Error Probability Evaluation of a Novel Cooperative Communications Signaling Strategy in CDMA Systems

Ho Van Khuong and Hyung Yun Kong

Abstract: **The powerful benefits of multi-antenna systems can be obtained by cooperative communications among users in multiple access environments without the need for physical arrays. This paper studies a novel cooperative signaling strategy that achieves high performance and low implementation complexity for synchronous code division multiple access (CDMA) wireless mobile networks. The validity of the proposed strategy under slow flat Rayleigh fading channel plus additive white Gaussian noise (AWGN) is verified through closed-form error probability expressions and Monte-Carlo simulations. A variety of analytical results reveal that the new cooperative strategy significantly outperforms direct transmission subject to the same spectral efficiency and transmit power constraint.**

Index Terms: **Additive white Gaussian noise (AWGN), code division multiple access (CDMA), cooperative communications, Rayleigh fading.**

I. INTRODUCTION

Signal fading due to multi-path propagation is a serious problem in wireless communications. Using a diversified signal in which information related to the same data appears in multiple time instances, frequencies, or antennas that are independently faded can reduce considerably this effect of the channel [1]. Among well-known diversity techniques, the spatial diversity has received a great deal of attention in recent years because of the feasibility of deploying multiple antennas at both transmitter and receiver in many cases where the wireless channel is neither significantly time-variant nor highly frequency selective [2]. However, when wireless mobiles may not be able to support multiple antennas due to size or other constraints [3], the conventional space-time coding cannot be used for transmit diversity. To overcome this restriction, a new technique, called cooperative communications [3]–[16], was born which allows single-antenna mobiles to obtain some benefits of spatial diversity. The main idea is that in a multi-user network, two or more users share their information and transmit jointly as a virtual antenna array [9]–[11]. This enables them to obtain higher diversity than they could have individually. The way the users share information is by tuning into each other's transmitted signals and by processing information that they overhear. Since inter-user channel is noisy and faded, this overheard information is not perfect. Hence, one has to carefully study the possible signaling strategies that can exploit the benefits of cooperative communications at most.

There are multiple different protocols to process signals a user receives from its partner in cooperation process [4]–[6]. Among them, the amplify-and-forward protocol is examined the most extensively [12]–[16]. This comes from the fact that each user only retransmits the scaled version of the signal received from its partner to the destination. Therefore, delay time, implementation complexity as well as consumed power for the signal processing are reduced significantly compared to the other protocols. As a result, this protocol is also used to assist our proposed signaling strategy in this paper.

The proposed cooperative signaling strategy involves the spreading code sharing among cooperative users. This way ensures that partners as well as target receiver can transmit and receive the signals simultaneously. In cooperation process, each user simply estimates its partner's information by performing the despreading the received signals and forwards the resultant signals in a specific format to the destination. Therefore, delay time due to the signal processing at each user can be negligible. Moreover, due to only estimating the partner's information instead of recovering it as in [4], our strategy can prevent the wrong decisions induced by partners that can be detrimental to the eventual detection at the destination. However, similar to the strategy in [4], ours only obtains 2/3 of the data rate of direct transmission (or noncooperation). In order to avoid the loss of transmission bandwidth in comparison to direct transmission, the high-level modulation techniques are required to our signaling strategy as well as that in [4]. With the novel cooperative signaling strategy proposed in this paper, the signal detection at the destination can be easily performed based on maximum likelihood detection technique [17] which offers the full diversity order and low implementation complexity.

In this paper, besides suggesting a new cooperative signaling strategy, we derived closed-form bit error rate (BER) expressions for each cooperative user under the transmit power constraints and slow and flat Rayleigh fading channel plus Gaussian noise for synchronous code division multiple access (CDMA) systems. The rest of the paper is organized as follows. Section II discusses the proposed signaling strategy and signal analysis in details. Theoretical performance analysis and numerical results are described and analyzed in Sections III and IV, respectively. Finally, the paper is closed in Section V with a summary and discussion of our results along with some potential extensions. Summary of the signaling strategy in [4] for reference and error probability derivation for direct transmission are relegated to Appendices 1 and 2.

II. PROPOSED COOPERATIVE COMMUNICATIONS SIGNALING STRATEGY

The feature of spreading code assignment in the proposed cooperative communications signaling strategy is similar to that in

---

Manuscript received April 18, 2005; approved for publication by Iickho Song, Division I Editor, July 15, 2006.

The authors are with the Department of Electrical Engineering, University of Ulsan, Korea, email: khuongho2001@yahoo.com, hkong@mail.ulsan.ac.kr.

Table 1. Transmit and receive signals of cooperative users.

	MS1	
Phase	Transmit	Receive
1	$\beta_{11}x_{11}C_1$	y_{11}
2	$-\beta_{12}x_{12}^*C_1 + p_{12}\overline{y}_{11}^*C_2$	y_{12}
3	$\beta_{13}x_{11}C_1 - p_{13}\overline{y}_{12}^*C_2$	

	MS2		BS
Phase	Transmit	Receive	Receive
1	$\beta_{21}x_{21}C_2$	y_{21}	
2	$-\beta_{22}x_{22}^*C_2 + p_{22}\overline{y}_{21}^*C_1$	y_{22}	y_{BS2}
3	$\beta_{23}x_{21}C_2 - p_{23}\overline{y}_{22}^*C_1$		y_{BS3}

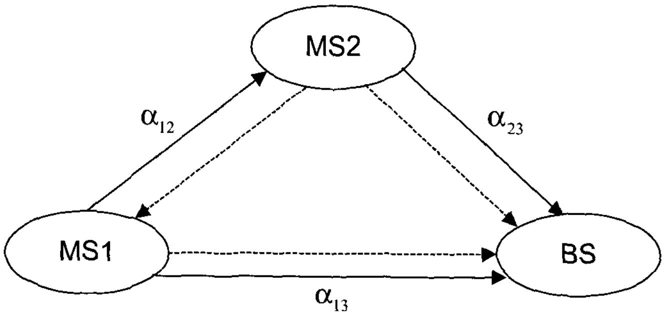


Fig. 1. Cooperative network model. The solid lines denote MS1's propagation paths and the dash lines are MS2's propagation paths.

the conventional CDMA-based wireless networks where each user is allocated a unique spreading code which has a low cross-correlation with those of the other users such that the receiver can reliably distinguish the transmitted signals. Our signaling strategy is illustrated in Table 1 where every two modulated data symbols are transmitted in consecutive 3 symbol intervals. This strategy is proved to be applicable to MPSK-modulated signals or any kind of constant envelope modulation (see next section) but we limit the study to MPSK modulation with Gray mapping in the sequel.

Before explaining the cooperation mechanism, it is noted that we consider a synchronous CDMA system [4] and as a result, the orthogonality of the spreading codes is preserved for each user's signal to be completely separated at the receivers. 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 the cooperative communications consisting of two mobiles (MS1 and MS2) communicating with a base station (BS) in a cellular system as shown in Fig. 1. 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 and spectral efficiency as a comparable direct transmission system.

For convenience of discussion, we present notations used throughout this paper as follows.

- x_{ij} denotes user i's modulated symbol in phase j. Without the loss of generality, its amplitude is assumed to be 1 and equally likely.
- $C_i(t)$ represents user i's spreading code given by

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

  where $c_i(n)$ is the n-th chip of the i-th code, $p(t)$ a unit-amplitude rectangular pulse with time duration equal to chip duration, and N the code length.
- β_{ij} is the amplification factor for user i's own signal in phase j.
- p_{ij} is the amplification factor for the estimated signal of partner of user i in phase j. 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 over 3-symbol interval [4].
- $y_{ij}(t)$ is the signal of user i's partner received during phase j.
- $y_{BSi}(t)$ denotes the received signal at the base station in phase i.

In addition, there are the other channel parameters for use in the paper such as $\alpha_{12}, \alpha_{13}, \alpha_{23}$ being path gains of channels between MS1 and MS2, MS1 and BS, MS2 and BS, respectively which reflect the fading level from transmitter to receiver. We assume slow and flat Rayleigh fading, hence they are modeled as independent samples of zero-mean complex Gaussian random variables (ZMCGRV) with variances $\lambda_{12}, \lambda_{13}, \lambda_{23}$ and constant during 3-symbol transmission of any given user, but independently change over longer intervals. Because of slow fading, accurate channel estimation is possible at receivers [4]. Thus, we will assume perfect channel-state information (CSI) at all the respective receivers. For inter-user channel (between MS1 and MS2), it is also assumed to be reciprocal.[1] The alternative parameters $n_{1ij}(t), n_{0k}(t)$, $(i \in \{1,2\}; j \in \{1,2\}; k \in \{2,3\})$ are noise samples corrupting the inter-user channel and MS-BS channel which are modeled as independent ZMCGRVs with variances η_1, η_2, correspondingly. Finally, Gaussian noise and Rayleigh fading are considered to be statistically independent.

For simplicity of exposition, we use complex equivalent baseband models to express all the signals. Cooperation process for transmitting 2 symbols (although the analysis is illustrated on a per-symbol basis, the results also hold for block-based schemes under a block-fading assumption) includes three phases. During the first phase, users send their own data spread by their spreading codes. The received signal at user i, $i \in \{1,2\}$, is hence given by

$$\begin{aligned} y_{11}(t) &= \alpha_{12}\beta_{21}x_{21}C_2(t) + n_{111}(t) \quad (1)\\ y_{21}(t) &= \alpha_{12}\beta_{11}x_{11}C_1(t) + n_{112}(t). \quad (2)\end{aligned}$$

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

$$\begin{aligned} \overline{y}_{11} &= \frac{1}{NT_C}\int_0^{NT_C} y_{11}(t)C_2(t)dt \\ &= \alpha_{12}\beta_{21}x_{21} + \overline{n}_{111} \quad (3)\end{aligned}$$

---

[1] The channel characteristics are similar for both directions. Note that this assumption is the same as in [4].

$$\begin{aligned}\overline{y}_{21} &= \frac{1}{NT_C}\int_0^{NT_C} y_{21}(t)C_1(t)dt \\ &= \alpha_{12}\beta_{11}x_{11} + \overline{n}_{112}. \end{aligned} \tag{4}$$

Without the loss of generality, chip duration can be considered to be 1 time unit ($T_C = 1$). Thus, $\overline{n}_{1ij}$ are ZMCGRVs with variance η_1/N hereafter, $i \in \{1,2\}$, $j \in \{1,2\}$.

Since each user must transmit and receive at the same time in the same frequency band in the first and second phases, we follow the assumption of perfect echo cancellation which was justified to be relatively reasonable by strong arguments in [4, p. 1928] and [21] for convenience of analysis.

It is noticed that the base station pays no attention to the detecting data of mobile stations in the first phase but rather, it can utilize this information to estimate the channel state. In the next two phases, each user performs two operations: 1) Estimating the signal of its partner transmitted in the previous phase by despreading the received signal; 2) amplifying the resulting signal with the gain p_{ij} and sending it along with each user's spread own data. For example, during the second phase, the user i receives

$$y_{12}(t) = \alpha_{12}\left\{-\beta_{22}x_{22}^*C_2(t) + p_{22}\overline{y}_{21}^*C_1(t)\right\} + n_{121}(t) \tag{5}$$

$$y_{22}(t) = \alpha_{12}\left\{-\beta_{12}x_{12}^*C_1(t) + p_{12}\overline{y}_{11}^*C_2(t)\right\} + n_{122}(t) \tag{6}$$

where $\overline{y}_{21}$, $\overline{y}_{11}$ are the partner's noised signals in the first phase; $(\cdot)^*$ denotes complex conjugation.

The despread signals produced at the end of this phase corresponding to the above are given by

$$\begin{aligned}\overline{y}_{12} &= \frac{1}{NT_C}\int_0^{NT_C} y_{12}(t)C_2(t)dt \\ &= -\alpha_{12}\beta_{22}x_{22}^* + \overline{n}_{121} \end{aligned} \tag{7}$$

$$\begin{aligned}\overline{y}_{22} &= \frac{1}{NT_C}\int_0^{NT_C} y_{22}(t)C_1(t)dt \\ &= -\alpha_{12}\beta_{12}x_{12}^* + \overline{n}_{122}. \end{aligned} \tag{8}$$

Therefore, user i will send the following signal in the third phase

$$\beta_{i3}x_{i1}C_i(t) - p_{i3}\overline{y}_{i2}^*C_{i'}(t)$$

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

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

$$\begin{aligned}y_{BS2}(t) &= \alpha_{13}\left\{-\beta_{12}x_{12}^*C_1(t) + p_{12}\overline{y}_{11}^*C_2(t)\right\} \\ &\quad +\alpha_{23}\left\{-\beta_{22}x_{22}^*C_2(t) + p_{22}\overline{y}_{21}^*C_1(t)\right\} + n_{02}(t) \end{aligned} \tag{9}$$

$$\begin{aligned}y_{BS3}(t) &= \alpha_{13}\left\{\beta_{13}x_{11}C_1(t) - p_{13}\overline{y}_{12}^*C_2(t)\right\} \\ &\quad +\alpha_{23}\left\{\beta_{23}x_{21}C_2(t) - p_{23}\overline{y}_{22}^*C_1(t)\right\} + n_{03}(t) \end{aligned} \tag{10}$$

where $\overline{y}_{12}$, $\overline{y}_{22}$ are expressed in (7) and (8).

Now, BS carries out decoding separately the signals for MS1 and MS2 during the 2nd and 3rd phases by user-specific spreading codes.

A. For User 1

At BS, MS1's estimated signals at the output of the chip-matched filter corresponding to the 3rd and 2nd phases are given by, respectively

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

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

where $\overline{n}_{0ij}$ are ZMCGRVs with variance η_2/N in the sequel, $i \in \{2,3\}$ and $j \in \{1,2\}$. The last expressions in (11) and (12) are derived by replacing $\overline{y}_{21}$, $\overline{y}_{22}$ with those in (4)–(8).

We choose

$$\beta_{13} = \beta_{12}, \; p_{23}\beta_{12} = p_{22}\beta_{11}. \tag{13}$$

Then, (11) and (12) can be rewritten as

$$r_{11} = \gamma_{11}x_{11} + \gamma_{12}x_{12} - \alpha_{23}p_{23}\overline{n}_{122}^* + \overline{n}_{031} \tag{14}$$

$$r_{12} = -\gamma_{11}x_{12}^* + \gamma_{12}x_{11}^* + \alpha_{23}p_{22}\overline{n}_{112}^* + \overline{n}_{021} \tag{15}$$

where

$$\gamma_{11} = \alpha_{13}\beta_{13}, \; \gamma_{12} = \alpha_{23}p_{23}\alpha_{12}^*\beta_{12}. \tag{16}$$

(14) and (15) are analytical expressions at the receiver for 2-transmit antenna and 1-receive antenna space diversity using the Alamouti STC 2 × 2 [17]. Therefore, for MPSK modulation or any kind of constant envelope modulation, maximum likelihood (ML) detection generates the estimated values of x_{11} and x_{12} as follows [17]

$$\overline{x}_{11} = r_{11}\gamma_{11}^* + r_{12}^*\gamma_{12} \tag{17}$$

$$\overline{x}_{12} = r_{11}\gamma_{12}^* - r_{12}^*\gamma_{11}. \tag{18}$$

Compared to the detectors in [4] (see Appendix 1), it is obvious that the proposed one is much simpler in implementation complexity because it applies a unique detector which is completely different from [4] where two detectors are switched to recover two consecutive symbols. Moreover, the partial cooperation (only one cooperating symbol) and hard decision at each partner's side in [4] didn't exploit the potential of the cooperation at most and as a result, the overall performance is not much improved. In contrast, our cooperative signaling strategy exposes the total cooperation and avoids the hard decision to reduce the error probability.

Substituting r_{11} and r_{12} in (14) and (15) into (17) and (18), we have

$$\begin{aligned} \overline{x}_{11} &= \left(|\gamma_{11}|^2 + \gamma_{12}|^2\right) x_{11} + n_{11} && (19)\\ \overline{x}_{12} &= \left(|\gamma_{11}|^2 + \gamma_{12}|^2\right) x_{12} + n_{12} && (20)\end{aligned}$$

where

$$\begin{aligned} n_{11} &= \left(-\alpha_{23}p_{23}\overline{n}_{122}^* + \overline{n}_{031}\right)\gamma_{11}^* \\ &\quad + \left(\alpha_{23}p_{22}\overline{n}_{112}^* + \overline{n}_{021}\right)^* \gamma_{12} && (21)\\ n_{12} &= \left(-\alpha_{23}p_{23}\overline{n}_{122}^* + \overline{n}_{031}\right)\gamma_{12}^* \\ &\quad - \left(\alpha_{23}p_{22}\overline{n}_{112}^* + \overline{n}_{021}\right)^* \gamma_{11}. && (22)\end{aligned}$$

(19) and (20) show that the proposed cooperative signaling strategy can provide exactly the performance as the 2-level receive maximum ratio combining.

B. For User 2

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

$$\begin{aligned} r_{21} &= \frac{1}{NT_C}\int_0^{NT_C} y_{BS3}(t)C_2(t)dt \\ &= \alpha_{13}p_{13}\alpha_{12}^*\beta_{22}x_{22} + \alpha_{23}\beta_{23}x_{21} - \alpha_{13}p_{13}\overline{n}_{121}^* \\ &\quad + \overline{n}_{032} && (23)\\ r_{22} &= \frac{1}{NT_C}\int_0^{NT_C} y_{BS2}(t)C_2(t)dt \\ &= \alpha_{13}p_{12}\alpha_{12}^*\beta_{21}x_{21}^* - \alpha_{23}\beta_{22}x_{22}^* + \alpha_{13}p_{12}\overline{n}_{111}^* \\ &\quad + \overline{n}_{022}. && (24)\end{aligned}$$

Choose

$$\beta_{23} = \beta_{22},\ p_{13}\beta_{22} = p_{12}\beta_{21}. \qquad (25)$$

Let

$$\gamma_{21} = \alpha_{23}\beta_{23},\ \gamma_{22} = \alpha_{13}p_{13}\alpha_{12}^*\beta_{22}. \qquad (26)$$

Then, (23) and (24) are of the following form

$$\begin{aligned} r_{21} &= \gamma_{21}x_{21} + \gamma_{22}x_{22} - \alpha_{13}p_{13}\overline{n}_{121}^* + \overline{n}_{032} && (27)\\ r_{22} &= -\gamma_{21}x_{22}^* + \gamma_{22}x_{21}^* + \alpha_{13}p_{12}\overline{n}_{111}^* + \overline{n}_{022} && (28)\end{aligned}$$

and user 2's estimated symbols are given by

$$\begin{aligned} \overline{x}_{21} &= r_{21}\gamma_{21}^* + r_{22}^*\gamma_{22} \\ &= \left(|\gamma_{21}|^2 + \gamma_{22}|^2\right) x_{21} + n_{21} && (29)\\ \overline{x}_{22} &= r_{21}\gamma_{22}^* - r_{22}^*\gamma_{21} \\ &= \left(|\gamma_{21}|^2 + \gamma_{22}|^2\right) x_{22} + n_{22} && (30)\end{aligned}$$

where

$$\begin{aligned} n_{21} &= \left(-\alpha_{13}p_{13}\overline{n}_{121}^* + \overline{n}_{032}\right)\gamma_{21}^* \\ &\quad + \left(\alpha_{13}p_{12}\overline{n}_{111}^* + \overline{n}_{022}\right)^* \gamma_{22} && (31)\\ n_{22} &= \left(-\alpha_{13}p_{13}\overline{n}_{121}^* + \overline{n}_{032}\right)\gamma_{22}^* \\ &\quad - \left(\alpha_{13}p_{12}\overline{n}_{111}^* + \overline{n}_{022}\right)^* \gamma_{21}. && (32)\end{aligned}$$

C. Amplification Factors

The amplification factors β_{ij} and p_{ij} are chosen to satisfy the power constraint which is required to be constant over 3 phases [4] as follows:

The power constraint condition for user 1 (see the transmit signals of user 1 in Table 1) is

$$\mathrm{E}\left\{\frac{\beta_{11}^2|x_{11}|^2+\beta_{12}^2|x_{12}|^2+p_{12}^2|\overline{y}_{11}|^2+\beta_{13}^2|x_{11}|^2+p_{13}^2|\overline{y}_{12}|^2}{3}\right\} = P_1$$

and for user 2,

$$\mathrm{E}\left\{\frac{\beta_{21}^2|x_{21}|^2+\beta_{22}^2|x_{22}|^2+p_{22}^2|\overline{y}_{21}|^2+\beta_{23}^2|x_{21}|^2+p_{23}^2|\overline{y}_{22}|^2}{3}\right\} = P_2$$

where $P_1,\ P_2$ denote the average limited powers of users 1 and 2 over consecutive 3-symbol interval, correspondingly; $\mathrm{E}\{\cdot\}$ signifies the expectation operator. The values $E\left\{|\overline{y}_{ij}|^2\right\}$ can be calculated from (3), (4), (7), and (8):

$$\begin{aligned} \mathrm{E}\left\{|\overline{y}_{11}|^2\right\} &= \beta_{21}^2\lambda_{12} + \eta_1/N \\ \mathrm{E}\left\{|\overline{y}_{12}|^2\right\} &= \beta_{22}^2\lambda_{12} + \eta_1/N \\ \mathrm{E}\left\{|\overline{y}_{21}|^2\right\} &= \beta_{11}^2\lambda_{12} + \eta_1/N \\ \mathrm{E}\left\{|\overline{y}_{22}|^2\right\} &= \beta_{12}^2\lambda_{12} + \eta_1/N. \end{aligned}$$

Here, $|x_{ij}|^2 = 1$ as assumed before. Thus, combining with the equalities in (13)–(25), we obtain

$$\beta_{11}^2 + 2\beta_{12}^2 + 2p_{12}^2\beta_{21}^2\lambda_{12} + \left(p_{12}^2 + p_{13}^2\right)\frac{\eta_1}{N} = 3P_1 \qquad (33)$$

$$\beta_{21}^2 + 2\beta_{22}^2 + 2p_{22}^2\beta_{11}^2\lambda_{12} + \left(p_{22}^2 + p_{23}^2\right)\frac{\eta_1}{N} = 3P_2. \qquad (34)$$

III. ERROR PROBABILITY ANALYSIS

Only user 1 is analyzed in the sequel and establishing the expressions for user 2 is followed in the similar manner because of the symmetry. In addition, for simplicity in analyzing the error probability, we consider the case that 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, (33) and (34) can be rewritten as

$$p^2 = \frac{3P - 3\beta^2}{2\left(\beta^2\lambda_{12} + \frac{\eta_1}{N}\right)} \qquad (35)$$

which requires $\beta^2 \leq P$.

The equality "=" of the above expression holds when users stop cooperating. If we let $\beta^2 = \delta P$ where $0 < \delta \leq 1$ represents the power sharing level for the cooperation, then (35) has the following form

$$p^2 = \frac{3(1-\delta)P}{2\left(\delta P\lambda_{12} + \frac{\eta_1}{N}\right)}. \qquad (36)$$

Now, (19) and (20) can be expressed in more compact form

$$\overline{x}_{11} = \lambda x_{11} + n_{11} \qquad (37)$$

$$\overline{x}_{12} = \lambda x_{12} + n_{12} \qquad (38)$$

where

$$\begin{aligned} \lambda &= |\gamma_{11}|^2 + |\gamma_{12}|^2 \\ &= \beta^2|\alpha_{13}|^2 + \beta^2p^2|\alpha_{12}|^2|\alpha_{23}|^2. && (39)\end{aligned}$$

The last equality is deduced from substitution of γ_{11} and γ_{12} in (16).

From (21) and (22) and the fact that all r.v.'s $\overline{n}_{ijk}$, $i \in \{0,1\}$, $j \in \{1,2,3\}$, $k \in \{1,2\}$ are mutually independent of each other, conditioned on the channel realizations, n_{11} and n_{12} are also independent ZMCGRVs with the same variance

$$\begin{aligned} \zeta^2 &= \left(|\alpha_{23}|^2 p^2 \frac{\eta_1}{N} + \frac{\eta_2}{N}\right) \beta^2 |\alpha_{13}|^2 \\ &\quad + \left(|\alpha_{23}|^2 p^2 \frac{\eta_1}{N} + \frac{\eta_2}{N}\right) p^2 \beta^2 |\alpha_{12}|^2 \alpha_{23}|^2 \\ &= \left(|\alpha_{23}|^2 p^2 \frac{\eta_1}{N} + \frac{\eta_2}{N}\right) \lambda. \end{aligned} \tag{40}$$

Because x_{11} and x_{12} in (37) and (38) are attenuated and corrupted by the same fading and noisy level, their error probability is equal. As a result, BER of x_{11} is sufficient to evaluate the performance of user 1. Additionally since x_{11} is MPSK-modulated with Gray mapping, BER conditioned on the channel realizations is approximated by [18, (8.32)]

$$P_e \cong A \sum_{i=1}^{B} \mathrm{Q}\left(\sqrt{2C_i \gamma}\right) \tag{41}$$

where

$$\begin{aligned} A &= \frac{2}{\max(\log_2 M, 2)} \\ B &= \max\left(\frac{M}{4}, 1\right) \\ C_i &= \left[\sin\left(\frac{(2i-1)\pi}{M}\right)\right]^2. \end{aligned} \tag{42}$$

It is noted that (41) is quite accurate at both low and high SNR and is valid for all M. In (41), M is the number of possible modulation levels, $\mathrm{Q}(\cdot)$ the Q-function, and γ the signal-to-noise ratio (SNR) at the combiner output.

(37) gives the value of γ as $\gamma = \lambda^2/\zeta^2$. Inserting (39) and (40) into the expression of γ yields

$$\begin{aligned} \gamma &= \frac{\beta^2 |\alpha_{13}|^2 + \beta^2 p^2 |\alpha_{12}|^2 |\alpha_{23}|^2}{|\alpha_{23}|^2 p^2 \eta_1 / N + \eta_2 / N} \\ &= x + y \end{aligned}$$

where

$$\begin{aligned} x &= \frac{\beta^2 |\alpha_{13}|^2}{z p^2 \eta_1 / N + \eta_2 / N} \\ y &= \frac{z \beta^2 p^2 |\alpha_{12}|^2}{z p^2 \eta_1 / N + \eta_2 / N} \\ z &= |\alpha_{23}|^2. \end{aligned}$$

Since α_{ij} are ZMCGRVs with variances λ_{ij}, the r.v.'s $|\alpha_{ij}|^2$ have exponential distributions with mean values λ_{ij}. Therefore, it is straightforward to find out the *pdf*'s of x and y, conditioned on z as

$$\begin{aligned} f_{x|z}(x) &= \lambda_x e^{-\lambda_x x} \mathrm{U}(x) \\ f_{y|z}(y) &= \lambda_y e^{-\lambda_y y} \mathrm{U}(y). \end{aligned}$$

Here,

$$\begin{aligned} \lambda_x &= \frac{z p^2 \eta_1 + \eta_2}{\beta^2 \lambda_{13} N} \\ \lambda_y &= \frac{z p^2 \eta_1 + \eta_2}{z \beta^2 p^2 \lambda_{12} N} \end{aligned} \tag{43}$$

and $\mathrm{U}(\cdot)$ is the unit-step function.

Moreover, the *pdf* of z is also given by

$$f_z(z) = \lambda_z e^{-\lambda_z z} \mathrm{U}(z) \tag{44}$$

where $\lambda_z = 1/\lambda_{23}$.

Now, we can compute the *pdf* of γ, given z, by using convolution theorem

$$\begin{aligned} f_{\gamma|z}(\gamma) &= \int_{-\infty}^{\infty} f_{x|z}(x) f_{\gamma|z}(\gamma - x) dx \\ &= \frac{\lambda_x \lambda_y}{\lambda_x - \lambda_y} \left[e^{-\lambda_y \gamma} - e^{-\lambda_x \gamma}\right] \mathrm{U}(\gamma). \end{aligned}$$

Finally, the average BER is computed by averaging the P_e in (41) over the parameters γ and z

$$\begin{aligned} P_{e\_AVG} &= \int_0^{\infty} \left[\int_0^{\infty} P_e f_{\gamma|z}(\gamma) d\gamma\right] f_z(z) dz \\ &= \int_0^{\infty} \left[A \sum_{i=1}^{B} \int_0^{\infty} \mathrm{Q}\left(\sqrt{2C_i \gamma}\right) f_{\gamma|z}(\gamma) d\gamma\right] \\ &\quad \times f_z(z) dz \\ &= A \sum_{i=1}^{B} \int_0^{\infty} \left[\int_0^{\infty} \mathrm{Q}\left(\sqrt{2C_i \gamma}\right) f_{\gamma|z}(\gamma) d\gamma\right] \\ &\quad \times f_z(z) dz. \end{aligned} \tag{45}$$

The integral inside the square bracket in (45) can be reduced to

$$\begin{aligned} &\int_0^{\infty} \mathrm{Q}\left(\sqrt{2C_i \gamma}\right) f_{\gamma|z}(\gamma) d\gamma \\ &= \int_0^{\infty} \mathrm{Q}\left(\sqrt{2C_i \gamma}\right) \frac{\lambda_x \lambda_y}{\lambda_x - \lambda_y} \left[e^{-\lambda_y \gamma} - e^{-\lambda_x \gamma}\right] d\gamma \\ &= \frac{\lambda_x}{2(\lambda_x - \lambda_y)} \left[1 - \sqrt{\frac{1}{1 + \lambda_y / C_i}}\right] \\ &\quad - \frac{\lambda_y}{2(\lambda_x - \lambda_y)} \left[1 - \sqrt{\frac{1}{1 + \lambda_x / C_i}}\right]. \end{aligned}$$

Substituting the above together with λ_x and λ_y in (43), and $f_z(z)$ in (44) into (45), we obtain

$$P_{e\_AVG} = \frac{A}{2} \sum_{i=1}^{B} \int_0^{\infty} H(G - F) dz \tag{46}$$

where

$$\begin{aligned} H &= \frac{\beta^2 p^2 \lambda_{12} \lambda_{13} \lambda_z e^{-\lambda_z z}}{z p^2 \lambda_{12} - \lambda_{13}} \\ G &= \frac{z}{\beta^2 \lambda_{13}} \left[1 - \sqrt{\frac{z \beta^2 p^2 \lambda_{12} C_i N}{p^2 \eta_1 z + \eta_2 + z \beta^2 p^2 \lambda_{12} C_i N}}\right] \\ F &= \frac{1}{\beta^2 p^2 \lambda_{12}} \left[1 - \sqrt{\frac{\beta^2 \lambda_{13} C_i N}{z p^2 \eta_1 + \eta_2 + \beta^2 \lambda_{13} C_i N}}\right]. \end{aligned}$$

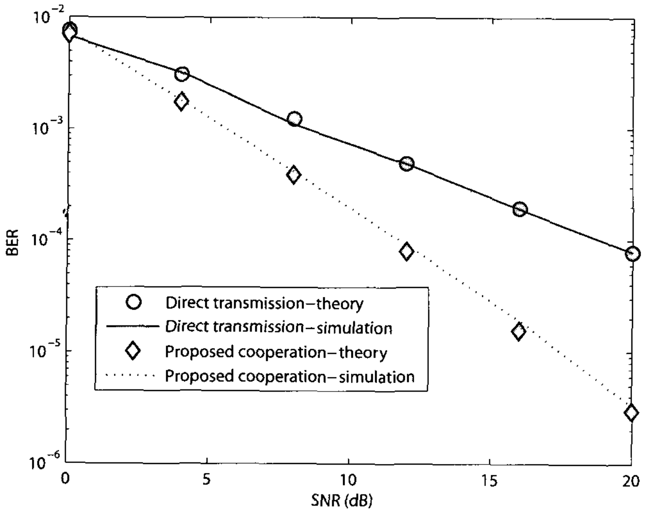


Fig. 2. Simulated and theoretical BER with $\delta = 0.75$.

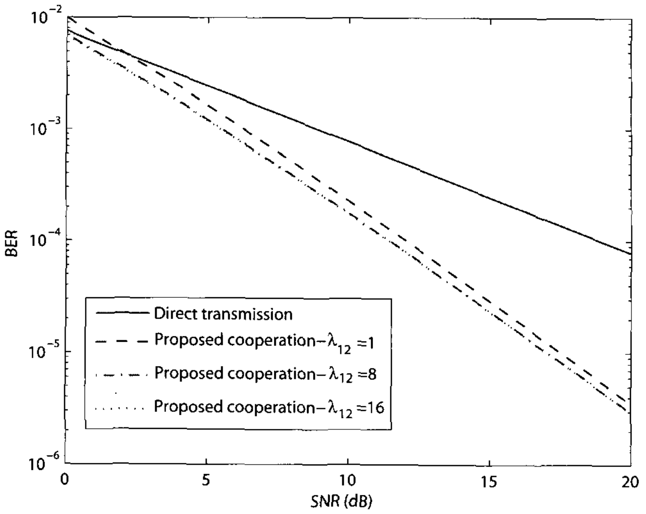


Fig. 3. Proposed cooperative strategy with $\delta = 0.75$.

This is a closed-form analytical expression for the error probability of user 1. The single-variable integral in (46) can be easily calculated by a numerical method [19].

IV. NUMERICAL RESULTS

In this section, we compare the performances of the proposed signaling strategy to that in [4] and direct transmission. The reason we choose the strategy [4] as a reference is that it has the same operation conditions as ours. For fair comparison in terms of bandwidth efficiency, we will compare two pairs as follows: 1) The direct transmission with QPSK signals versus the proposed strategy with 8-PSK signals, 2) the proposed strategy versus that in [4] (see Appendix 1 with equal amplification factors and optimal detector); both with BPSK signals. In addition, noise variances are unity ($\eta_1 = \eta_2 = \eta = 1$) and transmit power of each user is always equal to P with or without cooperation. Moreover, all spreading codes are taken from Walsh-Hadamard matrix of size 64 × 64.

In all figures presented, the signal-to-noise ratio is defined as SNR=P/η.

A. Symmetric Scenario

Symmetric scenario happens when the quality of user-destination channels is similar. Thus, the performances of users must be identical and so figures in this section only illustrate the performance of user 1. We consider this case by assigning $\lambda_{13} = \lambda_{23} = 1$.

First of all, we verify the validity of (46) and (56) (see Appendix 2) by comparing with Monte-Carlo simulations. Fig. 2 shows BER performance of CDMA system with and without cooperation where $\delta = 0.75$ and $\lambda_{12} = 10$. It is realized that the theoretical results well matches the simulated ones. Additionally, the proposed cooperation significantly outperforms the direct transmission with the gain of 8 dB at target BER of 10^{-4}. Due to achieving higher diversity order than the direct transmission, the cooperation provides more performance improvement when SNR increases.

Since the analysis agrees with the simulation, we will use (46) and (56) to evaluate the potentials of the proposed signaling strategy in enhancing BER performance in comparison to the direct transmission as well as to the strategy in [4] in the sequel.

Fig. 3 investigates BER performance of the proposed signaling strategy when fading level of inter-user channel changes. It is recognized that the cooperation performance is slightly degraded according to λ_{12} and quickly becomes constant for large values of λ_{12}. Specifically, the cooperation performs the same for $\lambda_{12} = 8$ and 16 at all values of SNR, and negligibly worse (gain loss of around 0.5 dB compared to $\lambda_{12} = 8$ and 16) for $\lambda_{12} = 1$ at high SNR. In addition, it is apparent that diversity order of our cooperative signaling strategy is higher than that of direct transmission regardless of variations of the inter-user channel. We observe an approximately 7 dB performance gain at BER of 10^{-4} for any value of λ_{12}. Additionally, BER improvement keeps increasing proportionally to SNR. As a result, the cooperation brings the benefit to both participants. However at low SNR and deep fade (e.g., $\lambda_{12} = 1$), the cooperation is not beneficial.

The influence of variation of power sharing level δ on the cooperation performance is depicted in Fig. 4. It is found that δ dramatically affects the cooperation performance. This is evident because the nature of the cooperation 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 cooperative communications, signal attenuation can arise from characteristics of propagation environment (e.g., fading and noise) as well as from power allocation to transmit each user's own data and its partner's data which is controlled by coefficients β and p. Therefore, the change of δ that leads to the variations of β and p certainly deteriorates the overall performance. However, the values of δ greater than 0.35 are enough to guarantee that the cooperation is superior to the direct transmission. Additionally, we can expect the optimum value of δ that

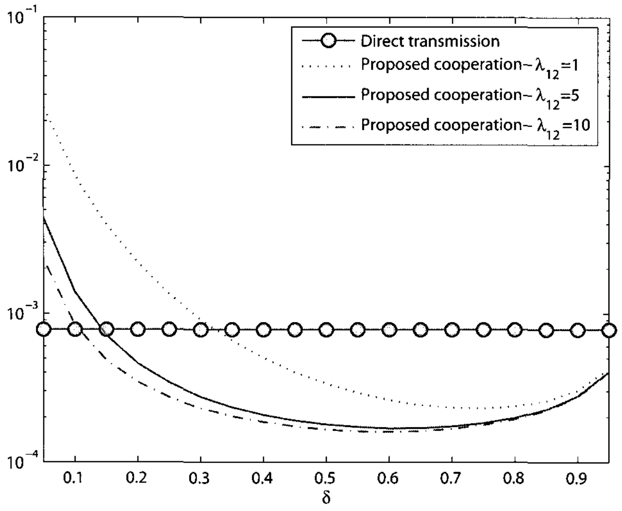


Fig. 4. Effect of δ on cooperation performance with SNR = 10 dB.

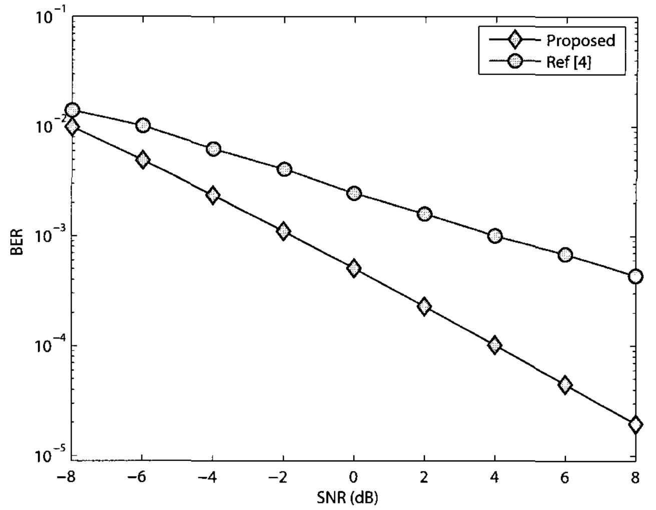


Fig. 5. BER comparison between the proposed strategy ($\delta = 0.7$) and that in [4] where $\lambda_{12} = 3$.

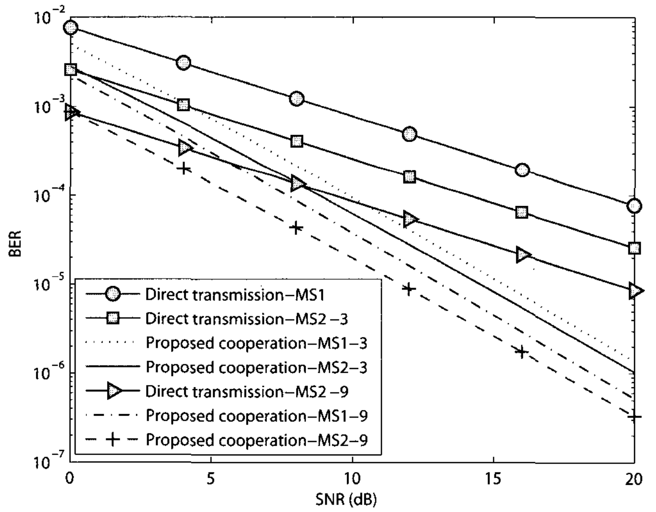


Fig. 6. Proposed signaling strategy with $\delta = 0.75$, $\lambda_{12} = \lambda_{23}$ corresponding to the numbers in the legend box (3, 9).

minimizes the error probability. As seen in Fig. 4, this value is a function of multiple arguments such as signal-to-noise ratio, fading, and noise level, etc. For example, for a set of parameters (SNR = 10 dB, $\lambda_{12} = \lambda_{13} = \lambda_{23} = 1$), the optimum δ is approximately 0.7.

Fig. 5 demonstrates the considerable superiority of the proposed signaling strategy to that in [4] for the whole range of SNR. For example, at target BER of less than 10^{-3}, our strategy provides a gain of greater than 6 dB and this gain increases dramatically with the increase of SNR. This follows the fact that the novel strategy achieves the full cooperation (the diversity order can reach 2) and limits the hard decision at the partner's side that can adversely affect the overall performance of the receiver (e.g., [4]). In fact, the strategy in [4] only exposes the partial cooperation because its BER is simply the average BER of non-cooperation phase and cooperation phase. Correspondingly, the diversity order is only slightly greater than 1 as shown in Fig. 5. In addition, the receiver in the proposed strategy is much simpler in hardware implementation than that in [4] because it applies a unique detector which is completely different from [4] where two detectors are switched to recover two consecutive symbols.

B. Asymmetric Scenario

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 $\lambda_{13} = 1$, $\lambda_{12} = \lambda_{23} \neq 1$.

Fig. 6 investigates the performance of our strategy via the variation in fading level of MS1–MS2 and MS2–BS channels. It is observed that regardless of the propagation environment conditions, the cooperative communications brings about a considerable improvement for both users compared to the direct 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 its partner. Moreover, the cooperation performance can be enhanced further when SNR increases. This is represented by the fact that the slope of cooperative BER curve is higher than that of non-cooperative curve.

Similar to Fig. 4, the factor δ also plays an important role in enhancing the cooperation performance as the symmetry of the user-destination channels is not guaranteed (see Fig. 7). In general, the cooperation is dramatically superior to the direct transmission when $\delta > 0.2$ for both users under any condition of inter-user and user-destination channels. The optimum value of δ for the lowest BER is still a function of SNR, fading and noise levels. However as seen in Fig. 7, this value slightly changes according to the fading level and it is approximately 0.7.

Once again, Fig. 8 shows that our strategy achieves a considerably better BER performance than that in [4] for the whole range of SNR in the asymmetric scenario. This is because the

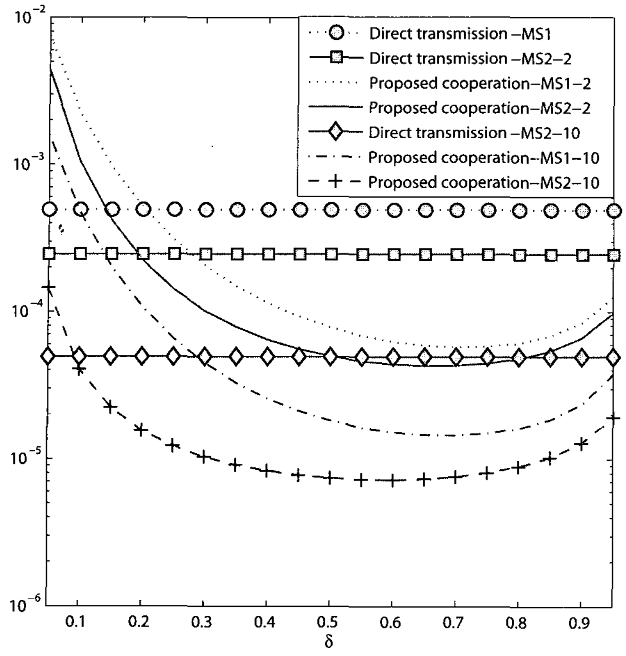


Fig. 7. BER performance of proposed signaling strategy via δ with SNR = 12 dB, $\lambda_{12} = \lambda_{23}$ corresponding to the numbers in the legend box (2, 10).

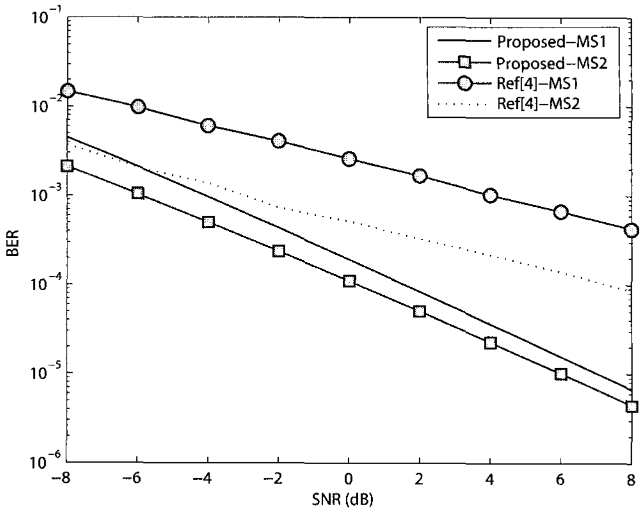


Fig. 8. BER comparison between the proposed strategy ($\delta = 0.8$) and that in [4] where $\lambda_{12} = \lambda_{23} = 5$.

diversity gain of the proposed strategy is higher than that in [4]. In addition, the performance gap between two users in our cooperative strategy is much smaller than that in [4]. In other words, our strategy provides the relatively equal performance improvement for all participants even though their channels to the destination have totally different qualities.

V. CONCLUSION

A novel cooperative communications signaling strategy for a pair of users in synchronous CDMA mobile communications network under slow flat Rayleigh fading channel plus Gaussian noise was proposed. The proposed cooperation brought a considerable performance improvement over that in [4] as well as direct transmission under any channel condition which was proved by the closed-form error probability expressions and Monte-Carlo simulations. In presented results, the fact that all users have the same transmit power constraint (that means there is no need for power-control mechanism from BS) exposes another advantage of the cooperation that the system is capable of resisting the near-far phenomenon. Also, we showed that there exists an optimum power sharing level δ that minimizes the error probability. This value is a function of signal-to-noise ratio and long-term statistics of noise and fading and thus, it can be set before the mobiles come to operation. Moreover, the cooperative strategy can achieve the maximum likelihood detection with the fullest space diversity without sacrificing hardware implementation complexity. Although the results of this paper serve the situation of two-user systems, it is straightforward to prove that the analytical expressions are applicable to multi-user systems without the performance degradation if the transmission synchronization is remained. Furthermore, we can combine this strategy with the deployment of multiple receive antennas at the destination to reduce further the error probability.

Although our strategy is more advantageous than that in [4] in terms of BER performance as well as implementation complexity under the same assumptions, it is still more complicated than direct transmission for the following reasons. The first is the need for synchronous transmission even though it is feasible in TDD-based wireless networks [4], [20], [21]. The second is the current hardware limitations for the simultaneous transmission and reception at mobiles though perfect echo cancellation was justified to be possible by strong arguments in [4] and [21]. The third is channel estimation, thus leading to loss of data rate due to CSI overhead. Although the instantaneous CSI is not necessary at mobiles (i.e., the implementation complexity at mobiles is low) since only long-term fading statistics is used to determine the amplification factors, the instantaneous CSI of all links through which a source signal can reach BS must be available at BS (i.e., most complexity poses on the destination). Therefore, that BS must obtain the CSI of inter-user channel for signal detection is still challenging to our strategy and that in [4] as well.[2] Finally, it may be the problem of assigning cooperative users. It is expected that the cooperation benefits all participants and the numerical results showed that this is only possible under certain favorable channel conditions. Therefore once BS attains

---

[2] As summarized in Appendix 1, the signal detection at the BS in [4] is performed by two detectors, one for the non-cooperation phase and the other for the cooperation phase. For the cooperation phase, either optimal detector (see (50)) or suboptimal one (see (52)) is used. Since the optimal detector requires P_{e12} in (51), the BS needs the inter-user CSI for the detection. If the suboptimal detector is used, the inter-user CSI is not necessary but in this case, an exhaustive search through computer simulations (no closed form BER expression exists) is required to find the optimal value of λ. In Section IV, since we compared the performance of the proposed scheme with that of the scheme in [4] using the optimal detector, channel estimation complexity and overhead are the same for both. However, our scheme is less complicated than that in [4] since it uses a unique detector while two detectors are switched in two phases in [4].

Table 2. Summary of transmit and receive signals of cooperative users (P denotes phase, Tx transmit, Rx receive).

	MS1		MS2		BS
P	Tx	Rx	Tx	Rx	Rx
1	$\beta_{11}x_{11}C_1$		$\beta_{21}x_{21}C_2$		y_{BS1}
2	$\beta_{12}x_{12}C_1$	y_{12}	$\beta_{22}x_{22}C_2$	y_{22}	y_{BS2}
3	$\beta_{13}x_{12}C_1+\beta_{14}\widehat{x}_{22}C_2$		$\beta_{23}\widehat{x}_{12}C_1+\beta_{24}x_{22}C_2$		y_{BS3}

CSI, it can use this information to decide "who cooperates with whom." Such a problem for multi-user OFDM networks was investigated in [22]. Although there exist multiple implementation difficulties, the high performance can be a key motivation to encourage further research efforts to overcome these challenges so as to deploy our strategy in practice.

ACKNOWLEDGMENTS

This research was supported by the Ministry of Information and Communication (MIC), Korea, under the Information technology Research Center (ITRC) support program supervised by the Institute of Information Technology Assessment (IITA).

APPENDICES

A. Appendix 1

The purpose of this appendix is to summarize the cooperative signaling strategy in [4] to make clear the differences from our proposed one and serve as a reference for comparison. This strategy is illustrated in Table 2 where x_{ij} denotes the user i's BPSK-modulated symbol in phase j, $\widehat{x}_{ij}$ the user i's recovered j-th symbol at its partner's side, β_{ij} the parameters controlling 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, $i \in \{1,\ 2\}$, over 3 phases given by

$$\sum_{j=1}^{4}\beta_{ij}^2 = 3P_i. \tag{47}$$

The cooperation process goes on as follows. Phase 1 is used to send data to BS only. However, phase 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 phase 3.

The signal detection at the BS is performed by two detectors, one for the cooperation phase and the other for the noncooperation phase. Because of symmetry, user 1 is only focused here.

For noncooperation phase, x_{11} is estimated by the chip-matched filter,

$$\begin{aligned}\overline{x}_{11} &= \text{sign}\left(\frac{1}{NT_C}\int_0^{NT_C} y_{BS1}(t)C_1(t)dt\right)\\ &= \text{sign}\left(\alpha_{13}\beta_{11}x_{11}+n_0\right)\end{aligned} \tag{48}$$

with BER given by

$$P_{e1} = \text{Q}\left(\alpha_{13}\beta_{11}\sqrt{\frac{N}{\eta_2}}\right). \tag{49}$$

In cooperation phase, restoring x_{12} is optional with either optimal detector or suboptimal one. For the optimal receiver that offers the minimum error probability, x_{12} is decided to be 1 if

$$Y > L. \tag{50}$$

Otherwise, it is assumed to be -1.

Here,

$$\begin{aligned}Y &= (1-P_{e12})W^{-1}e^{v_1^T y} + P_{e12}We^{v_2^T y}\\ L &= (1-P_{e12})W^{-1}e^{-v_1^T y} + P_{e12}We^{-v_2^T y}\\ v_1 &= [\alpha_{13}\beta_{12}\ \ (\alpha_{13}\beta_{13}+\alpha_{23}\beta_{23})]^T\sqrt{N/\eta_2}\\ v_2 &= [\alpha_{13}\beta_{12}\ \ (\alpha_{13}\beta_{13}-\alpha_{23}\beta_{23})]^T\sqrt{N/\eta_2}\\ W &= e^{\alpha_{13}\alpha_{23}\beta_{13}\beta_{23}N/\eta_2}\\ y &= [y_2\ \ y_3]^T\sqrt{N/\eta_2}\end{aligned}$$

with

$$\begin{aligned}y_2 &= \frac{1}{NT_C}\int_0^{NT_C} y_{BS2}(t)C_1(t)dt\\ y_3 &= \frac{1}{NT_C}\int_0^{NT_C} y_{BS3}(t)C_1(t)dt\\ y_{BS2}(t) &= \alpha_{13}\beta_{12}x_{12}C_1(t)+\alpha_{23}\beta_{22}x_{22}C_2(t)+n_0(t)\\ y_{BS3}(t) &= \alpha_{13}[\beta_{13}x_{12}C_1(t)+\beta_{14}\widehat{x}_{22}C_2(t)]\\ &\quad +\alpha_{23}[\beta_{23}\widehat{x}_{12}C_1(t)+\beta_{24}x_{22}C_2(t)]+n_0(t)\end{aligned}$$

and BER due to hard decision on $\widehat{x}_{12}$ given by

$$P_{e12} = \text{Q}\left(\alpha_{12}\beta_{12}\sqrt{\frac{N}{\eta_1}}\right) \tag{51}$$

where the channel parameters are denoted as in Section II but are real numbers as in [4]. This detector is not only rather complex, but also does not have a closed-form expression for the resulting BER.

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

$$\overline{x}_{12} = \text{sign}\left([\alpha_{13}\beta_{12}\ \ \lambda(\alpha_{13}\beta_{13}+\alpha_{23}\beta_{23})]y\right) \tag{52}$$

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.

BER of x_{12}, given λ, is of the form

$$P_{e2} = (1-P_{e12})\text{Q}\left(\frac{v_\lambda^T v_1}{\sqrt{v_\lambda^T v_\lambda}}\right) + P_{e12}\text{Q}\left(\frac{v_\lambda^T v_2}{\sqrt{v_\lambda^T v_\lambda}}\right) \tag{53}$$

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

It is noticed that (49), (51), and (53) are not closed form analytical expressions for performance of the suboptimal detector because it depends on the immediate parameters of channel characteristics such as α_{12}, α_{13}, and α_{23}.

B. Appendix 2

In this appendix, we derive the BER expression of direct transmission to facilitate in comparing between two transmission schemes: Cooperation and noncooperation. In noncooperation case, each user transmits its own data with full power P_j. Consequently, the signal at the chip-matched filter input of the BS is given by

$$y_{BS}(t) = \alpha_{13}\sqrt{P_1}x_1C_1(t) + \alpha_{23}\sqrt{P_2}x_2C_2(t) + n(t) \quad (54)$$

where x_j are the MPSK modulated data symbol of user j, $n(t)$ the ZMCGRV with variance η_2. Therefore, we obtain the despread signal as

$$\begin{aligned} r_j &= \frac{1}{NT_C}\int_0^{NT_C} y_{BS}(t)C_j(t)dt, \\ &= \alpha_{j3}\sqrt{P_j}x_j + \overline{n}_j \end{aligned} \quad (55)$$

for user j where $\overline{n}_j$ is ZMCGRV with variance η_2/N.

Averaging the conditional BER in (41) over the channel realization results in the average BER for user j

$$P_{eAVG\_j} = A\sum_{i=1}^{B}\int_0^{\infty} \mathrm{Q}\left(\sqrt{2C_i\gamma_j}\right) f_{\gamma_j}(\gamma_j)d\gamma_j$$

where A, B, C is given in (42) and $\gamma_j = NP_j|\alpha_{j3}|^2/\eta_2$ computed from (55) is an exponential r.v. with mean value of $\kappa_j = NP_j\lambda_{j3}/\eta_2$. Therefore, the above can be reduced to

$$\begin{aligned} P_{eAVG\_j} &= A\sum_{i=1}^{B}\int_0^{\infty} \mathrm{Q}\left(\sqrt{2C_i\gamma_j}\right)\frac{1}{\kappa_j}e^{-\gamma_j/\kappa_j}d\gamma_j \\ &= \frac{A}{2}\sum_{i=1}^{B}\left[1-\sqrt{\frac{\kappa_jC_i}{1+\kappa_jC_i}}\right]. \end{aligned} \quad (56)$$

REFERENCES

[1] J. G. Proakis, *Digital Communications*, Fourth Edition, McGraw-Hill, 2001.

[2] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block coding for wireless communications: Performance results," *IEEE Trans. Select. Areas Commun.*, vol. 17, no. 3, pp. 451–460, Mar. 1999.

[3] A. Nosratinia, A. Hedayat, and T. E. Hunter, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[4] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity. Part I–II," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1948, Nov. 2003.

[5] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[6] M. Janani, A. Hedayat, T. E. Hunter, and A. Nosratinia, "Coded cooperation in wireless communications: Space-time transmission and iterative decoding," *IEEE Trans. Signal Processing*, vol. 52, no. 2, pp. 362–371, Feb. 2004.

[7] X. Li, "Energy efficient wireless sensor networks with transmission diversity," *Electron. Lett.*, vol. 39, no. 24, pp. 1753–1755, 27 Nov. 2003.

[8] Z. Lin, E. Erkip, and A. Stefanov, "Cooperative regions for coded cooperative systems," in *Proc. IEEE GLOBECOM 2004*, vol. 1, 29 Nov.–3 Dec. 2004, pp. 21–25.

[9] M. Dohler, E. Lefranc, and H. Aghvami, "Virtual antenna arrays for future mobile communication systems," in *Proc. IEEE ICT 2002*, Beijing, China, June 2002.

[10] M. Dohler, J. Dominguez, and H. Aghvami, "Link capacity of virtual antenna arrays," in *VTC 2002-fall*, vol. 1, 24–28 Sept. 2002, pp. 440–443.

[11] R. Pabst, B. Walke, D. Schultz, P. Herhold, H. Yanikomeroglu, S. Mukherjee, H. Visvanathan, M. Lott, W. Zirwas, M. Dohler, H. Aghvami, D. Falconer, and G. Fettweis, "Relay-based deployment concepts for wireless and mobile broadband cellular radio," *IEEE Commun. Mag.*, vol. 42, no. 9, pp. 80–89, Sept. 2004.

[12] E. Zimmermann, P. Herhold, and G. Fettweis, "On the performance of cooperative relaying in wireless networks," *European Trans. Telecommun.*, vol. 16, no. 1, pp. 5–16, Jan.–Feb. 2005.

[13] J. Boyer, D. Falconer, and H. Yanikomeroglu, "A theoretical characterization of the multihop wireless communications channel with diversity," in *Proc. IEEE GLOBECOM 2001*, vol. 2, 25–29 Nov. 2001, pp. 841–845.

[14] J. Boyer, D. D. Falconer, and H. Yanikomeroglu, "Multihop diversity in wireless relaying channels," *IEEE Trans. Communun.*, vol. 52, no. 10, pp. 1820–1830, Oct. 2004.

[15] V. Emamian, P. Anghel, and M. Kaveh, "Multi-user spatial diversity in a shadow-fading environment," in *Proc. VTC 2002-fall*, vol. 1, 24–28 Sept. 2002, pp. 573–576.

[16] P. A. Anghel and M. Kaveh, "Exact symbol error probability of a cooperative network in a Rayleigh-fading environment," *IEEE Trans. Commun.*, vol. 3, no. 5, pp. 1416–1421, Sept. 2004.

[17] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Trans. Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[18] M. K. Simon and M. S. Alouini, *Digital Communication over Fading Channels*, Second Edition, John Wiley & Sons, Inc., 2005.

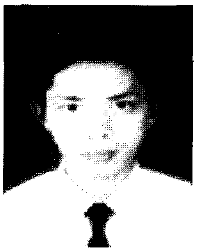
[19] A. Papoulis and S. U. Pillai, *Probability, Random Variables, and Stochastic Process*, Fourth Edition, McGraw-Hill, 2002.

[20] R. Esmailzadeh and M. Nakagawa, *TDD-CDMA for Wireless Communications*, Artech House Inc., 2003.

[21] T. Cover and A. E. Gamal, "Capacity theorems for the relay channel," *IEEE Trans. Inform. Theory*, vol. 25, no. 5, pp. 572–584, Sept. 1979.

[22] Z. Han, T. Himsoon, W. P. Siriwongpairat, and K. J. R. Liu, "Energy-efficient cooperative transmission over multiuser OFDM networks: Who helps whom and how to cooperate," in *Proc. WCNC 2005*, vol. 2, 13–17 Mar. 2005, pp. 1030–1035.

[23] K. Fazel and S. Kaiser, *Multi-Carrier and Spread Spectrum Systems*, John Wiley & Sons Ltd., 2003.



Ho Van Khuong received the B.E. (the first-ranked honor) and the M.S. degrees in Electronics and Telecommunications Engineering from HoChiMinh City University of Technology, Vietnam, in 2001 and 2003, respectively. From April 2001 to September 2004, he was a lecturer at Telecommunications Department, HoChiMinh City University of Technology. He is currently working toward the Ph.D degree in the Department of Electrical Engineering, University of Ulsan, Korea. His major research interests are modulation and coding techniques, MIMO system, digital signal processing, and cooperative communications.

Hyung Yun Kong received the Ph.D. and M.E. degrees in Electrical Engineering from Polytechnic University, Brooklyn, New York, USA, in 1996 and 1991, respectively. And he received B.E. in Electrical Engineering from New York Institute of Technology, New York in 1989. Since 1996, he was with LG electronics Co., Ltd. in multimedia research lab developing PCS mobile phone systems and LG chairman's office planning future satellite communication systems from 1997. Currently, he is an associate professor in Electrical Engineering at University of Ulsan, Ulsan, Korea. He performs several government projects supported by Information Technology Research Center (ITRC), Korean Science and Engineering Foundation (KOSEF), etc. His research area includes high data rate modulation, channel coding, detection and estimation, cooperative communications, and sensor network. He is member of IEEK, KICS, KIPS, and IEICE.