LETTER
An MMSE-Nulling Partial-PIC Receiver for Multiuser Downlink MIMO MC-CDMA Systems

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SUMMARY  A minimum mean square error (MMSE) nulling partial parallel interference cancellation (PPIC) receiver for downlink multiple-input multiple-output (MIMO) multicarrier (MC)-CDMA systems is proposed. Our analysis shows that, for multiuser MIMO MC-CDMA systems, interference due to frequency selectivity in multipath fading channel causes detrimental effects on cancelling, thus V-BLAST receiver shows severe performance degradation. The proposed receiver with multistage processing does not produce an error floor in frequency selective fading channel environments and achieves substantial performance gains. The system performance of the proposed receiver was evaluated through computer simulations. The simulation results show that, with two stage PPIC processing, the proposed receiver achieves performance gains of 2.5–4 dB at target BER of 10⁻³ over the linear MMSE receiver.

key words: MIMO, MC-CDMA, V-BLAST, PIC

1. Introduction

The development of wireless communication systems for high data rate transmission and high system flexibility is one of the main targets in next generation wireless communications research. MIMO MC-CDMA systems have attracted significant research interest due to its high spectral efficiency, large system capacity and high flexibility for data rate, and it has been proposed as one of the promising candidates for 4th generation wireless communication systems [1]. MIMO MC-CDMA systems are combinations of MIMO transmission, orthogonal frequency division multiplexing (OFDM) signaling and CDMA schemes. MC modulation, realized via OFDM, is well suited to high data rate applications such as multimedia packet transmission and mobile internet in frequency selective fading channels.

MIMO systems can achieve very high spectral efficiency without additional power or bandwidth in a rich multipath environment by exploiting the extra space dimension. Vertical Bell Labs Layered Space Time (V-BLAST) is a popular single-carrier single-user MIMO detection algorithm, which is based on the ordered successive interference cancellation (OSIC) [2]. The principle behind OSIC is that at the beginning of each stage, the substream with the highest post-detection signal to noise ratio (SNR) is selected for cancellation. This improves the quality of the decision and has been known to be optimal for point-to-point MIMO receiver. However, the performance of V-BLAST detector can deteriorate, since the OSIC structure is very vulnerable to interference due to unknown users for multiuser downlink MIMO MC-CDMA systems [3].

The multistage parallel interference cancellation (PIC) was shown to possess several desirable properties including the potential for near optimum performance, very low computational complexity and low decision latency. Recently, the basic PIC receiver has been extended to MC-CDMA systems [5].

In this paper, drawbacks, such as the degradation of performance of conventional V-BLAST, are analyzed and a new receiver based on partial PIC (PPIC) for inter-antenna interference (IAI) cancellation is proposed. Also, analytical results exposing several aspects on the performance are presented.

2. System Model

The block diagram of a MIMO MC-CDMA system is shown in Fig. 1, where \( x_k \) and \( \hat{x}_k \) denote the \( k \)th chip signal spread by \( k \)th code before and after chip interleaving, respectively. At the chip interleaver, successive chips are interleaved in the frequency domain using the pattern described in Fig. 1, where the interleaving size is \( N_c \). The system contains \( M \) transmit antennas and \( N \) receive antennas (\( M \leq N \)). At the transmitter, a single data stream is de-multiplexed into \( M \) substreams. Each block fed to one of the \( M \) transmit antennas has \( P \) modulation symbols that are first serial-to-parallel converted and then spread with a pre-assigned code at spreading factor of \( SF \). All \( P \times SF \) chips per antenna are mapped onto \( N_c \) subcarriers with optional chip interleaving and transformed into the time domain by \( N_c \) point inverse fast Fourier transform (IFFT). The parallel time-domain signals are first converted to serial and then added with a guard interval (GI) before transmission to the MIMO channel. We assume a slow frequency selective Rayleigh fading MIMO channel.

At the receiver, the GI of a received signal at each of the \( N \) receive antennas are removed and an \( N_c \) point fast Fourier transform (FFT) is performed. A frequency domain signal model for the outputs corresponding to \( j \)th (\( j = 1, \cdots, N_c \)) subcarrier at all \( N \) receive antennas can be written as (1).
\[
y^j = H^j \cdot x^j + n^j, \quad 1 \leq j \leq N_c
\]
\[
= h^j_1 \cdot x_1 + h^j_2 \cdot x_2 + \cdots + h^j_M \cdot x_M + n^j
\]
\[
x^j = \sum_{k=1}^{K} x^j_{1,k} + \sum_{k=K+1}^{K} x^j_{k},
\]
where \(H^j\) is a channel matrix, where \(h^j_m = [h^j_{1,m}, h^j_{2,m}, \ldots, h^j_{N_c,m}]^T\) indicates a channel vector whose element \(h^j_{c,m}\) is the frequency domain channel response between transmit antenna \(m (m = 1, \ldots, M)\) and receive antenna \(n (n = 1, \ldots, N)\), and \(x^j = [x^j_1, x^j_2, \ldots, x^j_M]^T\) and \(y^j = [y^j_1, y^j_2, \ldots, y^j_M]^T\) denote transmitted signal and received signal mapped on \(j\)th subcarrier, respectively. In (1), \(x^j_{1,k}\) is a chip signal after spreading with code \(k\) transmitted from \(i\)th antenna on \(j\)th subcarrier, and \(n^j = [n^j_1, n^j_2, \ldots, n^j_M]^T\) implies the additive white Gaussian noise (AWGN) vector on the \(j\)th subcarrier. It is assumed that the multiuser downlink MIMO MC-CDMA system supports only two users simultaneously for simplicity of explanation since it captures the key aspects of the proposed receiver, thus \(K\) codes among total \(K\) codes \((K \leq K)\) are assigned to the desired user in (1).

Since, as shown in (1), the received signal per subcarrier of MIMO MC-CDMA systems after FFT has a similar representation to that of single carrier systems, when there is no room for confusion, we will omit the subcarrier index \(j\) for simplicity hereafter.

### 3. Analysis of V-BLAST Receiver for MIMO MC-CDMA Systems

V-BLAST is composed of sequential nulling and cancelling for each transmit antenna based on the averaged post-detection SNR criterion. In this paper, we adopt a nulling vector based on minimum mean square error (MMSE) nulling criterion in [2] and [8]. Using (1) and nulling vector \(w_i = [w_{i,1}, \ldots, w_{i,M}]^T\) for \(i\)th transmit antenna, the nulling and cancelling for a multuser MIMO MC-CDMA system can be written as follows:

\[
z_{i}' = (w_i^j)^T \cdot y^j
\]
\[
\tilde{x}_{i,k} = MF_k(z_{i,1}', \ldots, z_{i,K}')
\]
\[
y^{i,j} = y^j - h^j \cdot \sum_{k=1}^{K} \tilde{x}_{i,k},
\]
where \(z_{i}', \tilde{x}_{i,k}, MF_k(x)\) and \(y^{i,j}\) denote \(j\)th chip signal of \(i\)th transmit antenna after nulling, detected symbol of \(i\)th transmit antenna after despreading with code \(k\), matched filter receiver for code \(k\), and received signal after cancelling of the regenerated signal for the \(i\)th transmit antenna, respectively. In V-BLAST receiver for MIMO MC-CDMA systems, chip level nulling is performed per subcarrier. On the other hand, ordering for SIC is determined after despreading in symbol level based on the averaged post-detection SNR criterion.

\[
z_1 = w_1^T \cdot y = w_1^T \cdot (h_1 \cdot x_1 + h_2 \cdot x_2 + \cdots + h_M \cdot x_M + n) = \alpha_{11} \cdot x_1 + \alpha_{12} \cdot x_2 + \cdots + \alpha_{1M} \cdot x_M + n_1'
\]
\[
= \alpha_{11} \cdot \left(\sum_{k=1}^{K} x^j_{1,k} + \sum_{k=K+1}^{K} x^j_{1,k}\right) + \alpha_{12} \cdot \left(\sum_{k=1}^{K} x^j_{2,k}\right) + \cdots + \alpha_{1M} \cdot \left(\sum_{k=1}^{K} x^j_{M,k}\right) + n_1'
\]
\[
y' = y - h_1 \cdot \left(\sum_{k=1}^{K} \tilde{x}_{1,k}\right) = h_1 \cdot \left(\sum_{k=1}^{K} \tilde{x}_{1,k}\right) + h_2 \cdot x_2 + h_3 \cdot x_3 + \cdots + h_M \cdot x_M + n
\]
\[
z_2 = w_2^T \cdot y' = w_2^T \cdot \left[ h_1 \cdot \left(\sum_{k=1}^{K} \tilde{x}_{1,k}\right) + h_2 \cdot x_2 + h_3 \cdot x_3 + \cdots + h_M \cdot x_M + n \right]
\]
\[
= \alpha_{21} \cdot \left(\sum_{k=1}^{K} x^j_{2,k} + \sum_{k=K+1}^{K} x^j_{2,k}\right) + \alpha_{22} \cdot \left(\sum_{k=1}^{K} x^j_{2,k}\right) + \cdots + \alpha_{2M} \cdot \left(\sum_{k=1}^{K} x^j_{M,k}\right) + n_2'
\]
Thus, cancelling is performed per subcarrier after spreading according to the symbol level ordering.

In the case of a multiuser downlink scenario, the desired user knows only $\tilde{K}$ codes among all $K$ codes, thus only $\tilde{K}$ detected symbols are removed in cancelling. We assume that nulling is ordered with increasing antenna index for simplicity. Then, nulling for antenna 1 is given by (3), where $\alpha_{1,j}$ and $\epsilon_{1,j}'$ denote the inner product of $\mathbf{w}_1$ and $\mathbf{h}_j$, and $\mathbf{w}_1$ and $\mathbf{n}_j$, respectively.

After nulling for antenna 1, the $\tilde{K}$ code signals are detected by $MF_k(x)$. The detected $\tilde{K}$ code signals for antenna 1 are spread and subtracted out from the received signal by cancelling as shown in (4), where $\hat{x}_{1,k}$ is an estimate of $x_{1,k}$ and $\epsilon_{1,k}$ denotes the detection error for $x_{1,k}$. Then, subsequent nulling for antenna 2 is performed by a new nulling vector $\mathbf{w}_2'$ obtained after $\mathbf{h}_1$ is removed from $\mathbf{H}$ [2]. Nulling for antenna 2 after cancelling is shown in (5), where $D$, $I_1$, $I_2$, $E_i$, and $\alpha_{2,j}'$ denote the desired signal from antenna 2, interference due to unknown codes from antenna 2, interference arising from other antennas, interference from previous cancelling, and the inner product of $\mathbf{w}_2'$ and $\mathbf{h}_j$, respectively. In (5), as can be seen in $E_i$, the propagated detection error $\epsilon_{1,k}$ and interference from unknown codes $x_{1,k}$ are accumulated. The accumulated interference $E_i$ increases with subsequent nulling and cancelling of V-BLAST and it causes severe performance degradation.

4. MN-PPIC Receiver

In this section, we first show the reasons for performance degradation of V-BLAST from a viewpoint of the effects of interference due to frequency selectivity and the accumulated interference described by $E_i$ in (5) for downlink MIMO MC-CDMA systems. Then, we propose a new detection algorithm and present some analytical results that show several aspects on the performance gain of the proposed algorithm.

For MC-CDMA systems, as the number of multipath increases, the received chip signal undergoes more severe frequency selectivity and we can obtain higher frequency diversity. However, orthogonality between codes is destroyed and the inter-code interference increases in proportion to the frequency selectivity. Thus, we can obtain more frequency diversity by chip interleaving with larger degree of interference, and there is some tradeoff between the frequency diversity and the interference [6]. From these features, the main reasons for the drawbacks of V-BLAST are as follow. First, V-BLAST based on OSIC is not effective in high frequency selective channels, since there are not significant differences among received signal powers due to the increased frequency diversity. Second, since $\mathbf{w}_i'$ in (5) is obtained regardless of $\mathbf{h}_i$, it can not suppress $\mathbf{h}_i$ fully and $\alpha_{2,j}'$ may be large to some degree. Third, as can be seen in (5), interference from antenna 1, composed of $\epsilon_{1,k}$ and $x_{1,k}$, is multiplied by $\alpha_{21}'$ and accumulated in $E_i$, thus $E_i$ is susceptible to amplification, and interference effects due to $E_i$ increase with subsequent nulling and cancelling of antenna 3 and so on. Consequently, the three interference effects mentioned above become dominant factors for the performance degradation of V-BLAST receiver.

Although it was shown that the linear MMSE receiver is superior to V-BLAST for multiuser MIMO MC-CDMA systems [3], it is not optimal without cancellation for MIMO detection [4]. Thus, based on the idea that it is most important to control the effect of $E_i$ in (5), we propose combinations of MMSE nulling (MN) and partial PIC (PPIC) receiver, which mitigate the excessive amplification of $E_i$ effectively and cancel interference from other transmit antenna sufficiently.

The proposed algorithm substitutes V-BLAST block in Fig. 1 and the details are as follow. We present the derivation for antenna 1 only, however extensions to the remaining antennas are straightforward. First, MMSE nulling is simultaneously performed for all transmit antennas and we obtain $\tilde{x}_{i,k} \ (1 \leq i \leq M, 1 \leq k \leq \tilde{K})$ in the same manner as (2). It is used in $l$th stage PIC as an estimates of the $x_{i,k}$ of previous stage. Each MMSE nulling is followed by a PPIC to suppress interference from other transmit antennas, as shown in (6), where $x_{i,k}^{(l+1)}$ and $\tilde{x}_{i,k}^{(l)}$ denote output signal of $l$th stage PIC for transmit antenna 1 and an estimate of $x_{i,k}^{(l+1)}$ obtained from the previous PPIC stage, respectively.

Second, since signals from other antennas act as interference for detecting antenna 1 substream, we perform PPIC in order to cancel the interference associated with other antennas by using the matched filtered outputs of previous stage, $\tilde{x}_{i,k}^{(l)} \ (2 \leq i \leq M, 1 \leq k \leq \tilde{K})$ in (6), where $\beta$ is an interference rejection weight that controls the degree of interference cancellation [7]. In (6), we defined detection error using $\beta$ as $x_{i,k}^{(l+1)} = x_{i,k} - \beta \tilde{x}_{i,k}^{(l)} \ (2 \leq i \leq M)$. After $l$th stage PIC for all transmit antennas, we obtain $x_{i,k}^{(l+1)} \ (1 \leq i \leq M)$, the output of the $l$th stage PPIC. In the subsequent stage, after matched filtering in the same manner as (2), $x_{i,k}^{(l+1)}$ substitutes for $\tilde{x}_{i,k}^{(l+1)}$ in (6) with increased reliability, since interference from other antennas are suppressed.

The main reasons for the performance enhancement of the MN-PPIC receiver are as follow. First, at the high frequency selective environments, there are not significant differences among interference signal powers due to the increased frequency diversity, thus the detections of the current stage using PIC with the interference estimations of the previous stage become more accurate than OSIC, since the ordering becomes less effective. Thus, MN-PPIC receiver is more advantageous than V-BLAST. Figure 2 shows chip level post-detection SNR and symbol level averaged post-detection SNR corresponding to each transmit antenna for two typical cases of frequency selective channel environments. We assume $L = 2$ and 24-paths Rayleigh fading channel with an exponential decay of the average received power levels with a sampling interval of 0.01 $\mu$sec [9], whose maximum delay spread is shown in Table 1. As shown in Fig. 2, the difference between post-detection SNR of transmit antennas decreases as the frequency selectivity increases.
\[ z_1^{(k+1)} = w_1^* \left[ y - \beta \left( h_2 \sum_{k=1}^{K} x_{2,k}^{(l)} + \ldots + h_M \sum_{k=1}^{K} x_{M,k}^{(l)} \right) \right] = z_1 - \beta \left( \alpha_{12} \sum_{k=1}^{K} x_{2,k}^{(l)} + \ldots + \alpha_{1M} \sum_{k=1}^{K} x_{M,k}^{(l)} \right) \]

\[ = \alpha_{11} \left( \sum_{k=1}^{K} x_{1,k} + \sum_{k=K+1}^{K} x_{1,k} \right) + \alpha_{12} \sum_{k=1}^{K} x_{2,k}^{(l)} + \ldots + \alpha_{1M} \sum_{k=1}^{K} x_{M,k}^{(l)} + \alpha_{12} \sum_{k=K+1}^{K} x_{2,k}^{(l)} + \ldots + \alpha_{1M} \sum_{k=K+1}^{K} x_{M,k}^{(l)} + h_1^* \] (6)

Second, as shown in (6), there is no interference due to unknown codes in \( E_P \), and detection errors in \( E_P \) become lower with well chosen \( \beta \) and multistage processing. Third, nulling vectors for all corresponding transmit antennas function reasonably well and interference due to unknown codes in \( I_2 \) are well controlled. From these observations, the effects of \( E_P \) in (6) is more effectively controlled as the stage of the MN-PPIC receiver increases.

In a computational complexity point of view, the proposed MN-PPIC receiver has advantages over V-BLAST. The proposed method requires nulling vector calculation only once, while V-BLAST calculates nulling vector per transmit antenna. Since pseudo inverse is the dominant factor in computational complexity and requires \( O(M^3) \) computational order, V-BLAST requires \( O(M^3) \) computational order and MN-PPIC requires almost \( O(M^2) \) order with two stage PPIC [10]. Thus, MN-PPIC receiver requires less computational power than V-BLAST.

5. Simulation Results

The performance of V-BLAST and MN-PPIC receiver for multiuser downlink MIMO MC-CDMA system was evaluated through computer simulations. The simulation parameters used are shown in Table 1, where the optimal value of \( \beta \) was empirically determined to be 0.4. As can be seen in Table 1, there are no multipath waves with delay time exceeding the guard interval in the simulation.

For the multiuser case, two users were considered, and the first user was assumed to be the desired user. In this case, 14 codes are evenly assigned to each user (\( K = 14, K = 28 \)). The degree of frequency selectivity is important to the receiver performance, thus we performed simulations for two different cases of delay spread as shown in Table 1 with chip interleaving.

Simulation results showed that significant performance improvement is achievable with the proposed method over V-BLAST. Figure 3 and Fig. 4 show simulation results of BER vs. \( E_b/N_0 \) for 2 and 24-paths channel, respectively. As can be seen in Fig. 3 and Fig. 4, for multiuser downlink MIMO MC-CDMA systems, the V-BLAST receiver yields an error floor in the higher \( E_b/N_0 \) region under high frequency selective environments, but the proposed method does not give an error floor. With the two stage PPIC processing, we are able to obtain a significant gain of 4 dB and 2.5 dB over the linear MMSE receiver at target BER of \( 10^{-3} \) for the two cases of delay spread shown in Table 1, respectively. With the simulation results, two stages of MN-PPIC is sufficient for overall system performance considering system complexity.
receiver for multiuser downlink MIMO MC-CDMA systems and proposed MN-PPIC receiver to enhance system performance based on the idea that PIC can obtain more attractive trade-off benefits between diversity and interference due to frequency selectivity.

Simulation results illustrate that, while V-BLAST detection shows an error floor for multiuser MIMO MC-CDMA systems under high frequency selective environments, the proposed MN-PPIC receiver is not interference limited and gives performance gains of 2.5–4 dB at target BER of $10^{-3}$ with two stage PPIC processing over linear MMSE receiver.

6. Conclusions

We analyzed some drawbacks of the conventional V-BLAST

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References


