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Decode-and-forward relaying based on orthogonal complementary codes

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Abstract: In this note, we propose a full-duplex decode-and-forward cooperative diversity scheme based on code division with orthogonal complementary codes. We consider a simple case in which a single user is assisted by a single relay to achieve cooperative diversity. When the cooperation is full-duplex, the operational delay of the relay makes the channel asynchronous and this may cause multiple-access interference (MAI) between the user and relay. The orthogonal complementary codes have perfect autocorrelation and cross-correlation properties that provide MAI-free operation in asynchronous channels. In the proposed scheme, the user and relay terminals spread their messages with complementary codes and the spread messages can reach the destination without interfering with each other. The numerical results reveal that the proposed scheme reaches the same bit-error-rate performance in both synchronous and asynchronous channels. The results are also compared with the conventional orthogonal code sets, such as Hadamard sets, which fail to provide diversity.

Key words: Decode-and-forward relaying, orthogonal complementary codes, CDMA, in-band relays

1. Introduction

Cooperative wireless communication has been proposed as an alternative diversity technique to overcome fading effects [1][2]. In cooperative diversity, user and relay terminals share the same resources and provide transmit diversity gain. Cooperative communication has been considered in the most recent wireless standards such as 3GPP LTE-Advanced and IEEE 802.16 [3][4].

One of the pioneering works on using cooperative diversity techniques for cellular networks in [2] considers a full-duplex protocol for the synchronous CDMA channel with orthogonal spreading codes. However, the CDMA uplink channel does not allow synchronous transmission and using orthogonal codes introduces multiple-access interference (MAI) to the system. In the literature, there are some works that aimed to achieve cooperative diversity in asynchronous CDMA channels. In [5], the authors proposed a multiple-relay coded cooperation strategy in order to overcome the MAI in the network. In [6], a medium access control (MAC) protocol was proposed to provide orthogonality in asynchronous channels. The outage analysis of cooperative diversity in asynchronous CDMA uplink channels was presented in [7][8]. In [9], a half-duplex cooperation with a single user and multiple-relay CDMA uplink channel was considered. It was reported that the MAI between the relay terminals significantly limits the system performance.

In an asynchronous CDMA uplink channel, when the cooperation is half-duplex (i.e. it is based on time division), the MAI in each time slot should be considered. For instance, if it is a multiple-user and multiple-

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relay network, in the first phase interuser MAI and in the second phase interrelay MAI degrade the cooperation performance. On the other hand, in full-duplex relaying, MAI may occur between each terminal in the network.

In this note, we propose a full-duplex cooperative communication scheme based on code division with orthogonal complementary codes. We limit our discussion to a simple scenario with one user and one relay. Even in this case, MAI may arise due to the processing delay at the relay terminal. This problem may occur in both full-duplex uplink and downlink channels. The proposed scheme provides MAI-free full-duplex cooperation in asynchronous channels.

Complementary coded CDMA (CC-CDMA) was proposed in [10] as a candidate for the next-generation CDMA networks. Complementary coded CDMA has some advantages over traditional CDMA networks. The main advantage is that the complementary code sets provide perfect autocorrelation and cross-correlation properties, which yield a MAI-free network [11]. In addition, CC-CDMA networks do not require complex power control algorithms. One disadvantage is that the number of available complementary code sets is limited. In [12], the authors proposed a code hopping technique for CC-CDMA to extend the number of supported users in the network.

The main novelty of this work is that we demonstrate a MAI-free full-duplex cooperative communication in an asynchronous CDMA channel. In addition to MAI, full-duplex relaying systems also suffer from the loop interference that can arise due to the leakage from one antenna of the relay to the other antenna. In the literature, there are some works that modeled the loop interference and investigated the system performance [13][14]. There are also some studies designed to cancel the loop interference using physical layer algorithms; however, in practice, these schemes are imperfect [15][16]. The presented scheme in this work can also suppress the loop interference with the aid of perfect correlation properties of the complementary codes.

The paper is organized as follows. Section 2 reviews the orthogonal complementary codes. Section 3 introduces the proposed decode-and-forward strategy. Section 4 presents the numerical results. Finally, the paper is concluded in Section 5.

2. Orthogonal complementary codes

This section presents a brief review on complementary coded CDMA networks. Assume a complementary code $\mathbf{C}_k$ is assigned to the user k in the network. A complementary code consists of N number of element codes, i.e. $\mathbf{C}_k = [\mathrm{c}_{k1}\ \mathrm{c}_{k2}\ \mathrm{c}_{k3}\ \ldots\ \mathrm{c}_{kN}]$. The data stream at the user k is applied to N different spreading modulator and the spread streams are sent over N different subcarriers $f_1, f_2, ..., f_N$. Figure 1 illustrates the transmitter and receiver blocks of DS/CC-CDMA system for user k when $N = 2$.

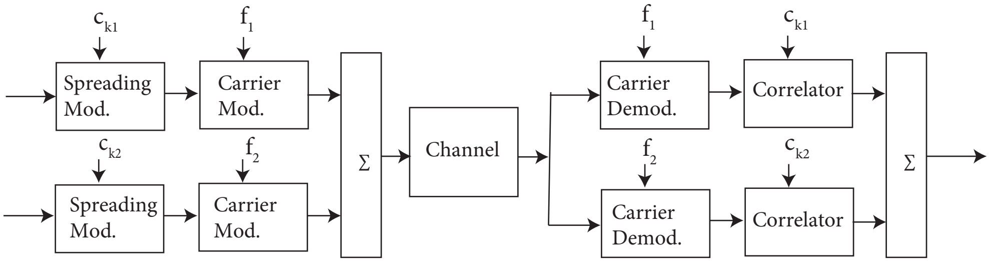


Figure 1. Transmission model of point-to-point complementary coded CDMA when $N = 2$.

At the receiver side, received signals at the different subcarriers are first demodulated and then a despreading process is applied with the corresponding element code. The decoded streams are then summed and fed to the decision device.

The multicarrier transmission provides strong autocorrelation function (ACF) and cross-correlation function (CCF) behaviors. Although the individual ACFs of the element codes $R(c_{kj};\tau)$ have many side lobes, the ACF of their sum over different channels

$$R(\mathbf{C}_k;\tau)=\sum_{j=1}^{N}\int_{-\infty}^{+\infty}c_{kj}(t)c_{kj}(t-\tau)dt \tag{1}$$

is zero for any time shift τ except zero shift. This property of CC-CDMA provides multipath-interference (MI)-free transmission. Similarly, although the individual CCFs of the element codes for different users of the same subcarrier, $\rho(c_{kj},c_{k'j};\tau)$, are not ideal, the CCF of the sum

$$\rho(\mathbf{C}_k,\mathbf{C}_{k'};\tau)=\sum_{j=1}^{N}\int_{-\infty}^{+\infty}c_{kj}(t)c_{k'j}(t-\tau)dt \tag{2}$$

is zero for all possible time shifts, which suppresses the MAI in the network [10][11][17].

3. Proposed decode-and-forward strategy

3.1. System model and transmission

We adopt a three-node topology in which only source (S), relay (R), and destination (D) terminals exist. Figure 2 draws the model. The presented model is valid for both downlink and uplink channels. The distances between the terminals are given in order to include the long-term path loss effects. If the channel gain for the S→D link is unity $G_{sd}=1$ and $d_{sd}=1$, then the channel gains for the R→D and S→R links become $G_{rd}=(d_{sd}/d_{rd})^p$ and $G_{sr}=(d_{sd}/d_{sr})^p$, respectively. p is the propagation exponent.

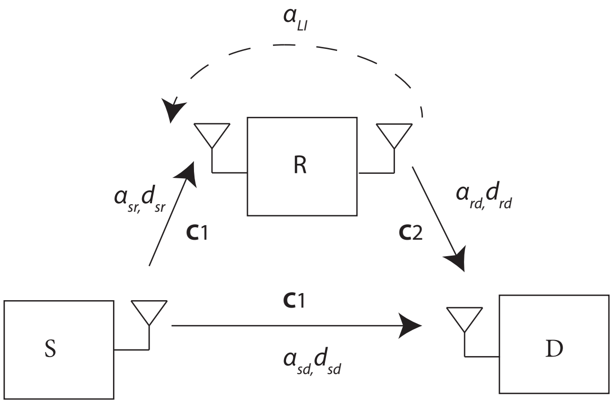


Figure 2. System model of single-relay in-band cooperative communications.

Consider a complementary coded CDMA scheme with two subcarriers, $N=2$. The complementary codes $\mathbf{C}_1$ and $\mathbf{C}_2$ are assigned to the source and relay terminals, respectively. The transmitted signal by the source, $s(t)$, is

$$s(t)=\sqrt{P}a(t)[c_{11}(t)cos(2\pi f_1 t)+c_{12}(t)cos(2\pi f_2 t)], \tag{3}$$

where P is the transmitted power of the source, f_1 and f_2 are the carrier frequencies, $a(t)$ is the transmitted information, and $c_{11}(t)$ and $c_{12}(t)$ are the element codes corresponding to two different subcarriers of $\mathbf{C}_1$. The transmitter structure of the source is given in Figure 3a.

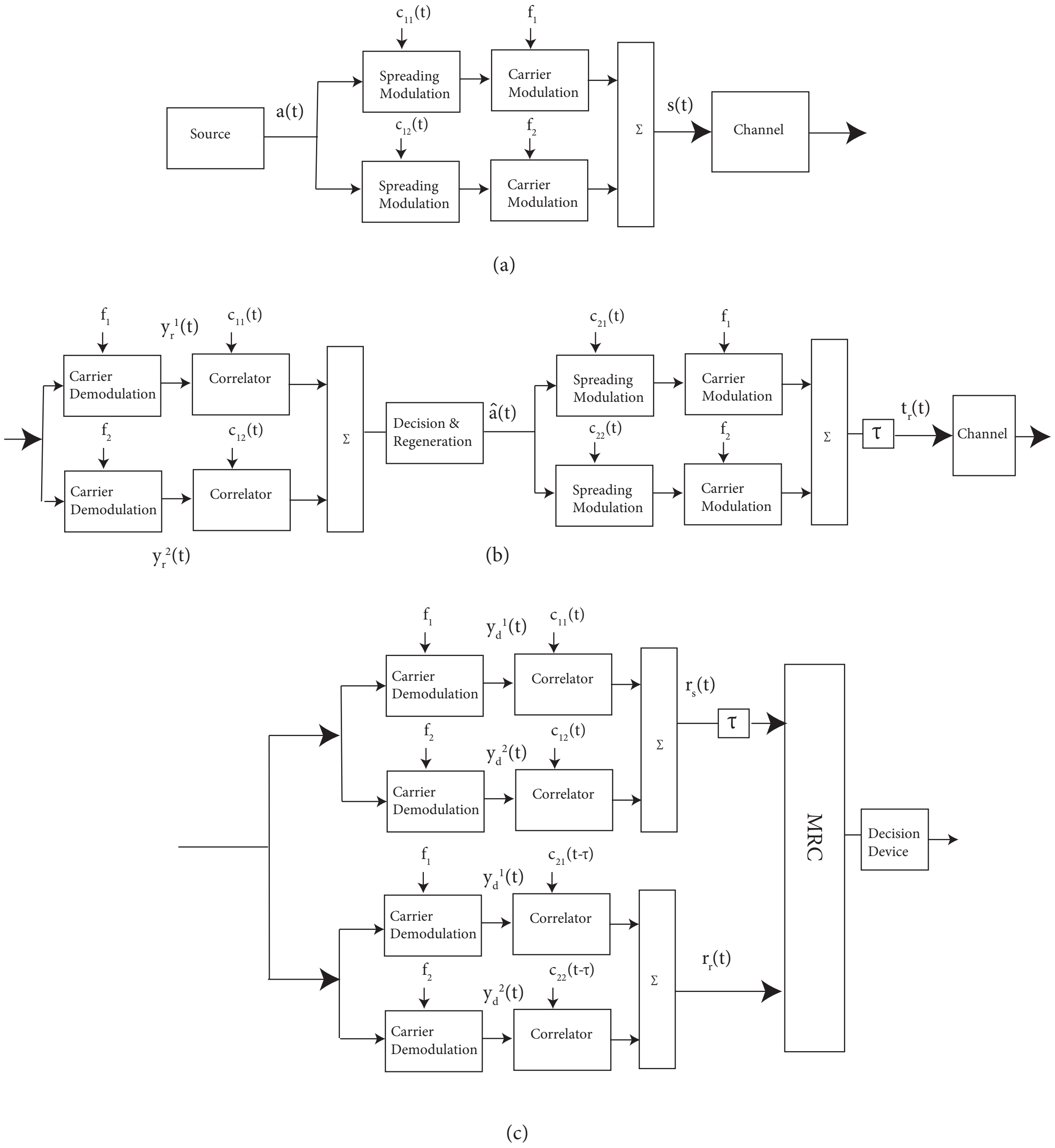


Figure 3. Block diagram DF: (a) source terminal, (b) relay terminal, (c) receiver terminal.

The transmitted information waveform $a(t)$ is written as

$$a(t) = \sum_{n=0}^{\infty} a[n]p(t - nT_b), \tag{4}$$

where $a[n]$ is the binary information sequence, $p(t)$ is the waveform of rectangular shape, and T_b is the bit duration.

The relay terminal receives a signal from the source terminal through a fading channel. In the derivations, the channel is assumed flat over the two subcarriers. The received signals by the relay terminal after the carrier demodulation are

$$y_r^1(t) = \sqrt{PG_{sr}}a(t)c_{11}(t)\alpha_{sr} + n_r(t), \tag{5}$$

$$y_r^2(t) = \sqrt{PG_{sr}}a(t)c_{12}(t)\alpha_{sr} + n_r(t), \tag{6}$$

where $y_r^1(t)$ and $y_r^2(t)$ are the received signals at the two subcarriers, α_{sr} is the fading amplitude of the channel for S→R link, and $n_r(t)$ is the AWGN at the relay terminal with double-sided power spectral density of $N_0/2$.

The relay terminal regenerates the information and forwards it to the destination. The relay receives and transmits simultaneously in the same bands. The processing time of the relay terminal, including regeneration and amplification, will add delay to the transmission. If the processing delay is τ, then the transmitted signal from the relay terminal becomes

$$t_r(t) = \sqrt{P}\hat{a}(t-\tau)[c_{21}(t-\tau)cos(2\pi f_1(t-\tau)) + c_{22}(t-\tau)cos(2\pi f_2(t-\tau))], \tag{7}$$

where $\hat{a}(t)$ is the regenerated information signal, and $c_{21}(t)$ and $c_{22}(t)$ are the element codes of $\mathbf{C}_2$, which is a sequence of the orthogonal pair with $\mathbf{C}_1$. The transmission power of the relay terminal is the same as the source terminal, which makes the total power $2P$ be equally shared between the source and relay terminals. The receiver and transmitter structures of the relay terminal are given in Figure 3b.

3.2. Detection scheme

The transmitted signals from the source and relay terminals are added in the medium and arrive at the destination over two subchannels. After carrier demodulation, the received signals at the destination from the two subcarriers $y_d^1(t)$ and $y_d^2(t)$ can be written as

$$y_d^1(t) = \sqrt{P}a(t)c_{11}(t)\alpha_{sd} + \sqrt{PG_{rd}}\hat{a}(t-\tau)c_{21}(t-\tau)\alpha_{rd} + n_d(t), \tag{8}$$

$$y_d^2(t) = \sqrt{P}a(t)c_{12}(t)\alpha_{sd} + \sqrt{PG_{rd}}\hat{a}(t-\tau)c_{22}(t-\tau)\alpha_{rd} + n_d(t), \tag{9}$$

where α_{sd} and α_{rd} are the fading amplitudes of the channels for S→D and R→D links, and $n_d(t)$ is the additive white Gaussian noise at the destination. In decode-and-forward relaying, since it is difficult to find closed-form expression for the received signal due to the decoding errors at the relay terminal, we leave $\hat{a}(t)$ as the decoded and forwarded version of the message waveform.

Our aim is to combine the signals from the source and relay terminals. As seen in Eqs. (8) and (9), the signals from the source and relay terminals are transmitted in the same bands and the destination terminal needs to separate them successfully. Figure 3c draws the block diagram of the destination terminal. The first part of the receiver is to obtain the signal from the source terminal. The destination correlates the received signals in Eqs. (8) and (9) with $c_{11}(t)$ and $c_{12}(t)$, respectively, and obtains the signal from the source terminal $r_s(t)$ as

$$\begin{aligned} r_s(t) &= y_d^1(t)c_{11}(t) + y_d^2(t)c_{12}(t) \\ &= [\sqrt{P}a(t)c_{11}(t)\alpha_{sd} + \sqrt{PG_{rd}}\hat{a}(t-\tau)c_{21}(t-\tau)\alpha_{rd} + n_d(t)]c_{11}(t) + \\ &\quad [\sqrt{P}a(t)c_{12}(t)\alpha_{sd} + \sqrt{PG_{rd}}\hat{a}(t-\tau)c_{22}(t-\tau)\alpha_{rd} + n_d(t)]c_{12}(t) \\ &= \sqrt{P}\mathrm{PG}a(t)\alpha_{sd} + [c_{11}(t) + c_{12}(t)]n_d(t), \end{aligned} \tag{10}$$

where PG is the processing gain. In Eq. (10), although the autocorrelation of individual element codes has side lobes, their summation is a perfect peak, $c_{11}(t)c_{11}(t) + c_{12}(t)c_{12}(t)$, and is equal to PG. Similarly, even though the cross-correlation of each element code is not zero, the sum of $c_{11}(t)c_{21}(t-\tau) + c_{12}(t)c_{22}(t-\tau)$ gives zero for any time shift τ. This cancels the signal from the relay terminal and obtains only the signal from the source terminal.

The second part of the receiver is set to detect the signal from the relay terminal. The signal from the relay terminal $r_r(t)$ can be obtained as

$$\begin{aligned} r_r(t) &= y_d^1(t)c_{21}(t-\tau) + y_d^2(t)c_{22}(t-\tau) \\ &= [\sqrt{P}a(t)c_{11}(t)\alpha_{sd} + \sqrt{PG_{rd}}\hat{a}(t-\tau)c_{21}(t-\tau)\alpha_{rd} + n_d(t)]c_{21}(t-\tau) + \\ &\quad [\sqrt{P}a(t)c_{12}(t)\alpha_{sd} + \sqrt{PG_{rd}}\hat{a}(t-\tau)c_{22}(t-\tau)\alpha_{rd} + n_d(t)]c_{22}(t-\tau) \\ &= \sqrt{PG_{rd}}\mathrm{PG}\hat{a}(t-\tau)\alpha_{rd} + [c_{21}(t-\tau) + c_{22}(t-\tau)]n_d(t). \end{aligned} \tag{11}$$

In Eq. (11), again the ideal ACF and CCF properties of the complementary codes yield the separation of the signal sent by the relay terminal. In this scheme, it is assumed that τ is known to the destination, which can be achieved by inserting a pilot tone [18].

An illustrative example is given in Figure 4. The number of complementary codes is two (one for the source and one for the relay). Each complementary code has two element codes, $N = 2$ with 4 chips. The element codes are $c_{11} = [+1\ +1\ +1\ -1]$, $c_{12} = [+1\ -1\ +1\ +1]$, $c_{21} = [+1\ +1\ -1\ +1]$, and $c_{22} = [+1\ -1\ -1\ -1]$. It is assumed that the packet (+1 –1 +1) is transmitted. The processing gain of such a system is 8 ($N \times 4$). The relayed signal arrives at the destination with a delay of one chip duration. In Figure 4, only the detection of the second bit of the packet from the source is given. The despreading is applied with the element codes c_{11} and c_{12} at the corresponding bands. The sum of the detected symbols in f_1 and f_2 gives –8 and hence the second bit can be recovered in the presence of the relayed signal in the same channel.

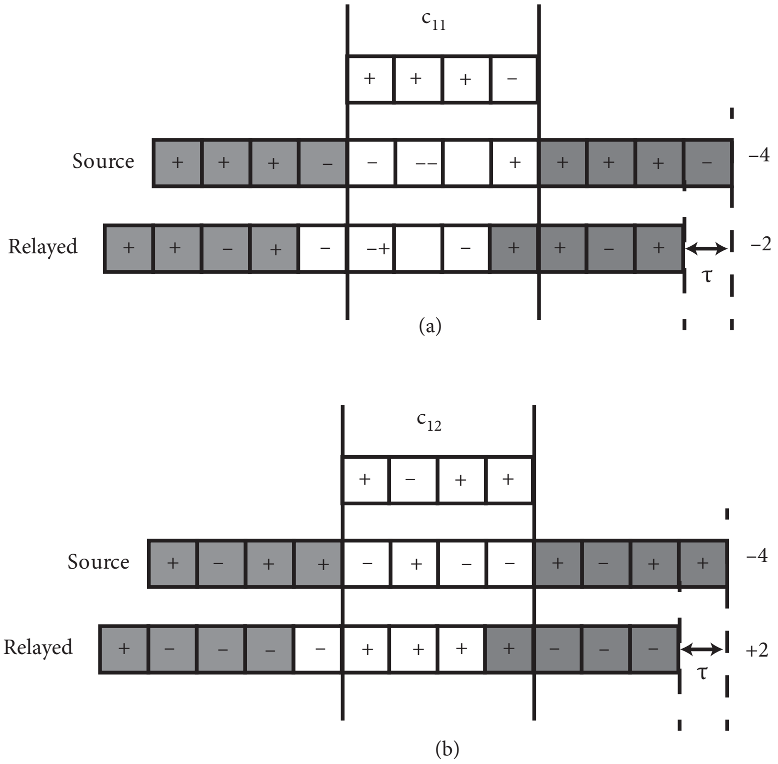
3.3. Loop interference suppression

The loop interference can be defined as the leakage signal from the transmitting antenna of the relay to its receiver antenna. As seen in Figure 2, the receiver of the relay terminal applies despreading with $\mathbf{C}_1$ and the transmitter of the relay terminal spreads the information with $\mathbf{C}_2$.

Incorporating the loop link, the received signal by the relay terminal in Eqs. (5) and (6) can be rewritten as

$$y_r^1(t) = a(t)c_{11}(t)\alpha_{sr} + \hat{a}(t-\tau)c_{21}(t-\tau)\alpha_{LI} + n_r(t), \tag{12}$$

$$y_r^2(t) = a(t)c_{12}(t)\alpha_{sr} + \hat{a}(t-\tau)c_{22}(t-\tau)\alpha_{LI} + n_r(t), \tag{13}$$



(a)

(b)

Figure 4. Detection of the second bit of the information transmitted by the source. Second bit is (–4 – 2) + (–4 + 2) = –8. (a) Detection in the first band. (b) Detection in the second band.

where α_{LI} is the channel coefficient for the loop link. The cross-correlation of the orthogonal complementary codes will give zero, including any possible time shift τ, $\rho(\mathbf{C}_1, \mathbf{C}_{2'}; \tau) = 0$. Hence, the receiver of the relay terminal will suppress any signal spread by $\mathbf{C}_2$. Therefore, the proposed scheme will not suffer from loop interference.

4. Numerical results

In this section, we evaluate the bit-error-rate (BER) performance of the proposed scheme though computer simulation. We consider a BPSK modulation scheme. The fading amplitudes α_{sd}, α_{sr}, and α_{sr} are Rayleigh-distributed. In the simulations, the channel estimation is ideal and the combining scheme is maximal-ratio-combining.

We assume the distance for the S→D link is equal to unity, $\mathrm{d}_{sd} = 1$, and all three terminals are placed on a straight line. The distances d_{sr} and d_{rd} are then normalized to d_{sd}. The propagation exponent is taken as 2.

Figures 5 and 6 show the BER performance of CDMA-based decode-and-forward relaying with orthogonal complementary codes and with traditional Hadamard codes, respectively. The performance of the system is given for both synchronous and asynchronous transmission. In the synchronous case, the relay terminal does not introduce any delay to the transmission, which is an ideal case for comparison. In the asynchronous case, the operational delay at the relay terminal is taken as a single chip duration of the element code. The same delay time corresponds with the double chip duration in the Hadamard code set in order to occupy the same bandwidth.

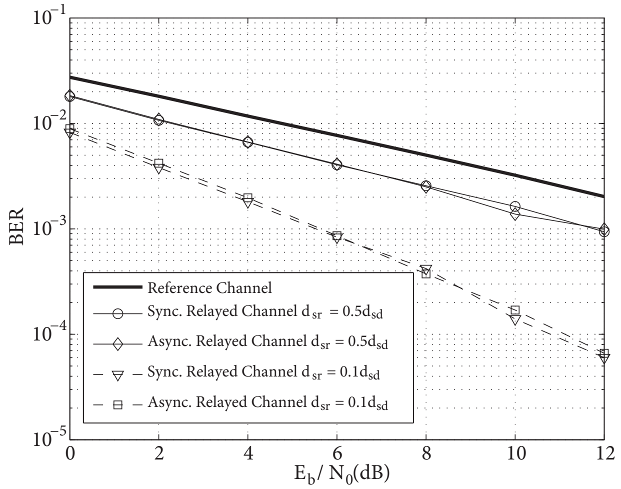


Figure 5. BER performance of the decode-and-forward relaying with orthogonal complementary codes.

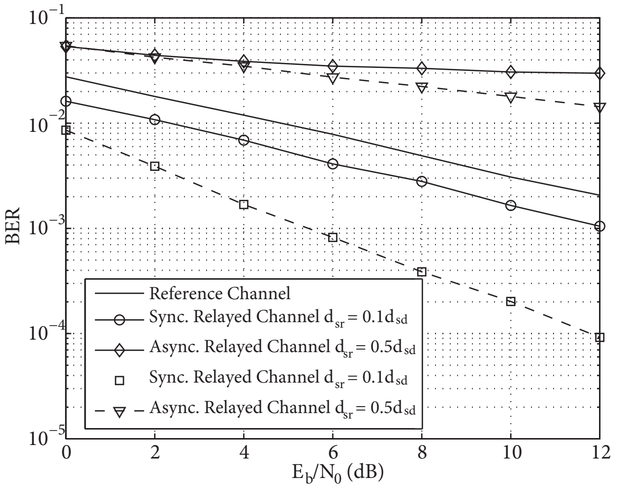


Figure 6. BER performance of the decode-and-forward relaying with Hadamard codes.

We have considered the code set c_{11} = [+1 +1 +1 –1], c_{12} = [+1 –1 +1 +1], c_{21} = [+1 +1 –1 +1], and c_{22} = [+1 –1 –1 –1], which provides the processing gain of 8. The Hadamard codes we have used with the same processing gain are c_1 = [+1 +1 -1 +1 –1 –1 –1 –1] and c_2 = [+1 +1 –1 –1 –1 –1 +1 +1]. The performance of the transmission without relaying operation is also given as a reference channel. The consumed powers in the reference and the relaying models are kept the same for fair comparison.

In the simulations, the relay terminal is placed at different locations: half way between the source and the relay terminals, $d_{sr} = 0.5 d_{sd}$, and closer to the source terminal, $d_{sr} = 0.1 d_{sd}$. Since the diversity reception heavily depends on the decoding performance of the relay, we expect more diversity gain when the relay is closer to the source terminal.

In Figure 5, the BER performance of the cooperative transmission based on orthogonal complementary codes is given. When $d_{sr} = 0.5 d_{sd}$, the BER performance is the same for synchronous and asynchronous transmission. Therefore, the operational delay added by the relay terminal does not affect the system performance when complementary codes are used. When the relay terminal is moved closer to the source, the diversity effect is more distinct.

In Figure 6, we see the performance of the Hadamard code set for the same decode-and-forward relaying scenario. If there is no delay introduced by the relay terminal (synchronous transmission), the two channels from the source and relay are orthogonal and the performance is the same as the complementary coded cooperation, as expected. However, in a practical case where there is a delay (asynchronous transmission), the orthogonality between the channels is destroyed and the performance of the diversity receiver is degraded due to the MAI.

5. Conclusions

This work proposes a novel full-duplex code division-based cooperative communication architecture based on orthogonal complementary codes. The results have revealed that the proposed scheme can accommodate another channel for the R → D link without interference due to perfect correlation properties of the orthogonal complementary codes.

We have considered a case with a single user and a single relay. However, it is known that CC-CDMA networks offer MAI-free operation for multiuser cases as well [10]. We expect that the proposed scheme can also work in multiuser scenarios. The only limitation in the multiuser case is the number of available complementary codes, which are less than the traditional code sets.

In full-duplex relaying, both uplink and downlink channels are asynchronous due to the processing delay at the relay. The proposed scheme can be applied to both uplink and downlink channels. For half-duplex relaying, considering the asynchronous nature of uplink channel in CDMA networks, the proposed scheme can help to achieve cooperative diversity in the uplink with less overhead.

In this work, we have set the processing delay of relay to a single chip duration. However, any delay including fractional chip durations will not affect the perfect ACF and CCF properties of the complementary codes [10]. In the proposed scheme, the delay introduced by the relay should be estimated at the receiver, which is the only requirement of the system.

The discussion has been kept limited to flat fading channels and the extension to multipath fading channels is left as a future work. It is known that complementary codes keep their properties in multipath fading channels with an adaptive recursive multipath signal reception filter [19].

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