THE JOINT SPACE-TIME SIGNAL DETECTION ALGORITHM FOR MIMO DS-CDMA SYSTEMS WITH MULTIPATH FADING CHANNELS

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Abstract

This paper proposes the joint space time signal detection algorithms for downlink DS-CDMA systems with multiple-input-multiple-output (MIMO) multipath wireless channels. The proposed algorithm first decomposes the multipath channel into a set of independent parallel additive white Gaussian noise (AWGN) subchannels each with the signal of the user of interest. Signal detection can then be achieved on a path-wise-combining basis. According to different multiple access interference (MAI) suppression techniques, two algorithms respectively referred to as the JST-MVDR and JST-COP are proposed.

Keywords: DS-CDMA, MIMO, Signal Detection.

I. INTRODUCTION

Multiple-input-multiple-output (MIMO) systems using antenna arrays have received significant attention recently because of their capability of system transmission rate improvement in rich scattering environment [1]. Diversity techniques are often adopted to enhance the channel reliability in wireless MIMO systems. To obtain a set of diversity channels, conventional spatial diversity techniques generally assume that the signal fadings at the receive antenna elements are independent and the optimum diversity can be achieved by the elementwise maximum ratio combining. However, in real propagation environments, especially when the receive antenna elements are spaced insufficiently far apart, fading effects are much more uncorrelated among multipaths than among the receive antenna elements [2]. With this understanding, we design the diversity combiners based on the signals received from each individual path instead of combining the signals received from the antenna elements. By exploiting the path structure, we develop a space time path-wise combiner for the downlink direct sequence code division multiple access (DS-CDMA) systems with MIMO wireless channels using antenna arrays.

II. SYSTEM MODEL

Consider a downlink MIMO DS-CDMA system with M_{T} transmit antennas. Each antenna simultaneously transmits K data streams at rate $\frac{1}{T}$ (symbols/sec.), respectively, for K users. The baseband signal of the m^{th} transmit antenna is thus given by

$$z_m(t) = \sum_i \sum_{n=0}^{N-1} \sum_{k=1}^{K} d_{m,k}(i)\, s_{m,k}(n)\, g\left(t - (iN+n)T_{\mathrm{c}}\right), \tag{1}$$

where $d_{m,k}(i)$ denotes the i^{th} transmit data symbol for the k^{th} user of the m^{th} transmit antenna, and $s_{m,k}(0), \cdots, s_{m,k}(N-1)$ is the N-chip spreading sequence, N is the spreading gain, $T_{\mathrm{c}} = \frac{T}{N}$ is the DS-CDMA chip period, and $g(t)$ is the normalized L chip long pulse-shaping waveform. Due to multipath propagation, signals experience fading effects, delay spreads and angle spreads when they go through a wireless channel. Assuming totally P paths arrive at the receiver, after coherent frequency down-conversion, the complex baseband equivalent representation of the received signals can be expressed as

$$\mathbf{x}(t) = \sum_{m=1}^{M_{\mathrm{T}}} \sum_{p=1}^{P} \mathbf{a}_p \beta_p(t)\, z_m(t - \tau_p) + \mathbf{n}(t), \tag{2}$$

where $\mathbf{a}_p$ denotes the spatial signature of the p^{th} multipath corresponding to the response vector of the receive antenna array with respect to the direction of arrival (DOA) of that multipath. $\beta_p(t)$, a zero mean complex Gaussian process, is the fading amplitudes of the p^{th} multipath, $\{\tau_p\}$ is the path delays, and $\mathbf{n}(t)$ is AWGN. Also in (2), $p = 1, \cdots, P$, and $m = 1, \cdots, M_{\mathrm{T}}$. The fading amplitudes, though time varying, are assumed constant within a Q-symbol period of channel coherence time. Sampled ρ times per chip period T_{c}, the Q receive symbols can be expressed as

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$$\mathbf{X}(i)=\left[\begin{array}{ccc}\mathbf{x}(iT), \cdots, & \mathbf{x}\left((i+Q-1)T-\frac{T_c}{\rho}\right)\end{array}\right]=\sum_{m=1}^{M_\mathrm{T}}\sum_{k=1}^{K}\mathbf{A}\mathbf{B}\mathbf{G}^T\mathbf{S}_{m,k}d_{m,k}(i)+\tilde{\mathbf{N}}, \tag{3}$$

where $\mathbf{A}=\left[\begin{array}{ccc}\mathbf{a}_1, & \cdots, & \mathbf{a}_P\end{array}\right]$ denotes the $M_\mathrm{R}\times P$ receive spatial signature matrix with M_R denoting the number of the receive antenna elements, $\mathbf{B}=diag\{\boldsymbol{\beta}\}$ with $\boldsymbol{\beta}=\left[\begin{array}{ccc}\beta_1 & \cdots & \beta_P\end{array}\right]$ is the $P\times P$ fading matrix, $\mathbf{G}=\left[\begin{array}{ccc}\mathbf{g}(\tau_1), & \cdots, & \mathbf{g}(\tau_P)\end{array}\right]$ is the $L\rho\times P$ temporal signature matrix with $\mathbf{g}(\tau_p)$ denoting the sampled version of $g(t-\tau_p)$. The spreading-code matrix for the m^{th} transmit antenna of the k^{th} user, $\mathbf{S}_{m,k}$, is a Toeplitz matrix constituted by the spreading sequence $\{s_{m,k}(n)\}$ and appropriate zeros to represent the convolution between the pulse-shaping waveform and spreading sequence. The noise matrix $\tilde{\mathbf{N}}$ is again assumed to be AWGN. Furthermore, throughout this paper, we assume the data symbol $d_{m,k}(i)$ is BPSK differentially-encoded.

The spatial signatures and temporal signatures can be accurately estimated by many channel parameter estimation algorithms [3]. Before exploring the proposed algorithm, we assume that the spatial signatures and temporal signatures of the received signal are known to the receiver. In addition, without loss of generality we assume that the first user of each transmit antenna is the user of interest and the spreading sequences $\{s_{m,1}(n)\}_{m=1}^{M_\mathrm{T}}$ are also known.

III. The Proposed approach

Shown in Fig. 1 is the structure of the proposed joint space time signal detection algorithm which consists of a space time multipath channel decoupler and a path-wise signal combiner. The multipath channel decoupler is used to decompose a multipath channel into a set of independent subchannels and then the path-wise signal combiner takes over to detect the signal of the user of interest. According to different MAI suppression criteria used by the decoupler, two algorithms are developed. One is referred to as the JST-complementary orthogonal projection (JST-COP) algorithm, and the other is referred to as the JST-minimum variance distortionless response (JST-MVDR) algorithm.

A. The Space Time Multipath Channel Decoupler

The space time channel decoupler decomposes a multipath channel according to the space time signature of each multipath. To obtain the space time signatures of the channel, by stacking all columns of $\mathbf{X}(i)$ in (3), and making use of the rules $vec\{\mathbf{XYZ}\}=\left(\mathbf{Z}^T\otimes\mathbf{X}\right)\cdot vec\{\mathbf{Y}\}$ and $vec\{\mathbf{X}_1+\mathbf{X}_2\}=vec\{\mathbf{X}_1\}+vec\{\mathbf{X}_2\}$, we can rewrite the receive space-time vector as

$$\mathbf{x}^{\mathrm{JST}}(i)=vec(\mathbf{X}(i))=\sum_{m,k}d_{m,k}(i)\,\mathbf{Q}_{m,k}\boldsymbol{\beta}+\mathbf{n}^{\mathrm{JST}}, \tag{4}$$

where

$$\mathbf{Q}_{m,k}=\left[\begin{array}{ccc}\mathbf{S}_{m,k}^T\mathbf{g}_1\otimes\mathbf{a}_1, & \cdots, & \mathbf{S}_{m,k}^T\mathbf{g}_P\otimes\mathbf{a}_P\end{array}\right]\triangleq\left[\begin{array}{ccc}\mathbf{q}_{m,k,1} & \cdots & \mathbf{q}_{m,k,P}\end{array}\right], \tag{5}$$

and $\mathbf{q}_{m,k,p}=\mathbf{S}_{m,k}^T\mathbf{g}_p\otimes\mathbf{a}_p$ is referred to as the space time signature of the p^{th} path contributed from the m^{th} transmit antenna for the k^{th} user. Based on the space time signatures of the user of interest, the space time channel decoupler of the JST-COP algorithm isolates each path by using the COP matrix of an appropriate self-exclusive matrix. To retain the p^{th} path of the channel and null out the others, we define the space time self-exclusive matrix as

$$\mathbf{Q}_{p,m}^{\mathrm{COP}}=\left[\{\mathbf{q}_{m',1,p'}\}_{(p',m')\neq(p,m)}\right], \tag{6}$$

The corresponding COP matrix is then expressed as

$$\mathbf{U}_{p,m}^{\mathrm{COP}}=\mathbf{I}-\mathbf{Q}_{p,m}^{\mathrm{COP}}\left(\mathbf{Q}_{p,m}^{\mathrm{COP}}\right)^{\dagger}.$$

Furthermore, in addition to isolating each subchannel, the space time channel decoupler performs to help suppressing the MAIs and scalarizing the vector signal in (4). To do this, in conjunction with the space time signature of the user of interest, the weight vectors of the JST-COP space time channel decoupler are given as

$$\mathbf{w}_{p,m}^{\mathrm{COP}}=\mathbf{U}_{p,m}^{\mathrm{COP}}\mathbf{q}_{m,1,p}, \tag{7}$$

and thus the outputs of these decouplers are

$$u_{p,m}(i)=\left(\mathbf{w}_{p,m}^{\mathrm{COP}}\right)^H\mathbf{x}^{\mathrm{JST}}(i)\approx d_{m,1}(i)\,\beta_p+n_{p,m}^{\mathrm{COP}}. \tag{8}$$

By collecting all $u_{p,m}$ as $\mathbf{u}_m(i) = \left[\begin{array}{ccc} u_{1,m}(i), & \ldots, & u_{P,m}(i) \end{array}\right]^T = d_{m,1}(i)\,\boldsymbol{\beta}^T + \mathbf{n}_m^{\mathrm{COP}}$, signal detection can be performed by combining the signal of the user of interest through the differential decoding as

$$d_{m,1}(i) = -sign(\mathbf{u}_m^H(i-1)\,\mathbf{u}_m(i)).$$

Alternatively, the space time channel decoupler can also be implemented based on the MVDR filters. The MVDR filters have been deployed in many signal processing applications, such as spatial beamformers and frequency filters, which seek to find an optimum weight vector so as to minimize both the interference and the noise at the filter outputs. To design an MVDR space time channel decoupler for our purpose, we define the corresponding constraint matrix and response vector, respectively, as

$$\mathbf{C}_{p,m} \triangleq \left[\begin{array}{cc} \mathbf{q}_{m,1,p} & \{\mathbf{q}_{m',1,p'}\}_{m' \neq m,\, p' \neq p} \end{array}\right] \tag{9}$$

and

$$\mathbf{f} = \left[\begin{array}{cccc} 1 & 0 & \cdots & 0 \end{array}\right]_{P \times 1}^T. \tag{10}$$

The MVDR space time channel decoupler $\mathbf{w}_{p,m}$ can then be formulated as

$$\mathbf{w}_{p,m} = \arg\min_{\mathbf{w}} E\left\{|\bar{u}_{p,m}(i)|^2\right\},\ \text{s.t. } \mathbf{C}_{p,m}^H \mathbf{w} = \mathbf{f}, \tag{11}$$

where $\bar{u}_{p,m}(i) = \mathbf{w}_{p,m}^H \mathbf{x}^{\mathrm{JST}}(i)$ is the output of the space time channel decoupler $\mathbf{w}_{p,m}$. We may readily solve (11) by using the constraint optimization method and obtain

$$\mathbf{w}_{p,m} = (\mathbf{R}_w)^{-1} \mathbf{C}_{p,m} \left[\mathbf{C}_{p,m}^H (\mathbf{R}_w)^{-1} \mathbf{C}_{p,m}\right]^{-1} \mathbf{f}, \tag{12}$$

where $\mathbf{R}_w = E\left\{\mathbf{x}^{\mathrm{JST}}(i)\,\mathbf{x}^{\mathrm{JST}}(i)^H\right\}$ is the space time covariance matrix of $\mathbf{x}^{\mathrm{JST}}(i)$. The output of the MVDR filters can thus be expressed as

$$\bar{u}_{p,m}(i) \approx \beta_p d_{m,1}(i) + n_{p,m}, \tag{13}$$

where $n_{p,m} = \mathbf{w}_{p,m}^H\ \mathbf{n}^{\mathrm{JST}}(i)$ is the noise at the MVDR filter output. From (8) and (13), it is obviously that the space time channel decoupler successively decomposes a multipath multiuser channels into a set of independent AWGN subchannels. Combiner with differential decoding can again extract the phase difference between neighboring $d_{m,1}'s$ to eliminate the phase ambiguity caused by β_p.

IV. SIMULATIONS AND DISCUSSIONS

Consider a $M_{\mathrm{T}} = 2$ and $M_{\mathrm{R}} = 10$ system with half wavelength spaced uniform linear array (ULA) at both the transmitter and the receiver. Differentially encoded data sequences, each spreaded with a gold code sequence of 31-bit long, $N = 31$, are transmitted over the channel. We assume a Rayleigh-fading multipath channel with totally 3 paths seen at the receiver for the user of interest. The direction of arrivals and delays of the three paths are, respectively, $\boldsymbol{\theta} = \left[\begin{array}{ccc} -21.5^\circ & -20.1^\circ & 34^\circ \end{array}\right]$ and $\boldsymbol{\tau} = \left[\begin{array}{ccc} 0.54T_{\mathrm{c}} & 2.42T_{\mathrm{c}} & 0.52T_{\mathrm{c}} \end{array}\right]$, where $T_c = 0.8\mu s$ is the chip period. The average fadings of the multipaths are assumed equal and normalized to 0 dB. Within the time span of our interest, each path is assumed to have a randomly selected but constant fading. Five hundred Monte Carol trials are carried out as the number of multiusers are set at $K = 1$ and $K = 5$, respectively. Two hundred symbols are processed in each trial.

Fig.2-3compare the bit error rate (BER) of the proposed algorithms with the space time RAKE receivers[4]. When in the single user $K = 1$ case, since there is no MAIs, Fig.2 shows that the proposed JST-COP and the JST-MVDR algorithms perform almost the same as the JST-RAKE receiver while significantly outperform the T-RAKE receiver. In the presence of MAIs, with significantly better performance in interference cancellation, Fig. 3 shows that the JST-MVDR algorithm outperforms the others when $K = 5$.

V. CONCLUSIONS

This paper proposes a space time algorithm for signal detection for wireless DS-CDMA down-link MIMO systems. Signals received at the antenna array are decomposed in the space-time domain, and then the path-wise combiner is applied to detect the data of the user of interest. The JST-MVDR algorithm generally has better BERs than the JST-COP algorithm, since the former is capable of suppressing more interferences including ISIs and MAIs.

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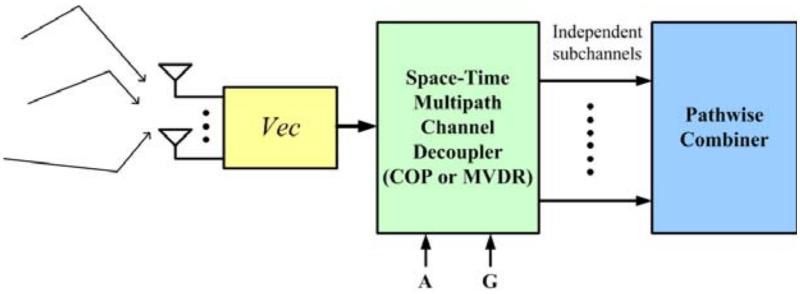

Fig. 1: The structure of the proposed algorithm

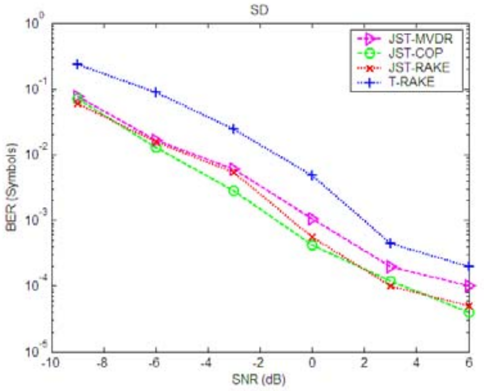

Fig. 2: The BER of the proposed algorithm when K=1

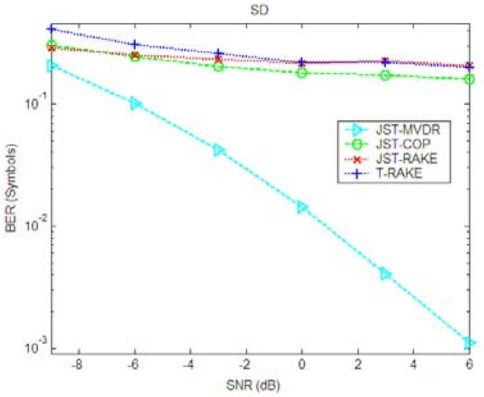

Fig. 3: The BER of the proposed algorithm when K=5.