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Performance of Space-Time Block Coded CDMA Systems with Adaptive Beamforming

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1 Introduction

Recently, there have been a large number of works on use of multiple antenna to combat multipath fading and provide spatial diversity, among which space-time block codes [1, 2] have been known as the most efficient ones due to its provision of full spatial diversity and simple linear decoder. For multiuser communication systems, space-time block codes can be used in conjunction with receive adaptive beamforming to suppress co-channel interferences (CCIs)[3]. Besides, space-time block codes have been also proposed to use with direct sequence code division multiple access (DS-CDMA) to combat the impairments of multiuser channels [4, 5].

In this paper, similar to [4] we explore performance of two space-time block coded (STBC) CDMA systems: one with space-time block encoding implemented before spreading (symbol-level space-time encoding) and the other after spreading (chip-level space-time encoding). The difference, however, is that we are interested in STBC multiple input multiple output (MIMO) CDMA rather than STBC multiple input single output (MISO) CDMA systems. In the transmit side of an up-link communication, mobile terminals (MTs) employ the simple Alamouti-type space-time block code to transmit their signals over 2 transmit antennas. At the base station (BS), the adaptive beamforming approach [3] is adopted to decode STBC symbols and separate signals from co-channel users. The beamforming approach also has advantages in that it can easily applied for any arbitrary number of receive antennas and, what is more, it does not require explicit channel state information (CSI) for decoding.

The remainder of this paper is organized as follows. We give a brief overview on adaptive beamforming for space-time block code and then describe the signal models of the two STBC MIMO CDMA systems in Sect. 2. Simulation results are presented in Sect. 3 and, finally, Sect. 4 concludes the paper.

2 Space-Time Block Coded CDMA Systems

2.1 Space-Time Block Code and Adaptive Beamforming

We consider a multiuser uplink communication system where K MTs use the Alamouti's space-time block coding scheme to encode and transmit their signals over their two transmit antennas. At time t the kth MT transmits $b_1^{(k)}$ over its the first antenna and $b_2^{(k)}$ over the second antenna. At the next time slot, i.e., $(t+T)$, it transmits $-\big(b_2^{(k)}\big)^*$ over the first antenna and $\big(b_1^{(k)}\big)^*$ over the second antenna, where T is the symbol duration and $(.)^*$ means complex conjugate. This encoding scheme can be expressed by an encoding matrix as

$$\boldsymbol{B} = \begin{bmatrix} b_1^{(k)} & -\big(b_2^{(k)}\big)^* \\ b_2^{(k)} & \big(b_1^{(k)}\big)^* \end{bmatrix}. \tag{1}$$

For this space-time block code, Alamouti [1] proposed a very simple linear processing decoder which uses the explicit channel state information (CSI) to coherently decode the encoded symbols. Although the Alamouti's decoding scheme is simple, it relies on the CSI obtained from

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a separate channel estimator and, what is more, it is not suitable for multiuser systems where CCIs exist. In [3] we have proposed an adaptive beamforming scheme for the Alamouti's space-time block code which has capability to suppress CCIs and also does not require the explicit CSI for decoding.

Let the channel between the mth transmit antenna of the kth MT and the nth antenna of the BS be $h_{nm}^{(k)}$, where $m \in \{1, 2\}$ and $n = 1, 2, \dots, N$. Denote the independent and identically distributed (i.i.d.) noises in the nth receive antenna at time t and $(t + T)$ as n_{n1} and n_{n2}, and similarly the received signals in the nth antenna at time t and $(t + T)$ as x_{n1} and x_{n2}, respectively. The reception processing part decomposes (serial-to-parallel (S/P) converts) the receive signal at each antenna to create [3]

$$x_{n1} = \sum_{k=1}^{K} b_1^{(k)} h_{n1}^{(k)} + b_2^{(k)} h_{n2}^{(k)} + n_{n1} \tag{2}$$

$$x_{n2} = \sum_{k=1}^{K} -\left(b_2^{(k)}\right)^* h_{n1}^{(k)} + \left(b_1^{(k)}\right)^* h_{n2}^{(k)} + n_{n2}, \tag{3}$$

where the channels have been assumed static over two consecutive symbols. Let $\boldsymbol{x}_n = [x_{n1} \quad x_{n2}^*]^{\mathsf{T}}$, $\boldsymbol{x} = [\boldsymbol{x}_1^{\mathsf{T}} \quad \boldsymbol{x}_2^{\mathsf{T}} \dots \boldsymbol{x}_N^{\mathsf{T}}]^{\mathsf{T}}$ and denote $\boldsymbol{d}^{(k)} = \left[d_1^{(k)} \quad d_2^{(k)}\right]^{\mathsf{T}}$ the pilot signal of the kth MT, where $(.)^{\mathsf{T}}$ is the vector transpose operation. The minimum mean square error (MMSE) beamforming solves the following cost function to find the optimal weight vectors [3]

$$\boldsymbol{w}_{\ell_{opt}}^{(k)} = \arg\min_{\boldsymbol{w}_\ell} \mathcal{E}\left\{\left|d_\ell^{(k)} - \left(\boldsymbol{w}_\ell^{(1)}\right)^{\mathsf{H}} \boldsymbol{x}\right|^2\right\}, \tag{4}$$

where $\mathcal{E}\{.\}$ means the expected operation, $(.)^{\mathsf{H}}$ is the complex conjugate transpose operation, and $\ell \in \{1, 2\}$. Solutions of (4) are the optimal weight vectors $\boldsymbol{w}_{1_{opt}}^{(k)}$ and $\boldsymbol{w}_{2_{opt}}^{(k)}$

$$\boldsymbol{w}_{\ell_{opt}}^{(k)} = \boldsymbol{R}_{xx}^{-1} \boldsymbol{r}_{xd_\ell}^{(k)}, \tag{5}$$

where $\boldsymbol{R}_{xx} = \mathcal{E}\left\{\boldsymbol{x}\boldsymbol{x}^{\mathsf{H}}\right\}$ and $\boldsymbol{r}_{xd_\ell}^{(k)} = \mathcal{E}\left\{\boldsymbol{x}\left(d_\ell^{(k)}\right)^*\right\}$ are the covariance matrix and correlation vector, respectively [6]. Using these optimal weight vectors, estimates of transmit symbols b_1 and b_2 are given by

$$\tilde{b}_\ell^{(k)} = \left(\boldsymbol{w}_{\ell_{opt}}^{(k)}\right)^{\mathsf{H}} \boldsymbol{x} \tag{6}$$

2.2 Symbol-level STBC MIMO CDMA System

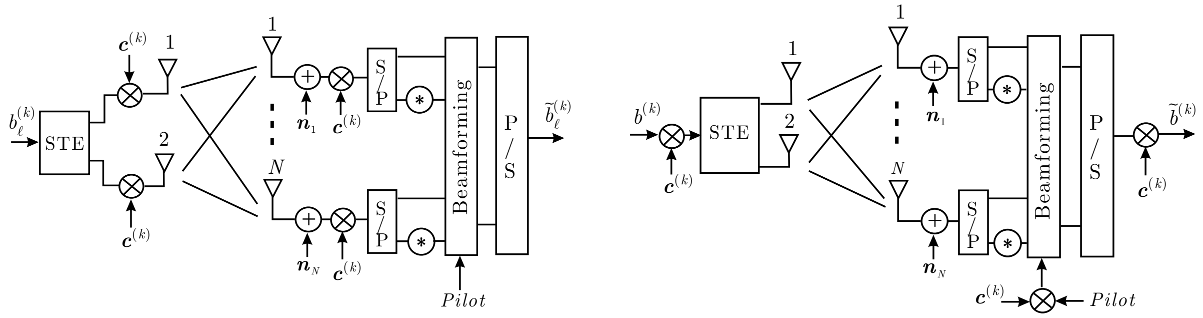
The schematic diagram of the symbol-level STBC MIMO CDMA system is shown in Fig.1.a. Data symbols $b_\ell^{(k)}$ from the kth user after being space-time encoded (STE) are spread by its P-length spreading code $\boldsymbol{c}^{(k)}$. Both encoding and spreading operations can be summarized by the following coding matrix

$$\boldsymbol{C} = \begin{bmatrix} b_1^{(k)} \boldsymbol{c}^{(k)} & -\left(b_2^{(k)}\right)^* \boldsymbol{c}^{(k)} \\ b_2^{(k)} \boldsymbol{c}^{(k)} & \left(b_1^{(k)}\right)^* \boldsymbol{c}^{(k)} \end{bmatrix}. \tag{7}$$

Assume that that the channel are static over 2 symbols, the received signals at two branches of the nth base station antenna are given by

$$\boldsymbol{x}_{n1} = \sum_{k=1}^{K} b_1^{(k)} \boldsymbol{c}^{(k)} h_{n1}^{(k)} + b_2^{(k)} \boldsymbol{c}^{(k)} h_{n2}^{(k)} + \boldsymbol{n}_{n1} \tag{8}$$

$$\boldsymbol{x}_{n2} = \sum_{k=1}^{K} -\left(b_2^{(k)}\right)^* \boldsymbol{c}^{(k)} h_{n1}^{(k)} + \left(b_1^{(k)}\right)^* \boldsymbol{c}^{(k)} h_{n2}^{(k)} + \boldsymbol{n}_{n2}, \tag{9}$$



(a). Space-time encoding before spread (b). Space-time encoding after spread

Figure 1: Space-Time Block Coded MIMO CDMA Systems.

where $\boldsymbol{n}_{n\ell}$ are vectors containing i.i.d. complex noise samples and $h_{n\ell}^{(k)}$ has been assumed static over two consecutive transmit symbols. After being despread by $\boldsymbol{c}^{(k)}$ the received signals become

$$x'_{n1} = \left(\boldsymbol{c}^{(k)}\right)^{\mathsf{H}} \boldsymbol{x}_{n1} = \sum_{k=1}^{K} b_1^{(k)} h_{n1}^{(k)} + b_2^{(k)} h_{n2}^{(k)} + \left(\boldsymbol{c}^{(k)}\right)^{\mathsf{H}} \boldsymbol{n}_{n1} \tag{10}$$

$$x'_{n2} = \left(\boldsymbol{c}^{(k)}\right)^{\mathsf{H}} \boldsymbol{x}_{n2} = \sum_{k=1}^{K} -\left(b_2^{(k)}\right)^{*} h_{n1}^{(k)} + \left(b_1^{(k)}\right)^{*} h_{n2}^{(k)} + \left(\boldsymbol{c}^{(k)}\right)^{\mathsf{H}} \boldsymbol{n}_{n2}, \tag{11}$$

Now let $\boldsymbol{x}_n = [x'_{n1} \quad x'^{*}_{n2}]^{\mathsf{T}}$ and $\boldsymbol{x} = [\boldsymbol{x}_1^{\mathsf{T}} \quad \boldsymbol{x}_2^{\mathsf{T}} \ldots \boldsymbol{x}_N^{\mathsf{T}}]^{\mathsf{T}}$ then using (4), (5) and (6) we can find estimated symbols $\tilde{b}_1(k)$ and $\tilde{b}_2(k)$ for the kth MT.

2.3 Chip-level STBC MIMO CDMA System

Different from the symbol-level STBC MIMO CDMA system both space-time encoding at MTs and adaptive beamforming at the BS are done at the chip-level (see Fig.1.b). Assuming that a symbol $b^{(k)}$ needs to be sent to the BS from the kth MT. The MT spreads this symbol by its code sequence $\boldsymbol{c}^{(k)}$ to give $\boldsymbol{s}^{(k)} = b^{(k)}\boldsymbol{c}^{(k)}$. Denote samples of the spread sequence $\boldsymbol{s}^{(k)}$ as $s_\ell^{(k)}$. The spread sequence $\boldsymbol{s}^{(k)}$ are then STE using the encoding matrix in (1) with symbols $b_\ell^{(k)}$ replaced by samples $s_\ell^{(k)}$, i.e.

$$\boldsymbol{S} = \begin{bmatrix} s_1^{(k)} & -\left(s_2^{(k)}\right)^{*} \\ s_2^{(k)} & \left(s_1^{(k)}\right)^{*} \end{bmatrix}. \tag{12}$$

Similar to the Sect. 2.1, the received signals at each branch of a BS antenna are given by

$$x_{n1} = \sum_{k=1}^{K} s_1^{(k)} h_{n1}^{(k)} + s_2^{(k)} h_{n2}^{(k)} + n_{n1} \tag{13}$$

$$x_{n2} = \sum_{k=1}^{K} -\left(s_2^{(k)}\right)^{*} h_{n1}^{(k)} + \left(s_1^{(k)}\right)^{*} h_{n2}^{(k)} + n_{n2}, \tag{14}$$

where x_{n1} and x_{n2} have been redefined to denote signal samples and the channels have been assumed static over the 2 consecutive samples. Let $\boldsymbol{x}_n = [x_{n1} \quad x^{*}_{n2}]^{\mathsf{T}}$ and $\boldsymbol{x} = [\boldsymbol{x}_1^{\mathsf{T}} \quad \boldsymbol{x}_2^{\mathsf{T}} \ldots \boldsymbol{x}_N^{\mathsf{T}}]^{\mathsf{T}}$. It is now possible to use the cost function (4) to optimize beamforming weights. However, since chip-level beamforming is considered the pilot signals $d_\ell^{(k)}$ are now different. Let $d^{(k)}$ be the pilot signal for the kth MT. To create a reference signal at chip level, this pilot signal is spread by spreading code $\boldsymbol{c}^{(k)}$ to have $\boldsymbol{d}'^{(k)} = d^{(k)}\boldsymbol{c}^{(k)}$. Decompose this spread pilot sequence into odd and even sequences, and denote odd and even samples $d_1'^{(k)}$ and $d_2'^{(k)}$, respectively, we have the cost function to optimize beamforming weights as

$$\boldsymbol{w}_{\ell_{opt}}^{(k)} = \arg\min_{\boldsymbol{w}_\ell} \mathcal{E}\left\{ \left| d_\ell'^{(k)} - \left(\boldsymbol{w}_\ell^{(k)}\right)^{\mathsf{H}} \boldsymbol{x} \right|^2 \right\}, \tag{15}$$

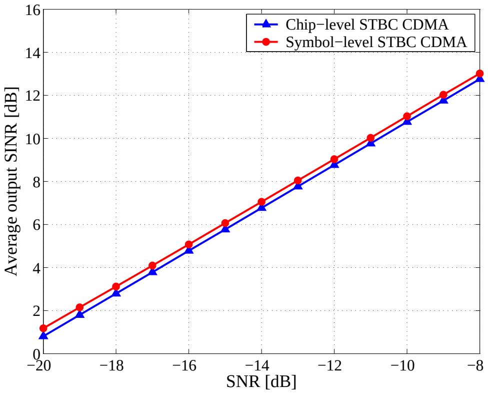


Figure 2: SINR of STBC 2×4 MIMO CDMA

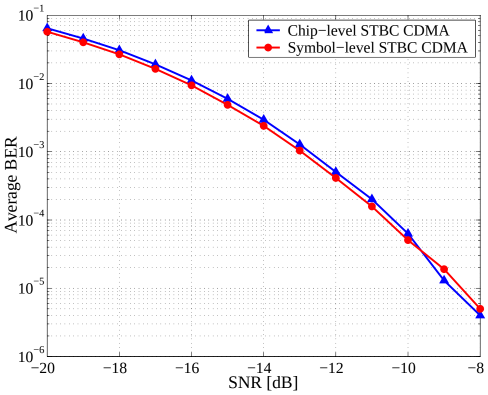


Figure 3: BER of STBC 2×4 MIMO CDMA

Using (15), (5) and (6) we can find estimated odd and even sequences $\tilde{b}_1^{(k)}$ and $\tilde{b}_2^{(k)}$. Converting these samples into serial (P/S: parallel-to-serial conversion) and despread them by spreading code $\boldsymbol{c}^{(k)}$ we obtain the estimated symbol $\tilde{b}^{(k)}$ of the transmitted symbol $b^{(k)}$.

3 Simulation Results

We compare performance of the two STBC MIMO CDMA systems over Rayleigh fading channel. A 2×4 MIMO system is set up with 2 antennas for MT and 4 antennas for BS. Alamouti's space-time block encoding is used for MT and MMSE adaptive beamforming is used for BS. Each MT uses 32-chip length Walsh code to spread 500 BPSK symbols either before (chip level) or after (symbol level) space-time encoding. Transmit power from each MT's antenna is normalized to 1/2, and channels $h_{nm}^{(k)}$ are generated using a complex Gaussian random function with normalized power, i.e., $\left|h_{nm}^{(k)}\right|^2 = 1$. In order to use MMSE beamforming we assume that the channels are static. The sample matrix inversion algorithm (SMI) is used to optimize beamforming weights. For the sake of simplicity, we assume that the transmit data is known and also use it as the pilot signal. Simulation results are averaged over 10,000 loops of simulation.

Figures 2 and 3 compare the signal to interference plus noise ratio (SINR) and bit error rate (BER) performance of the two STBC MIMO CDMA systems. It is immediately noticed that both the STBC MIMO CDMA systems have the same performance. However, since adaptive beamforming is performed at the chip-level the symbol-level STBC MIMO CDMA system thus requires much larger computational complexity.

4 Conclusions

We have explored performance of two STBC MIMO CDMA systems with adaptive beamforming: one with space-time encoding is done at symbol level and the other at chip level. Simulation results showed that both the systems have the same performance. However, the symbol level STBC MIMO CDMA system requires larger computational complexity. The performance comparison of the two systems in a multiuser frequency selective fading environment will be studied further in the future work.

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