Non-Iterative Joint Decoding of Space-Time Codes and Multiuser Interference in Asynchronous DS-CDMA Systems

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Abstract—Space-time coding (STC) is an efficient technique to combat severe fading effects and improve system capacity in wireless communications. However, for CDMA communications, multi-antenna transmission increases the multiuser interference (MUI). In addition, if the data rate is high, the processing gain can be quite small, and thus the MUI is further enhanced.

In this paper we propose a new non-iterative multiuser decoder for space-time coded asynchronous DS-CDMA. Non-iterative decoding schemes are important in situations where decoding delay must be minimized, for example in interactive applications such as videoconferencing. The proposed scheme introduces a novel reduced-state multiuser sequence detection algorithm suitable to decode few co-located users with high data rates (i.e., users within a beam with short spread sequences). We evaluate the performance of the proposed scheme in high and moderate multiuser interference channels. Simulation results show that a major performance improvement over a conventional receiver is achieved with the proposed scheme even in moderate interference channels. In high interference channels, where the conventional receiver is useless, the proposed scheme performs near the single user bound at practical frame error rates and with reasonable complexity.

I. INTRODUCTION

One of the most effective diversity schemes is space-time coding, which integrates channel coding, modulation and multiple transmit antennas to achieve higher data rates and simultaneously provide diversity to combat fading [1][2]. The main disadvantage of space-time coding with multi-antenna transmission for multiple access communications is that MUI is increased [3][4][5][6]. In addition, if the data rate is high, the processing gain can be quite small, and thus the MUI is enhanced even further, owing to the higher cross-correlation of the spreading sequences.

In [3] a co-channel interference (CCI) cancellation method for synchronous multiuser STC systems using beamforming-based angle diversity is proposed. In the case of CDMA systems, where the number of users is larger than the number of elements in the array, canceling the interferer signal does not significantly improve the signal to interference ratio (SIR). An improved method would be to form beams toward groups of users, thus reducing the effective number of interferers to those mobiles that fall within each beam [7][8]. In this situation, each beam can be considered as a co-channel cell, and thus all spreading sequences can be reused inside the beam. If the bandwidth-limited spread spectrum system supports large data rates, the multiuser interference within each beam can be a significant limitation on the system performance. This creates an opportunity for large performance improvements by taking advantage of multiuser detection techniques.

Multiuser receivers for synchronous multiple access channels with STC are considered in [6] and [9]. In [6], decoder structures for space-time block coded CDMA systems are derived for multi-path fading channels. In [9], an iterative receiver for synchronous multiuser STC (block and trellis) systems is proposed. This receiver approaches the performance of the single-user receiver at the expense of increasing the decoding delay. However, there are applications where large decoding delays are not acceptable. For example, the maximum tolerable delay is about 20ms for voice transmission and 10-80ms for real-time data services. This places constraints on the maximum block size in the case of turbo-type iterative receivers, or the number of cancellations in the case of successive cancellation receivers. Decoding delay restrictions usually result in limitations in performance. Non-iterative decoding schemes avoid this tradeoff, and therefore they provide an attractive alternative to iterative receivers in situations where the decoding delay must be limited.

In this paper, we propose a new non-iterative multiuser receiver for Space-Time Trellis-Coded (STTC) asynchronous CDMA systems. This receiver is based on a reduced-state multiuser sequence detection algorithm that builds upon the trellis-based multiuser detector proposed in [10]. Based on the coding information of all beam users and the multiuser interference within the beam, reduced-state trellises are constructed. Then, delayed decision sequence estimation is used to jointly decode the STTC and equalize the intra-beam multiuser interference. Although the complexity of the proposed scheme grows exponentially with the number of users and the constraint length of the users’ encoders, it is not prohibitive to decode few high bit rate users that have low processing gain (high MUI). We present simulation results for channels with high and moderate multiuser interference power (i.e., SIR). We show that performance near the single user bound can be achieved at practical frame error rates with this reduced-complexity receiver even when the SIR of each user at the input of the decoder is equal to 0 dB. Furthermore, the performance of the proposed scheme is compared with that of a conventional receiver. It is found that a
major performance gain can be achieved with the new scheme even for moderate SIRs. These performance improvements are obtained without increasing the decoding delay.

The rest of this paper is organized as follows. In Section II we present a mathematical model for multiuser detection. Section III derives the reduced state multiuser decoder. Section IV provides simulation results. Finally, conclusions are presented in Section V.

II. SYSTEM MODEL

We consider the asynchronous CDMA system with $K$ users, which is illustrated in Fig. 1. Each user employs space-time coding with $N$ transmit antennas and the same spreading sequence is used for the $N$-antennas. Moreover, the antenna elements within the transmitting arrays experience independent fading. The baseband received signal can be written as

$$r(t) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^{K} \sum_{j=1}^{N} h_{jk}(i) s_k(t - iT - \tau_k) + v(t),$$

where

- $h_{jk}(i)$ is the channel gain from the $j^{th}$ transmit antennas of the $k^{th}$ user to the received antenna.
- $c_k(i)$ is the coded symbol from the $j^{th}$ transmit antennas of the $k^{th}$ user.
- $s_k(t)$ is the signature sequence for the $k^{th}$ user, which is assumed zero outside the coded symbol interval $T$ (each user in the system has assigned a particular signature sequence).
- $\tau_k$ represents the time shift of the $k^{th}$ user relative to some reference time.
- $v(t)$ is a complex white Gaussian noise process with power spectral density $N_0$.

The coefficients $h_{jk}(i)$ are modeled as complex Gaussian random variables with zero mean and variance 0.5 per dimension. We assume that carrier phases, powers, time delays and signature waveforms of all users are known by the receiver. The received signal $r(t)$ is passed to a bank of $K$ matched filters (each one matched to the signature waveform of a different user), and sampled every $iT$ seconds. The $K$ matched filter outputs at time $i$ can be expressed as

$$\mathbf{r}(i) = G[1]s(i + 1) + G[0]s(i) + G[-1]s(i - 1) + \mathbf{w}(i),$$

where

$$\mathbf{r}(i) = [r_1(i), \ldots, r_K(i)]^T,$$
$$\mathbf{x}(i) = [x_1(i), \ldots, x_K(i)]^T,$$
$$x_k(i) = \sum_{j=1}^{N} h_{jk}c_k(i),$$
$$\mathbf{w}(i)$$ represents the zero mean colored Gaussian noise vector at the filter output, while $G[0]$, $G[1]$, and $G[-1]$ are the cross-correlation $K\times K$ matrices with elements defined by

$$G[i]_{kl} = \int_{-\infty}^{\infty} s_k(t - \tau_k) s_l(t + iT - n) dt.$$

Assuming that the users are ordered in increasing delay, $G[0]$ is a $K \times K$ Hermitian matrix and $G[1]$ is a lower-triangular matrix with zero diagonal. The z-transform of the discrete-time vector (2) is

$$R(z) = S(z)A X(z) + W(z),$$

where

$$S(z) = G[1]z + G[0] + G[-1]z^{-1}$$

is the spectrum matrix and $R(z)$, $X(z)$ and $W(z)$ are, respectively, the vector-valued z-transforms of the matched filter output sequence, the transmitted sequence, and the noise sequence at the output of the matched filters. The spectrum of the additive colored Gaussian noise is $S_m(z) = N_0 S(z)$. $S(z)$ is real-symmetric and non-singular on the unit circle. It can be factored as

$$S(z) = [F^T[0] + F^T[1]z].[F[0] + F[1]z^{-1}].$$

$F[0]$ is a lower triangular matrix and $F[1]$ is an upper triangular with zero diagonal. Thus, if $R(z)$ is fed to the

$$(F(z^{-1})^T)^{-1} = [F^T[0] + F^T[1]z^{-1}],$$

the output signal is

$$Y(z) = F(z)X(z) + N(z)$$

where $N(z)$ is the vector-valued z-transforms of the white Gaussian noise.

III. REDUCED-COMPLEXITY MULTIUSER RECEIVER FOR SPACE-TIME CODED CDMA SYSTEMS

In this section we propose a multiuser detection scheme based on maximum likelihood sequence estimation. This
scheme is a feasible and an efficient solution for bandwidth limited systems with few high data rate users (i.e. small processing gain). This situation arises when the system uses narrow beams towards the desired group of users, and the multiuser interference in the beam is high due to high data rate users.

The optimum decoder for asynchronous coded systems selects the coded sequence \( \{ \hat{x}_1(i)\hat{x}_2(i)\ldots\hat{x}_K(i) \} \) that minimizes the cumulative metric given by

\[
||Y(z) - F(z)X(z)||^2 = \sum_{k=1}^{K} \sum_{i=0}^{M} \left( y_k(i) - \sum_{l=1}^{k} F[0]_{kl}\hat{x}_l(i) - \sum_{l=k+1}^{K} F[1]_{kl}\hat{x}_l(i-1) \right)^2 
\]

(9)

\( F[0]_{kl} \) and \( F[1]_{kl} \) denote the elements of the matrices \( F[0] \) and \( F[1] \) respectively. The coded symbol \( x_k(i) \) depends on input vector \( \mathbf{b}_k(i) \) with \( q \) information bits and the encoder state \( \sigma_k(i) \), that is,

\[
x_k(i) = g(\mathbf{b}_k(i), \sigma_k(i)) \quad (10)
\]

with \( x_k \in \Omega_x \) (\( \Omega_x \) is the complex-valued \( Q \) dimensional symbol alphabet). Viewing the input \( \mathbf{a}(i) \) as a sequence of individual symbols rather than vectors, i.e. \( x_1(i)x_2(i)\ldots x_K(i)x_1(i+1)\ldots \), and assuming that each user encoder has \( S \) states, from (9) we verify that the optimum super-trellis requires

\[
S_{\text{opt}} = S^K 2^{(K-1)} 
\]

(11)

states, which is prohibitive in practical implementations.

To reduce the number of states, we proposed in [10] a sub-optimal scheme that uses the coding information of a subset of users and the information of the multiuser channel. The proposed receiver decodes a subset of \( M \) users (with \( M \leq K \)) and equalizes the MUI of the channel. The number of channel states is reduced applying the set partitioning principles inherent in TCM. We called this receiver trellis-based combined multiuser interference equalization with m-user decoding, TBCED(m).

In the system model described in Section II, the \( K \) asynchronous users can be decoded with \( K \) TBCED(1) receivers. In this case, the states of a user encoder and the channel states are used to construct the trellis of each decoder. The number of channel states depends on the level of subset partitioning used for each symbol of the multiuser channel and the number of antennas. If the channel state uses a partition of order \( P \) for all the symbols of the channel, the number of channel states necessary to decode the \( K \) users is given by \( S_{\text{TBCED(1)}} = S P^N (K-1) K \). If the number of channel states \( S \) is equal to or larger than \( P^N \), a better approach consists in using the coding information of all the users and ignoring the multiuser channel states. The proposed scheme has \( S^K \) states that are given by

\[
\mu = (\sigma_1, \sigma_2, \ldots, \sigma_K) \quad (12)
\]

The proposed receiver selects the sequence of symbols \( \hat{x}_k(i) \) that minimizes the cumulative metric

\[
M \left( \{ y_k(i) \}; \{ \hat{x}_k(i) \} \right) = \sum_{i=0}^{M} \sum_{k=1}^{K} ||y_k(i) - F[0]_{kk}\hat{x}_k(i) - \hat{P}_k(i)||^2,
\]

(13)

with

\[
\hat{P}_k(i) = \sum_{l=1}^{k-1} F[0]_{kl}\hat{x}_l(i) + \sum_{l=k+1}^{K} F[1]_{kl}\hat{x}_l(i-1). \quad (14)
\]

At each state, the path history is used to estimate the MUI \( \hat{I}_k(i) \).

In order to simplify the analysis, we consider a channel with two users. The STTC is shown in Fig. 2 a) and b). The reduced trellis has \( S^2 = 16 \) states and it is periodically time-varying with period 2 (the optimum MLSE has \( 4^2 * 2^2 = 64 \) states). Fig. 2 c) shows the 2-stage trellis. The states of the proposed receiver are given by \( \mu = (\sigma_1, \sigma_2) \), at the first stage the received symbol \( y_1(i) \) is used to compute the branch metric and the transitions only affect the first state component of \( \mu \) (the encoder state \( \sigma_1 \)). At the second stage, the branch metric uses the signal \( y_2(i) \) and the state transition affects the second state component of \( \mu \) (the encoder state \( \sigma_2 \)). Although the trellis is periodically time varying, it has a modular design. This can be appreciated from Fig. 3 where the states are ordered in a different way. This characteristic can be used to implement the proposed scheme in parallel processing systems.

IV. Simulations

In this section, we provide simulation results for the proposed scheme. We estimate the frame error rate (FER) using Monte Carlo simulations. Performance is evaluated over 2,500 frames with 100 symbols in each frame. A 4-state QPSK two-transmit and one-receive antenna scheme is used throughout [1]. In all cases the encoders are forced to the initial state (or state 0) (Fig. 2) at the end of each frame. We assume independent Rayleigh fading between transmit and receive antennas and perfect channel knowledge at the receiver. Fading is assumed constant within each block, but independent from block to block. These are the same assumptions used in [1]. The receivers analyzed in this paper use the whitening matched filter defined in [11]. The multiuser channel spectrum is given by

\[
S(D) = \begin{bmatrix}
1 & \rho + \rho D^{-1} \\
\rho + \rho D^{-1} & 1
\end{bmatrix}
\]

(15)

where \( \rho \) represents the cross-correlation of the signature waveforms and is used to control the multiuser interference power. The SIR is computed at the output of the whitening matched filter. All users are assumed to have equal powers.

First we analyze the performance of a conventional STC in the presence of co-channel interference. Fig. 4 shows that co-channel interference significantly degrades the performance of the space-time coded system with conventional receiver.
Fig. 5 shows a performance comparison between the conventional receiver and the proposed STTC scheme over a Rayleigh fading channel at SNR=18dB. These results demonstrate that, as the multiuser interference increases due to higher cross-correlation among signature waveforms, the performance of the new scheme does not degrade considerably. Note that the performance improvement of the introduced receiver over the conventional receiver increases as the multiuser interference increases. For moderate multiuser interference, the proposed receiver performs near the single user bound, while the performance of the conventional receiver is still far from this bound.

In Fig. 6 we present a performance comparison between the new scheme, the conventional STTC receiver, and the STTC single user bound. When the SIR=0 dB, the introduced scheme operates 2 dB away from the single user bound. Note the enormous performance gain over the conventional STTC receiver achieved by the new receiver. For SIR=16dB the introduced scheme gains 4 dB over the conventional STC at FER=0.1. For SIR lower than 16 dB our scheme performs close to the single user bound.

V. CONCLUSIONS

In this paper we proposed a non-iterative receiver for joint decoding of STC and multiuser interference. A key feature of the introduced scheme is that coding information of all users is exploited to cancel the high interference generated by multi-antenna transmission. Simulation results have shown that the performance of the proposed scheme was not significantly affected by the interfering multiuser signals. A major performance gain over the conventional receiver was obtained with this new receiver even for moderate MUI. Moreover, at practical frame error rates this reduced-complexity receiver performed near the single user bound even when the SIR of each
user at the input of the decoder is equal to 0 dB. It is important to observe that the performance improvements just described were obtained at the cost of a modest increase in complexity. In the example analyzed in this paper, the required number of decoder states is 16, versus 8 for the conventional receiver.

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