Joint Power Control and Multiuser Detection for MIMO Systems

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***Abstract*—In this paper, a joint iterative power control and parallel interference cancellation (PIC) scheme is proposed for turbo coded uplink DS-CDMA systems to suppress the multiple access interference (MAI) from co-channel users and inter-antenna interference (IAI) from adjacent antennas of each user. Simulation results show that the proposed scheme could compensate for some channel fading effect through power control, and improve the accuracy of the soft estimates from the turbo decoder to help with the reconstruction of the interference signals during the PIC processing, therefore, provides a significant reduction in the bit error rate (BER) compared to that of no power control.**

I. INTRODUCTION

Multiple antenna technologies have been proved to provide an enormous increase in spectral efficiency of wireless communication systems, therefore, have attracted a lot of attention over the past decade. Bell Laboratories layered space-time (BLAST) architecture is well known for achieving very high data rate in multiple-input multiple-output (MIMO) systems due to the multiplexing and diversity over space domain [1]. Therefore, in this paper, MIMO technologies, such as spatial mulplexing [2] are used in direct-sequence code-division multiple access (DS-CDMA) systems to provide spatial gain without requiring extra resources, such as wider bandwidth or more spreading codes since we consider the same spreading sequence is used to spread the transmitted signals on different transmit antennas of each user.

It is known that CDMA systems are interference-limited systems rather than thermal noise. Multiuser detection has been proposed to effectively suppress or cancel the multiuser interference (MAI) in CDMA systems [3-5]. Also, power control is an essential problem in CDMA systems to solve the near far problem. There has been some work in investigating joint power control and multiuser detection for CDMA systems with multiple users. In [6-7], joint receivers were derived to maximize the signal-to-interference-ratio (SIR), signal-to-noise ratio (SNR), and signal-to-interference-plus-noise ratio (SINR), respectively. In [8-9], an outage probability and a SINR constrained power control scheme for CDMA with minimum mean square error (MMSE) multiuser detection were investigated, respectively. An accelerated power control algorithm applicable for CDMA based communications systems employing advanced receiver techniques such as beamforming or multiuser detection was presented in [10]. However, these algorithms were proposed mainly to suppress the MAI in CDMA systems. There is not much work focused on suppressing the interference between multiple antennas (IAI) using both multiuser detection and power control methods.

For spatial multiplexing technologies, such as the BLAST technologies, a number of detection algorithms were proposed to remove the interference between multiple antennas, and therefore to achieve as much multiplexing and diversity gain as possible. In [11], by using nulling and successive interference cancellation to detect signals from the largest SNR layer to the smallest SNR layer at the receiver, called Ordered Successive Interference Cancellation (OSIC) was proposed. However, the algorithm suffers from long system delays and requires different receiver power between antennas. An alternative approach, Parallel Interference Cancellation (PIC), was proposed to cancel the interference from all the other antennas in parallel [12]. In PIC, the received signals are implemented by some detection algorithm firstly, such as zero-forcing (ZF) or minimum mean square error (MMSE). A rough estimate is then obtained and used to perform the interference cancellation over several iterations. However, PIC shows unsatisfactory performance because of the inaccurate estimates from the previous detection, causing error propagation in later stages of the signal detection. Recently, some enhanced PIC detection algorithms have been proposed. An efficient detection method utilizing the QR decomposition of the channel matrix was proposed by the authors in [13], and a combining QR and PIC detection scheme is proposed in [14]. In [15], the authors introduced adaptive partial weighting coefficients into the parallel multistage detection. In [16] and [17], two parallel interference techniques including pre-cancellation and post-cancellation, are proposed as a module to make the near maximum likelihood (ML) estimation. PIC was also applied in the multiuser detection of MIMO CDMA systems to suppress the MAI and IAI [18]. However, power control methods have not been considered in these algorithms.

Since power control methods have been proposed for spatial multiplexing systems with PIC based detection to improve the system performance in [19], therefore we consider to propose a two-step power control method jointly with the PIC based multiuser detection in a turbo-coded uplink DS-CDMA system, so that power control could help allocating the transmit power between multiple antennas at the transmitter of each user to obtain more accurate data estimates at the receiver. Hence, the data estimates could help improving the accuracy of the interference reconstruction and reducing the risk of error propagation in the PIC and MMSE based multiuser detection. Simulation results of our proposed schemes are compared with conventional PIC and MMSE based multiuser detection method in [18] with no power control under different iterations of signal processing, showing that significant BER reduction can be obtained through using the proposed scheme.

This paper is organized as follows. In section II, the system model is introduced. The proposed two-step power control and multiuser detection scheme is given in section III. In section IV, simulation results are shown to prove the effectiveness of our proposed schemes. And the last section summarizes this paper.

II. System Model

A synchronous Turbo coded MIMO CDMA uplink system with K users is considered, where each user is equipped with n_T transmit antennas and n_R receive antennas, as shown in Fig.1. The K users' data are first encoded by turbo encoders, and then spread by the signature sequences $S_1, S_2, \ldots, S_K$ after modulation. A diagonal spatial multiplexing (SM) method is employed here, of which the space-time multiplexer structure for space-time turbo codes is the same as described in [2]. We define a diagonal power control matrix $\mathbf{P}$, such that the power transmitted from the ith antenna for user k is multiplied by $P_{k,i}$ $(k=1,\cdots,K; i=1,\cdots,n_T)$. The received signal can then be written in the discrete-time form as:

$$\mathbf{r} = \mathbf{SHPb} + \mathbf{n} \tag{1}$$

in which $\mathbf{b} = [\mathbf{b}_1, \mathbf{b}_2, \ldots, \mathbf{b}_K]^T$ represents the transmitted data matrix with $\mathbf{b}_k = [b_{k,1}, b_{k,2}, \ldots, b_{k,n_T}]^T$. $\mathbf{H} = diag[\mathbf{H}_1, \mathbf{H}_2, \cdots, \mathbf{H}_K]$ stands for the fading channel with

$$\mathbf{H}_k = \begin{bmatrix} H_{k,1,1} & H_{k,1,2} & \cdots & H_{k,1,n_T} \\ H_{k,2,1} & H_{k,2,2} & \cdots & H_{k,2,n_T} \\ \vdots & \vdots & \vdots & \vdots \\ H_{k,n_R,1} & H_{k,n_R,2} & \cdots & H_{k,n_R,n_T} \end{bmatrix} \tag{2}$$

And $\mathbf{H}_k$ is normalized as $\sum_{i=1}^{n_R}\sum_{j=1}^{n_T}\left|H_{k,i,j}\right|^2 = n_T$, so that the received power will not increase with the number of receive antennas. $\mathbf{S} = [\mathbf{S}_1, \mathbf{S}_2, \cdots, \mathbf{S}_K]$ denotes the spreading sequence matrix with $\mathbf{S}_k = [s_{k,1}, s_{k,2}, \ldots, s_{k,N}]^T$, where $s_{k,n} = diag\underbrace{[s_{k,n}, s_{k,n}, \cdots, s_{k,n}]}_{n_R}$, $(k=1,\ldots,K)$ and N denotes the spreading factor. $\mathbf{n}$ denotes the Additive White Gaussian Noise (AWGN) with variance σ^2.

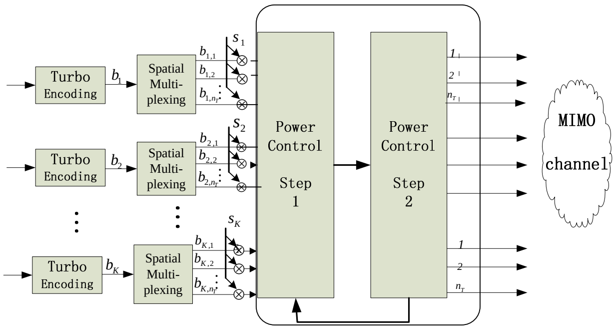

Fig.1 Block diagram of the multiple transmitters with proposed power control

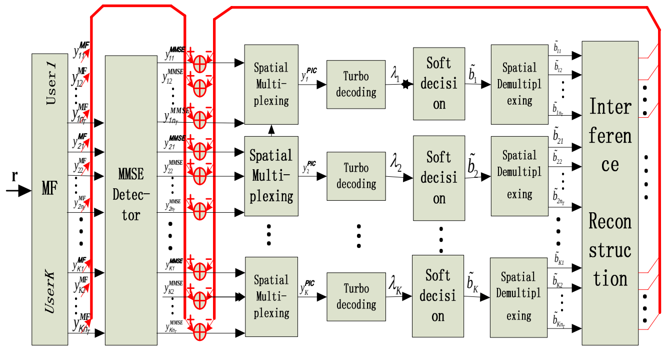

Fig.2 Block diagram of the multiuser detection

III. Joint Power Control and Multiuser Detection

The proposed joint two-step power control and multiuser detection is given in this section. The structure of the receiver is shown in Fig.2. The signals received are first combined and despread by a matched filter (MF). Then the output of the MF, $\mathbf{y}_{MF}$, are sent into a minimum mean square estimation (MMSE) multi-user- antenna detector to suppress the IAI and MAI[18]. The output of the MF (without power control) can be expressed as

$$\mathbf{y}_{MF} = \mathbf{H}^H\mathbf{S}^T\mathbf{r} = \mathbf{H}^H\mathbf{S}^T(\mathbf{SHb}+\mathbf{n}) = \mathbf{H}^H\mathbf{RHb} + \mathbf{n}' \tag{3}$$

where $\mathbf{R}=\mathbf{S}^T\mathbf{S}$ is the correlation matrix of the spreading sequence matrix, and $\mathbf{n}'=\mathbf{H}^H\mathbf{S}^T\mathbf{n}$. We can further rewritten equation (3) to obtain the estimates to be sent to the turbo decoder as the following

$$\hat{b}_{k,i}^{(1,1)} = \left\|\mathbf{h}_{k,i}\right\|^2 b_{k,i} + \sum_{j=1, j\neq i}^{n_T} \mathbf{h}_{k,i}^{*}\mathbf{h}_{k,j} b_{k,j} + \frac{1}{N}\sum_{j=1,w\neq i}^{n_T} \mathbf{B}_{k,w,j}^{*}\mathbf{B}_{k,w,j} b_{k,j} + \frac{\mathbf{n}''}{N} \tag{4}$$

where $\left\|\mathbf{h}_{k,i}\right\|^2$ is the norm of the ith column matrix of the channel matrix $\mathbf{H}_k$, $i = 1\cdots n_T$ and $\mathbf{B}_{k,w,j}$ represents the jth column vector of the $\mathbf{B}_{k,w}$ where is the $\mathbf{B}_{k,w}$ combined correlation matrix denoting the correlation between two different users in the system. Define that

$$\mathbf{B} = \mathbf{H}^H\mathbf{RH}$$

$$\mathbf{B} = \left\{\mathbf{B}_{i,j}\right\}; \quad i, j = 1,2,\ldots,K$$

and assume k is our target user, then $w \neq k$ represents other unwanted users. Therefore we have

$$\mathbf{B}_{k,w}=\begin{bmatrix}\beta_{k,w}[1,1] & \beta_{k,w}[1,2] & \cdots & \beta_{k,w}[1,n_T]\\ \beta_{k,w}[2,1] & \beta_{k,w}[2,2] & \cdots & \beta_{k,w}[1,n_T]\\ \vdots & \vdots & \vdots & \vdots\\ \beta_{k,w}[n_T,1] & \beta_{k,w}[n_T,2] & \cdots & \beta_{k,w}[n_T,n_T]\end{bmatrix}$$

. While first part on the right side of (4) represents the wanted signal of user k, the second part stands for the self IAI of each user, and the third part represents the MAI from other users. Therefore, the element of the diagonal power control matrix for the first step of our proposed power control scheme can be expressed as: $\mathbf{P}=\mathbf{P}_1=diag[\mathbf{P}_{1,1},\mathbf{P}_{1,2},\cdots,\mathbf{P}_{1,K}]$ with $\mathbf{P}_{1,k}=diag[p_{1,k,1}\quad p_{1,k,2}\quad\cdots\quad p_{1,k,n_T}]$, where $p_{1,k,i}=1\Big/\sqrt{\|\mathbf{h}_{k,i}\|^2}\ (i=1\cdots n_T)$.

After the first step of power control being applied, the output of the MMSE detector can be written as:

$$\mathbf{y}_{MMSE}=((\mathbf{HP_1})^H\mathbf{RHP}_1+\sigma_2\mathbf{I})^{-1}\mathbf{y}_{MF} \tag{5}$$

which can aslo be expressed as

$$\begin{aligned}\mathbf{y}^{MMSE}&=((\mathbf{HP}_1)^H\mathbf{R}(\mathbf{HP}_1)+\sigma^2\mathbf{I})^{-1}(\mathbf{HP}_1)^H\mathbf{S}^T(\mathbf{S}(\mathbf{HP}_1)\mathbf{b}+\mathbf{n})\\ &=\mathbf{Wb}+\mathbf{n}^*\end{aligned} \tag{6}$$

where $\mathbf{W}=(\mathbf{HP}_1)^H\mathbf{S}^T(\mathbf{SHP}_1(\mathbf{HP}_1)^H\mathbf{S}^T+\sigma^2\mathbf{I})^{-1}\mathbf{SHP}_1$, $\mathbf{n}^*=(\mathbf{HP}_1)^H\mathbf{S}^H(\mathbf{S}(\mathbf{HP}_1)(\mathbf{HP}_1)^H\mathbf{S}^H+\sigma^2\mathbf{I})^{-1}\mathbf{n}$ and $\mathbf{I}$ denotes an identity matrix. The output of the MMSE detector can then be written as

$$\begin{aligned}\hat{y}_1^{MMSE}&=\mu_1 b_1+n_1^*\\ \hat{y}_2^{MMSE}&=\mu_2 b_2+n_2^*\\ \vdots\quad&\vdots\\ \hat{y}_{K\times n_T}^{MMSE}&=\mu_{K\times n_T}b_{K\times n_T}+n_{K\times n_T}^*\end{aligned} \tag{7}$$

where $\boldsymbol{\mu}=diag[\mu_1,\mu_2,\ldots,\mu_{K\times n_T}]$ and

$\mathbf{n}^*=((\mathbf{HP}_1)^H\mathbf{RHP}_1+\sigma_2\mathbf{I})^{-1}(\mathbf{HP}_1)^H\mathbf{S}^T\mathbf{n}$ with $\mathbf{n}^*=[n_1^*,n_2^*,\ldots,n_{K\times n_T}^*]$.

The calculation of $\boldsymbol{\mu}_k$ is given as

$$\mu_i=\mathbf{H}^H(i,:)\mathbf{S}^H(\mathbf{SHH}^H\mathbf{S}^H+\sigma^2\mathbf{I})^{-1}\mathbf{SH}(:,i),\ (i=1,2,\ldots,K\times n_T) \tag{8}$$

In other words, the MMSE estimate of the symbol transmitted on the ith antenna for user k is multiplied by μ_i. Thus the second step of the power control scheme is to compensate at the transmitter for this factor by multiplying the transmitted symbols with $1/\mu_i$, i.e.:

$$P_{2,i}=1/\mu_i\ (i=1,2,\ldots,K\times n_T) \tag{9}$$

where $\mathbf{P}_2=diag[P_{2,1},P_{2,2},\ldots,P_{2,K\times n_T}]$.

The outputs of the MMSE detection after space-time demultiplexing are decoded by the Turbo decoder bank. In order to mitigation the error propagation caused by uncertain decision, the soft decisions described in [4], rather than hard decisions, have been employed to estimate the outputs of the Turbo decoder. Then the soft estimations are used to reconstruct the MAI between users.

$$\mathbf{y}_{PIC}=\frac{(\mathbf{y}_{MF}-(\mathbf{B}_{new}-diag(\mathbf{B}_{new})))\tilde{\mathbf{b}}^{(1,2)}}{N} \tag{10}$$

where $\tilde{\mathbf{b}}^{(1,2)}$ is the soft estimations of transmitted data $\mathbf{b}$ obtained from (7) after power control step two, and $\mathbf{B}_{new}=(\mathbf{HP}_1\mathbf{P}_2)^H\mathbf{R}(\mathbf{HP}_1\mathbf{P}_2)$. Since the calculation of $\mathbf{P}_1$ affects the calculation of $\mathbf{P}_2$, and the calculation of $\mathbf{P}_2$ will change that of $\mathbf{P}_1$, the above proposed power control scheme is then considered to be applied iteratively to compensate for the channel fading effect on each transmitted antenna of each user by calculating $\mathbf{P}_1$ and $\mathbf{P}_2$ correspondingly, therefore to obtain more accurate estimation of the transmitted symbols, $\tilde{\mathbf{b}}^{(m,2)}$, after m iterations, to reduce the error propagation in the PIC detection and improve the system performance.

IV. SIMULATION RESULTS

A synchronous uplink CDMA system with 10 equal power users is considered. 1024-bit, 1/3 rate with generator [13, 15] Turbo code is employed. Each user is equipped with 4 transmit and 4 receiver antennas. 31-chip Gold sequences and BPSK modulation are employed in the simulation. The wireless channel is assumed to be block fading Rayleigh channel, i.e. the channel is assumed to remain constant for the duration of 512 symbols within one block, and changes from one block to another.

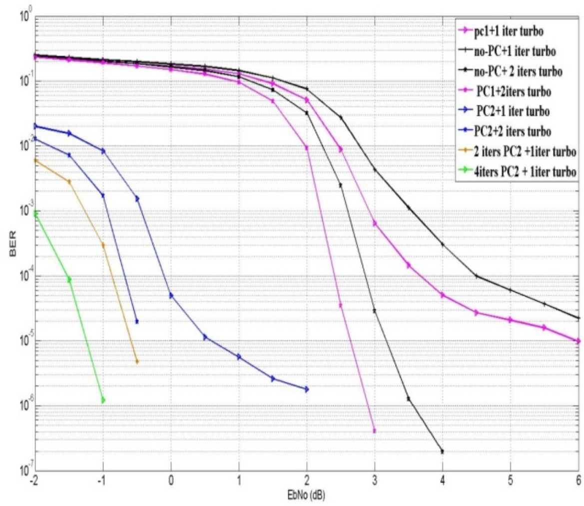

Fig.3 BER comparison between the proposed scheme and that of no power control under different iterations of processing

Fig.3 shows the BER performance is improved with the increasing number of iterations, and it indicates that BER performance with the proposed PC scheme is much better than that without PC. It is observed that using step 1 alone with 1 or 2 iterations of PIC and turbo decoding could provide an improvement of almost 0.4 dB at BER of 10^{-3}. With one iteration of the two-step power control and 1 or 2 iterations of PIC and turbo decoding, a more significant improvement: a performance improvement of 3 dB at BER of 10^{-3} can be obtained. With the increasing the iterations of the two-step power control schemes, further performance improvement could be obtained with our proposed scheme.

V. CONCLUSIONS

A joint power control and multiuser receiver employing Turbo decoding and MMSE-based PIC detection has been proposed in this paper for a MIMO CDMA system on the uplink. Simulation results demonstrated that the proposed scheme provided a significant reduction in the system BER compared to that of no power control. The proposed two-step power control effectively compensated for some channel fading effect, and thus benefited the MMSE detection in the multiuser receiver in obtaining more accurate estimates of the transmitted symbols. The outputs of the MMSE detection with improved accuracy then help the turbo decoder with more correctly recovered transmitted information, and therefore improve the system performance significantly.

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