Low-Complexity Iterative Interference Cancellation Multiuser Detection for Overloaded MIMO OFDM IDMA System

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Abstract—In this paper, interleave-division multiple access (IDMA) is used for overloaded multiple-input multiple-output (MIMO) coded orthogonal frequency division multiplexing (OFDM) systems. An iterative interference cancellation multiuser detection (IIC-MUD) method is proposed, which has almost the same complexity but can achieve almost optimal (MAP) performance, much better than that of elementary signal estimation (ESE) method. The main idea of this IIC-MUD is the log-likelihood ratio (LLR) calculation, which is based on the channel impulse responses (CIRs). By the LLR convertor, we can obtain more reliable LLRs for the decoder, which can make full use of CIRs to obtain the channel gain. The performance of the proposed IIC-MUD is assessed through simulation results.

Keywords-IDMA; MUD; RAKE; PIC; MIMO; OFDM.

I. INTRODUCTION

Interleave-division multiple access (IDMA) was first proposed for code division multiple access (CDMA) in 2002, which inherits many advantages from CDMA such as diversity against fading and mitigation of the worst-case other-cell user interference problem [1]. Combined with low-rate channel coding, user-specific interleavers are employed in IDMA for user separation. The attractive feature of IDMA is that it allows the use of a low-complexity iterative multiuser detection (MUD) technique.

However, the complexity of IDMA’s receiver still increases with the number of paths linearly, which can be overcome by combined orthogonal frequency division multiplexing (OFDM), called OFDM-IDMA [2]. Moreover, the extension of OFDM-IDMA into the MIMO transmission has also been proposed in [3] [4], which combines most of the advantages of the multiple access schemes and avoids their individual disadvantages. The key advantage of OFDM-IDMA is that the complexity of MUD can be reduced evidently for each user independent of the channel length, which is significantly lower than that of other alternatives [2].

Many previous works on OFDM-IDMA are based on elementary signal estimator (ESE) [1] [2]. The major research areas of using ESE are frequency synchronization, channel equalization, or signal to noise ratio (SNR) evolution [7-9]. For multipath channels, the main idea of low complexity of ESE is applied a simply rake-type operation, which however cannot make use of channel impulse responses (CIRs) effectively.

In this paper, we focus on the new MUD scheme, and generalize IDMA to overloaded MIMO OFDM system, where receive antennas are much less than the transmitters. We propose a low-complexity iterative interference cancellation multiuser detection (IIC-MUD) scheme that employs CIRs effectively for the log-likelihood ratio (LLR) calculation.

A simply RAKE receiver is used at the receiving end. A scaling factor then is applied to rescale the RAKE output signal, which can be obtained directly from CIRs, and make the LLRs more reliable due to the effective utilization of CIRs. Fed these LLRs to the decoders, the estimated data streams can be obtained, using the principle of soft symbol estimation, which are used for interference cancellation. Then full parallel interference cancellation (PIC) is applied for interference cancellation.

The rest of this paper is organized as follows: In Section II, the system model is introduced. Then we propose the new detection scheme in Section III. In Section IV, the simulation results are presented, and in Section V, we offer our conclusions.

II. OVERLOADED MIMO OFDM IDMA SYSTEMS

We consider an uplink multiple-access scenario where $M$ users with a total of $N_T$ transmit antennas simultaneously transmit data signals to the base station with $N_R$ receive antennas, where receive antennas are much less than the transmitters ($N_T \gg N_R$). Users are assumed to be uncorrelated and have only one antenna respectively, that is $M = N_T$.

The key principle of IDMA is that the interleavers should be different for different users. The structure of the system model is illustrated in Fig. 1. The users’ data are first encoded by using a low-rate channel code that is a concatenation of the convolutional and repetition codes. Then each coded bit sequence is interleaved by a user-specific interleaver. The interleavers are generated independently and randomly. Together with the user-specific interleaver, the repetition code performs a kind of spreading, somewhat similar to the spreading in a CDMA system.

Finally, the interleaved coded data is transmitted after the BPSK and OFDM modulation. To balance the $+1$ and $-1$, the repetition sequence should be $\{+1, -1, +1, -1, \cdots\}$.
For simplicity we used BPSK modulation in this paper: the method can be adapted for other modulation constellations.

Figure 1. The proposed MIMO-OFDM IDMA system: (a) transmitter and (b) receiver

We assume multipath block fading channels are used: in this case the channel coefficients stay constant during one data frame. For one data frame, the transmitted data are grouped into $N$ OFDM symbols, and each symbol has $K$ subcarriers.

For the $k$th subcarrier, the frequency domain received signal can be expressed as

$$r_k = H_k s_k + n_k,$$  \hspace{1cm} (1)

$$H_k = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_T} \\ h_{21} & h_{22} & \cdots & h_{2N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R1} & h_{N_R2} & \cdots & h_{N_RN_T} \end{bmatrix},$$  \hspace{1cm} (2)

$$s_k = \begin{bmatrix} s_{k1}^T \\ s_{k2}^T \\ \vdots \\ s_{kN_T}^T \end{bmatrix},$$  \hspace{1cm} (3)

$$n_k = \begin{bmatrix} n_{k1}^T \\ n_{k2}^T \\ \vdots \\ n_{kN_T}^T \end{bmatrix},$$  \hspace{1cm} (4)

where $H_k$ is an $N_R \times N_T$ equivalent frequency domain channel matrix, $s_k$ is the transmitted symbols and $n_k$ is the AWGN vector which has zero mean and variance $\sigma^2$, $k = 1 \ldots K$ is the subcarrier number.

III. ITERATIVE INTERFERENCE CANCELLATION MULTIUSER DETECTION

In this section, an IIC multiuser receiver structure is introduced, which has been proposed in [6]. This technique can effectively suppress the MAI and can achieve near-optimum BER performance for the overloaded system at low SNR. However for certain channels this detector will not converge to low BER, resulting in a significant outage probability.

In this paper, combined IDMA, the proposed scheme overcomes the above disadvantage with extremely low repetition code rate, and hence maintaining low complexity.

We assume that the CIRs are known to the receiver perfectly. At the first iteration, the received signal is first fed to the RAKE receiver. The received data will be processed through a spatial domain RAKE detector, corresponding to maximum ratio combining (MRC) in the spatial domain. The RAKE output can be expressed as

$$y_{\text{rake},k} = H_k^T r_k,$$  \hspace{1cm} (5)

$$= H_k^T H_k s_k + H_k^T n_k,$$  \hspace{1cm} (6)

$$= R_k s_k + \omega_k.$$  \hspace{1cm} (7)

Before passing to the soft-in soft-out (SISO) decoder, a scaling factor is applied to rescale the RAKE output by a LLR converter, which can provide more reliable LLR values.

For a valid LLR values, its probability density function (PDF) is close to the Gaussian distribution. According to [5], the mean and variance of a valid LLR, which is the input of the decoder, must fulfill

$$\mu_k = \sigma^2 / 2.$$  \hspace{1cm} (8)

The scaling factor $\beta_k$, supplied from LLR convertor, is calculated from CIRs, which is based on the mean value $\mu_{y,k}$ and variance $\sigma_{y,k}^2$ of the channel covariance matrix,

$$\beta_k = 2 \mu_{y,k} / \sigma_{y,k}^2.$$  \hspace{1cm} (9)

The channel covariance matrix of the channel can be written as

$$R_k = H_k H_k^T = \begin{bmatrix} R_{11} & \cdots & R_{1N_T} \\ \vdots & \ddots & \vdots \\ R_{N_T1} & \cdots & R_{N_TN_T} \end{bmatrix},$$  \hspace{1cm} (10)

then it is clear that

$$\mu_{y,k} = \text{diag}(R_k)^T.$$  \hspace{1cm} (11)

Denote

$$G_k = R_k - \text{diag}(\text{diag}(R_k)).$$
the variance

$$\sigma^2_{y,k,i} = \sum_{j=1}^{N_T} Re\{g_{ij}^k\}^2 + \sum_{l=1}^{N_R} Re\{h_l\}^2 \cdot \sigma^2,$$  \hspace{1cm} (13)

of which the first term is due to interference and the latter is from noise, \(i = 1 \ldots N_T\), and \(\sigma^2\) is the variance of AWGN.

Then the outputs of the LLR converter are decoded by the SISO decoder, and their outputs, the LLR values \(L_{\text{dec}}\), are used to calculate the soft estimate of the user data symbols. In the case of BPSK the soft estimates are obtained using:

$$\hat{s}_k = \tanh\left(\frac{t_{\text{dec}}^k}{2}\right).$$  \hspace{1cm} (14)

At the interference reconstruction part, using the SIC-based approach, we find the user data stream giving the largest soft estimate to interference ratio (EIR)

$$\text{EIR}_i = \sum_{j=1}^{N_K} llr_{ij}/\max(t_{\text{MAX}}),$$  \hspace{1cm} (15)

$$t_{\text{MAX}}^k = \max\left(\sum_{i,j}^N g_{ij}^k s_i^k\right) = \sum_{j=1}^{N_T} |g_{ij}^k|,$$  \hspace{1cm} (16)

where \(llr_{ij}\) is the (\(i,j\))th element of \(L_{\text{dec}}\) and \(i = 1 \ldots N_T\), and \(s_i^k\) is the detected symbol of user \(i\).

After the interference reconstruction, the resulting estimate of MAI can then be subtracted from the RAKE output [6]:

$$y_{\text{IC},k} = y_{\text{RAKE},k} - (R_k - \text{diag}(R_k)) \hat{s}_k.$$  \hspace{1cm} (17)

Note that this SIC-based approach is used only on the first iteration.

For subsequent iterations, the improved signals \(y_{\text{IC},k}\) are passed to the LLR converter. Then the rescaled LLR values are fed to the decoders, and new soft estimates can be obtained. Now the full PIC is used to reconstruct the interference, in which the interference estimate is based on the decoded data streams from all users.

As the iteration number increases, the interference decreases, so that the LLR values become more reliable. It is reasonable to expect that, after several iterations, the interference will be eliminated completely, and the first term of (13) tends to zero, the variance becomes

$$\sigma^2_{y,k,i} = \sum_{l=1}^{N_R} Re\{h_l\}^2 \cdot \sigma^2.$$  \hspace{1cm} (18)

Compared to the ESE [1], the computational complexity of the IIC-MUD receiver is similarly low, since all processing is linear. Even the CIR correlation matrix \(R\), needs to be calculated only once. We assume that the channel remains constant during one data frame, so this calculation has a complexity per frame of \(O(N_T^2 N_R K)\).

<table>
<thead>
<tr>
<th>TABLE I. COMPLEXITIES OF IIC-MUD RECEIVER</th>
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<tbody>
<tr>
<td>RAKE Receiver</td>
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<tr>
<td>CIR Correlation Matrix</td>
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<td>LLR Converter for first half iterations</td>
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<tr>
<td>LLR Converter for last half iterations</td>
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<tr>
<td>SIC Detection</td>
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<tr>
<td>PIC Detection</td>
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<tr>
<td>(O(N_T N_R N_K)) per frame</td>
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<td>(O(N_T^2 N_R K)) per frame</td>
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<tr>
<td>(O(N_T N_K)) per frame/iteration</td>
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In Table I, the computational complexities of the IIC-MUD receiver are estimated. This is a rough estimation and the complexity in practice depends on different communications scenarios. The SIC detection has the complexity of \(O(N_T N_R K)\). Note that the calculation of \(R\), RAKE reception, and SIC detection need to be calculated only once, and the LLR converter should be calculated twice, while only PIC detection should be repeated in each iteration, which is the domination of the whole complexity.

Compared to the MAP decoder, including reduced complexity version, such as the list sphere decoder, the complexity of the proposed method is significantly lower (IIC-MUD: \(O(N_T N_K)\) vs MAP: \(O((2^{N_T})^N)\)).

IV. SIMULATION RESULTS

In the simulations, a \(4 \times 1\) system and a \(4 \times 2\) OFDM-IDMA system are considered. Both users are assumed to employ 1024-bit/frame 10000 frames with a rate 1/2 convolutional code (with generator 7, 5) serially concatenated with a low rate repetition code, BPSK and OFDM modulation. A Rayleigh channel is assumed with uncorrelated fading between all transmit and receive antennas. A block fading channel is used, which means the channel coefficients stay constant for one frame period. 10 iterations are required for MAP, IIC-MUD and elementary signal estimation (ESE) MUD.

For the comparison, the bit error rate (BER) performance and frame error rate (FER) performance of \(4 \times 2\) OFDM system are shown in Fig. 2. Due to some deeply fading channel, the IIC-MUD cannot converge at high SNR, although in practice the FER performance corresponds to an
outage probability of less than 1%, good enough for mobile users.

better than that of ESE MUD. Especially for 2 taps channel, the BER performance of ESE MUD seems to have an error floor, which is the same as shown in Fig. 2.

From the figure, we can see that combined with IDMA, the IIC-MUD can make full use of CIRs and obtain the channel gain, and achieve almost the optimal (MAP) performance.

Fig. 3(a) shows the BER performance of $4 \times 1$ OFDM-IDMA system with rate-1/4 repetition code (1/8 total rate). We consider the multipath with 1 tap, 2 taps, 4 taps, and 8 taps. From the figure, we can see that when channel multipath is more than 1 tap, the performances of IIC-MUD are much better than ESE MUD. After 10 iterations, the IIC-MUD can achieve almost the optimal (MAP) performance.

Fig. 3(b) shows the BER performance of $4 \times 2$ OFDM-IDMA system with rate-1/2 repetition code (1/4 total rate). Compared to Fig. 2, the IIC-MUD now can work very well. The performances of proposed IIC-MUD are still much better than that of ESE MUD. Especially for 2 taps channel, the BER performance of ESE MUD seems to have an error floor, which is the same as shown in Fig. 2.

From the figure, we can see that combined with IDMA, the IIC-MUD can make full use of CIRs and obtain the channel gain, and achieve almost the optimal (MAP) performance.

V. CONCLUSIONS
A low complexity iterative interference cancellation multiuser detection method for overloaded multiuser MIMO OFDM IDMA systems is proposed in this paper. This technique can effectively suppress the MAI, make full use of CIRs to obtain the channel gain, and can achieve almost optimal (MAP) BER performance for the overloaded system.
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