figure 8 demonstrated this remark by simulation results. For poor inter-user channel quality (SNR1=-2 dB), the suboptimal detector's performance is similar to the non-cooperative case and begins to increase as SNR1 > -2 dB.

Figure 9 illustrates the BER performance in the asymmetrical scenario where the user 2 channel to the destination is fixed at a

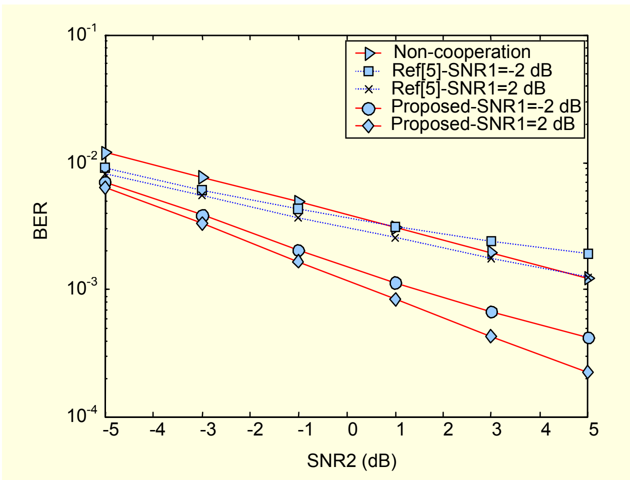

Fig. 8. BER comparison for the proposed scheme and the one in [5] in a symmetrical case: $\sigma_1^2 = 1, \sigma_2^2 = 1$, λ=0.6, and δ=0.53. SNR2=SNR3.

constant signal-to-noise ratio while the other (SNR2) is changed. This demonstrates that no matter which cooperative scheme is used, cooperation always provides a superior performance to non-cooperation. However, the suboptimal detector is slightly better than the non-cooperative one, and this enhancement is distributed equally to each user when the quality of the user channel to the receiver changes (BER curves of the suboptimal and non-cooperative detectors are parallel for a certain user). Completely different from the kind of equal performance improvement that the suboptimal detector yields with respect to the environment conditions, the proposed cooperative scheme offers tighter mutual dependence between partners, which helps them obtain a considerable gain over the suboptimal detection, and this gain increases irregularly for each user, which is represented by the distinct slopes of the BER graphs of cooperative users from those in the non-cooperative case (keeping in mind that the suboptimal detector generates the BER curve of almost the same slope as the non-cooperative detector). This is definitely derived from the fact that the new scheme brings the benefits for both transmitted symbols, while for the structure in [5] only one of them can have the gain from the cooperation.

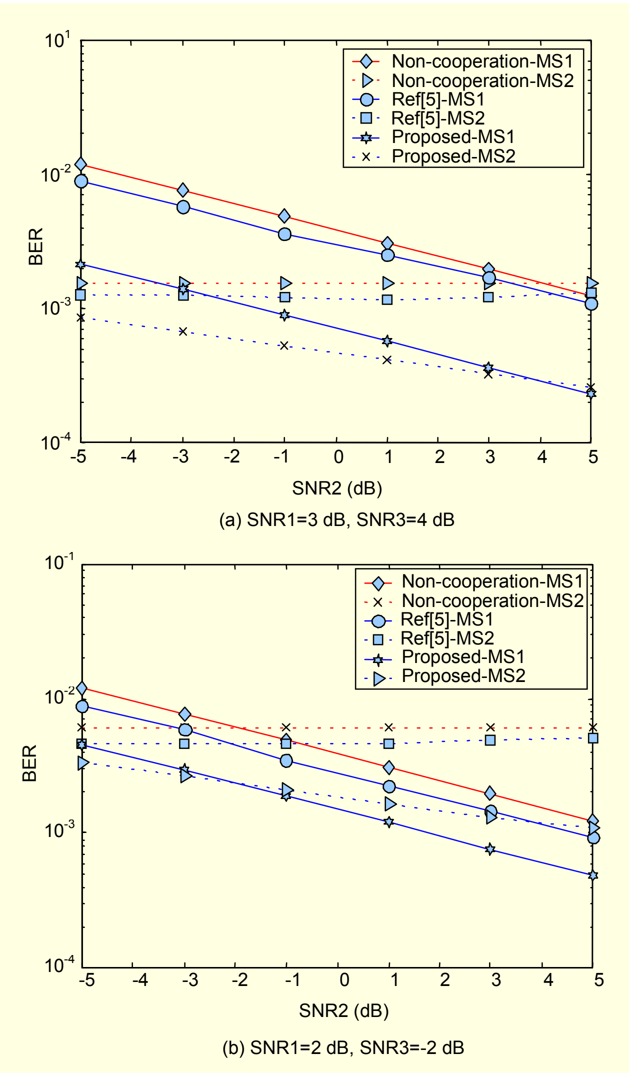

Fig. 9. BER comparison for the proposed scheme and the one in [5] in an asymmetrical case: $\sigma_1^2=1, \sigma_2^2=1$, λ=0.6, and δ=0.53.

2. MPSK Modulation

In this section, we show some simulation results for high-level modulation employed to the cases with and without

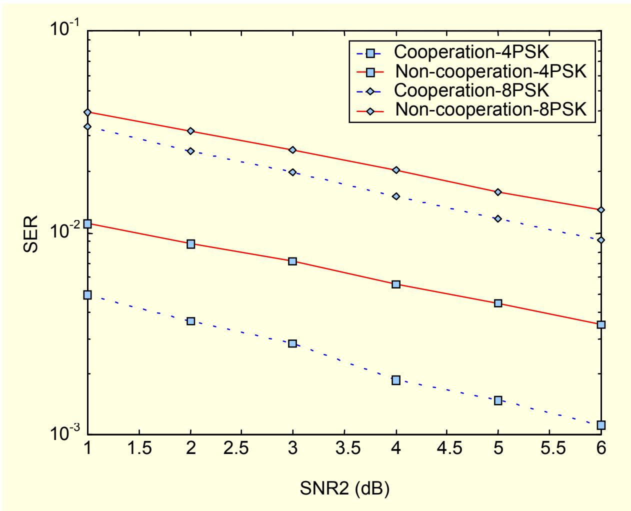

Fig. 10. BER performance in the symmetrical case for MPSK modulation. SNR1=2 dB, SNR2=SNR3.

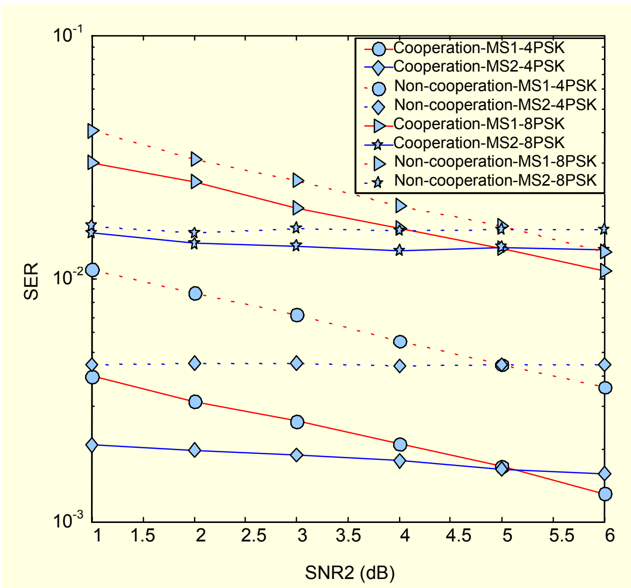

Fig. 11. BER performance in the asymmetrical case for MPSK modulation. SNR1=-1 dB, SNR3=5 dB.

cooperation (4-PSK and 8-PSK). In all illustrated results, the power of symbols is normalized to be 1. Figure 10 demonstrates the performance of the schemes in the symmetric scenario where SNR1= 2 dB and SNR2 = SNR3. It is seen that the cooperation attains a considerable gain over non-cooperation; in particular, this gain accelerates when the quality of user channel to the BS is improved. This is expressed by the slope of the cooperative BER curves being greatly higher than that of the non-cooperative BER graphs. The similar remark is also derived for the case in which both users experience different fading levels as shown in Fig. 11.

V. Conclusion

A novel cooperative transmission strategy for the uplink of a TDD-CDMA system under flat Rayleigh fading channel plus Gaussian noise was proposed. The cooperation brought a considerable performance improvement over a single transmission as well as to the scheme in [5] in any channel condition, which was proved by simulation programs and closed-form BER expressions. Through the numerical results, some useful comments are inferred:

1) In the presented results, the fact that all users have the same transmit power constraint (meaning there is no need of a power-control mechanism from the BS) exposes another advantage of the cooperation: the system is capable of resisting the near-far phenomenon.
2) Different from other cooperative schemes where the transmission rate is sacrificed to obtain spatial diversity gain, our scheme can get the full rate as non-cooperation.
3) There exists an optimum power sharing level δ that minimizes the probability of error. This value is very robust to the changes of the channel and thus can be set before the mobile comes to operation.
4) The cooperative scheme can achieve the fullest space-time diversity without increasing hardware implementation complexity because of the simple structure of the signal detector.
5) Although the results of this paper serve the situation of a two-user system, it is straightforward to verify that the analytical expressions are applicable to a multi-user system without performance degradation if transmission synchronization is remained.
6) This scheme can easily be extended to the cooperation of more than two users by rearranging the transmit signal sequence of each user and applying the high-level space-time codes [3] to reduce further the probability of error.
7) The deployment of multiple receive antennas at the BS is possible for further performance improvement.
8) Other multi-level modulation methods such as M-ary quadrature amplitude modulation can still be applied in the proposed scheme. Then, (13) and (14) are reused for signal detection. However, the theoretical BER expression formulation is more complicated and is left for future study.

Appendix

The goal of this appendix is to summarize the cooperative scheme in [5] to make clear the differences from our proposed one and serve as a reference for comparison. This scheme uses the cooperative transmission strategy given in Table A1 in which a_{ij} denotes user i's BPSK-modulated symbol in the symbol-period j; $\hat{a}_{ij}$ represents user i's recovered j-th bit at its partner's side; and β_{ij} are parameters controlling how much power is allocated to a user's own bits versus the bits of the partner, while maintaining an average power constraint of P_i for user i ($i = 1, 2$) over 3 periods given by

$$\sum_{j=1}^{4} \beta_{ij}^2 = 3P_i \quad . \tag{A1}$$

The cooperation process goes on as follows. Period 1 is used to send data to the BS only. However, period 2 is used to send data not only to the BS, but also to each user's partner. After this data is detected by each user's partner, it is used to construct a cooperative signal that is sent to the BS during period 3.

Table A1. Summary of transmit and receive signals of cooperative users.

P	MS1		MB2		BS
	Tx	Rx	Tx	Rx	Rx
1	$\beta_{11}a_{11}C_1$		$\beta_{21}a_{21}C_2$		y_{BS1}
2	$\beta_{12}a_{12}C_1$	y_{12}	$\beta_{22}a_{22}C_2$	y_{22}	y_{BS2}
3	$\beta_{13}a_{12}C_1+\beta_{14}\hat{a}_{22}C_2$		$\beta_{23}\hat{a}_{12}C_1+\beta_{24}a_{22}C_2$		y_{BS3}

The signal detection at the BS is performed by two detectors, one for the cooperative period and the other for the non-cooperative period. Because of symmetry, only user 1 is focused here.

For the non-cooperative period, a_{11} is recovered by the chip-matched filter,

$$\bar{a}_{11} = \text{sign}\left(\frac{1}{NT_C} \int_0^{NT_C} y_{BS1}(t) C_1(t) dt \right) = \text{sign}\left(\alpha_{13}\beta_{11}a_{11} + n_0 \right),$$

with the probability of bit error given by

$$P_{e1} = Q\left(\alpha_{13}\beta_{11}\frac{\sqrt{N}}{\sigma_2}\right). \quad \text{(A2)}$$

In the cooperative period, restoring a_{12} is optional with either an optimal detector or suboptimal one. For the optimal receiver that offers the minimum probability of error, a_{12} is determined to be 1 if

$$(1-P_{e12})A^{-1}e^{v_1^T y} + P_{e12}Ae^{v_2^T y} > (1-P_{e12})A^{-1}e^{-v_1^T y} + P_{e12}Ae^{-v_2^T y}. \quad \text{(A3)}$$

Otherwise, it is assumed to be -1.

Here, $v_1 = [\alpha_{13}\beta_{12} \quad (\alpha_{13}\beta_{13}+\alpha_{23}\beta_{23})]^T \sqrt{N}/\sigma_2$,

$v_2 = [\alpha_{13}\beta_{12} \quad (\alpha_{13}\beta_{13}-\alpha_{23}\beta_{23})]^T \sqrt{N}/\sigma_2$,

$A = \exp(\alpha_{13}\alpha_{23}\beta_{13}\beta_{23}N/\sigma_2^2)$, $y=[y_2 \quad y_3]^T \sqrt{N}/\sigma_2$ with

$$y_2 = \frac{1}{NT_C}\int_0^{NT_C} y_{BS2}(t)C_1(t)dt = \frac{1}{NT_C}\int_0^{NT_C} \{\alpha_{13}\beta_{12}a_{12}C_1(t)+\alpha_{23}\beta_{22}a_{22}C_2(t)+n_0(t)\}C_1(t)dt$$

$$y_3 = \frac{1}{NT_C}\int_0^{NT_C} y_{BS3}(t)C_1(t)dt = \frac{1}{NT_C}\int_0^{NT_C} \{\alpha_{13}[\beta_{13}a_{12}C_1(t)+\beta_{14}\hat{a}_{22}C_2(t)] + \alpha_{23}[\beta_{23}\hat{a}_{12}C_1(t)+\beta_{24}a_{22}C_2(t)]+n_0(t)\}C_1(t)dt$$

and the probability of bit error due to the hard decision on $\hat{a}_{12}$ is given by

$$P_{e12} = Q\left(\alpha_{12}\beta_{12}\frac{\sqrt{N}}{\sigma_1}\right), \quad \text{(A4)}$$

where the channel parameters were denoted as in section II. This detector is not only rather complex, but also does not have a closed-form expression for the resulting bit-error probability.

To correct this drawback, a_{12} can be detected in a suboptimal way as

$$\bar{a}_{12} = \text{sign}([\alpha_{13}\beta_{12} \quad \lambda(\alpha_{13}\beta_{13}+\alpha_{23}\beta_{23})]y),$$

where $\lambda \in [0,1]$ is a measure of the BS's confidence in the bits estimated by the partner. Its optimal value is only obtained numerically.

The probability of the bit error of a_{12}, given λ, is of the form

$$P_{e2} = (1-P_{e12})Q\left(\frac{v_\lambda^T v_1}{\sqrt{v_\lambda^T v_\lambda}}\right) + P_{e12}Q\left(\frac{v_\lambda^T v_2}{\sqrt{v_\lambda^T v_\lambda}}\right), \quad \text{(A5)}$$

in which $v_\lambda = [\alpha_{13}\beta_{12} \ \lambda(\alpha_{13}\beta_{13}+\alpha_{23}\beta_{23})]^T$.

Notice that (A2), (A4), and (A5) are not closed-form analytical BER expressions for the suboptimal detector because they depend on the immediate parameters of channel characteristics such as α_{12}, α_{13}, α_{23}.

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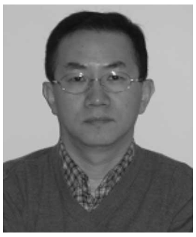

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