A Cross Decision Feedback GSC-based Capon Multiuser Receiver for Space-Time Block Coded CDMA Systems

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Abstract—This paper proposes a simple, yet effective generalized sidelobe canceller (GSC)-based Capon multiuser receiver for the Alamouti space-time block coded (STBC) multiple-input multiple-output code-division multiple-access (MIMO CDMA) systems. The new receiver makes full use of the space diversity provided by the antenna array and the time diversity provided by the decision feedback (DF) from the outputs of both of GSCs employed along with the transmit diversity induced in the Alamouti STBC to render superior performance. With an ingenious DF scheme, refer to as the the cross DF (CDF), the desired signals will be blocked more thoroughly after the blocking matrix so that the interference suppression capability can be further enhanced. Performance analysis is also provided to show that that the minimum mean squared error (MMSE) of the receiver using the CDF is indeed lower than those with or without the classical DF scheme. Conducted simulations show that the new receiver can not only provide superior performance compared with previous works, but it can also render faster convergence characteristics.

keyword: Alamouti space-time block code, GSC, decision feedback, CDMA, interference suppression

I. INTRODUCTION

The CDMA is one of the promise candidates for the next generation wireless communication systems due to its high transmission rate and spectral efficiency [1]. To meet the growing demand for higher quality of service (QoS) such as bandwidth efficiency and network throughput in wireless systems, deployment of multiple antennas at both the transmit and receive sides, referred to as the MIMO systems, has also received much interest. As such, the incorporation of the MIMO CDMA systems with some sophisticated space-time processing schemes or coding techniques such as the space-time trellis codes [2] or the STBC [3] has received a great amount of attention recently. However, the performance of the MIMO CDMA systems is severely impaired by the multiple access interference (MAI).

To overcome the dilemma, a flurry of researches have been conducted to develop ingenious receivers for MIMO CDMA systems [4]. For example, Li et al. [5] extended the renowned Capon beamforming [6] in the array processing literature and proposed a Capon multiuser receiver which minimizes the output power while retaining the desired symbol to be intact after passing the receiver. Yu [7] reformulated the receiver in [5] based on the GSC implementation [8] so as to reduce the overall complexity and to be more amenable to real-time implementations. Despite the effectiveness of these receivers, they are more susceptible to channel estimation errors and suffer low adaptive speed.

To overcome these dilemmas, in this paper, we present a GSC-based Capon multiuser receiver for the Alamouti STBC MIMO CDMA systems. The new receiver, as [7], also contains two GSC-based branches, each for one of the two consecutive symbols in the Alamouti STBC scheme. It, however, makes full use of the space diversity provided by the antenna array and the time diversity provided by the decision feedback (DF) from the outputs of both of GSCs employed along with the transmit diversity induced in the Alamouti STBC to render superior performance. Note that the DF has been widely utilized in the design of equalizers and multi-user detectors. Recently, it has also been incorporated in the GSC-based beamformer [9] to offset the leakage of the desired signal when passing through the blocking matrix so as to be more robust to the mismatch error and to enhance the convergence rate in adaptive processing. The new receiver incorporates a more sophisticated DF scheme similar to [10], refer to as the the CDF, so that the desired signal will be blocked more thoroughly after the blocking matrix so that the interference suppression capability can be further enhanced. Furthermore, performance analysis is provided to show that that the MMSE of the receiver using the CDF is indeed lower than the ones with or without the classical DF scheme. Conducted simulations show that the new receiver can not only provide superior performance compared with previous works, but it can also render faster convergence characteristics.

II. SYSTEM MODEL

Consider a downlink synchronous CDMA system, which contains $M = 2$ transmit antennas (Tx’s) and $N$ receive
antennas (Rx’s). Assume that there are K users and the Alamouti’s STBC [3] is employed and that the channel is frequency flat and fixed. According to the Alamouti’s STBC scheme, each user, say user k, will transmit two consecutive symbols $b_k(2i-1)$ and $b_k(2i)$ during two consecutive symbol intervals across these two transmit antennas. For the first symbol interval, $b_k(2i-1)$ and $b_k(2i)$ are transmit respectively form Tx1 and Tx2, whereas at the second interval, $-b_k^*(2i-1)$ and $b_k^*(2i)$, where the superscript $*$ denotes the complex conjugation, are transmit respectively form Tx1 and Tx2. Also, each user has two equal length-$N$ spreading sequences $c_{1k}$ for Tx1 and $c_{2k}$ respectively. The data vectors received during these two consecutive time intervals at the $n^{th}$ receiver antennas can then be expressed as [5]

$$x_n(2i-1) = \sum_{k=1}^{K} \sqrt{\rho_k} [h_{1k} c_{1k} b_k(2i-1) + h_{2k} c_{2k} b_k(2i)] + w_n(2i-1)$$

(1)

$$x_n(2i) = \sum_{k=1}^{K} \sqrt{\rho_k} [-h_{1k} c_{1k} b_k^*(2i) + h_{2k} c_{2k} b_k^*(2i-1)] + w_n(2i)$$

(2)

where the $J \times 1$ $x_n(i)$ consists of the data samples within the $i^{th}$ symbol interval at the $n^{th}$ Rx, $J$ is the spreading gain, $\rho_k$ is the power of user $k$, $h_{mn}$ is the channel coefficient form the $m^{th}$ Tx to the $n^{th}$ Rx and is a complex Gaussian random variable with zero-mean and unit-variance, $c_{nk}$ is the information symbol for user $k$ in the $i^{th}$ time interval drawn from a unit-energy constellation, $w_n(i)$ is spatial and temporal white noise with zero mean and covariance matrix $\sigma^2 I_J$. Stacking (1) and (2) into $y_n(i) = [x_n^T(2i-1), x_n^T(2i)]^T$ results in

$$y_n(i) = \sum_{k=1}^{K} \sqrt{\rho_k} [g_{nk} b_k(2i-1) + \bar{g}_{nk} b_k(2i)] + \nu_n(i)$$

(3)

where $g_{nk} = C_k h_{nk}$, $\bar{g}_{nk} = \mathcal{C}_k h_{nk}^*$, in which $h_{nk} = [b_{1k}, b_{2k}]^T$, $C_k = \begin{bmatrix} c_{1k} & 0 \\ 0 & c_{2k} \end{bmatrix}$ and $\mathcal{C}_k = \begin{bmatrix} 0 & -c_{1k} \\ -c_{2k} & 0 \end{bmatrix}$, and $\nu_n(i) = [w_n^T(2i-1), w_n^T(2i)]^T$. If we stack all the received data samples from the antenna array, we can obtain [5, 7]

$$y(i) = \sum_{k=1}^{K} \sqrt{\rho_k} [g_k b_k(2i-1) + \bar{g}_k b_k(2i)] + \nu(i)$$

(4)

where $y(i) = [y_1^T(i) \ldots y_N^T(i)]^T$, $g_k = D_k h$ and $\bar{g}_k = \mathcal{D}_k h^*$ are the composite signature vectors for user $k$ comprising the channel vector and the assigned spreading code, in which $D_k = I_N \otimes C_k$, $\mathcal{D}_k = I_N \otimes \mathcal{C}_k$, $h = [h_1^T \ldots h_N^T]^T$ is the channel vector form the two transmit antennas to the $N$ receive antennas, and $\otimes$ denotes the Kronecker product [11], and $\nu(i) = [\nu_1^T(i) \ldots \nu_N^T(i)]^T$. In what follows, our objective is to design a receiver that can suppress the MAI to render superior performance.

III. PROPOSED CDF GSC-BASED RECEIVER

To enhance the performance of the Capon receiver considered in [5], in what follows we consider a GSC-based receiver, as shown in Fig. 1, which makes use not only the space diversity and the temporal diversity, but also the Alamouti STBC through the use of a new cross decision feedback scheme.

Due to the use of the Alamouti STBC, the new receiver, as [7], consists of two GSC-based branches, each of which is intended to capture one of the transmitted symbol in (4). For brevity in the following discussion, we only consider the analysis for the signals in the lower branch as the analysis for the upper branch follows closely. To obtain the transmitted $b(2i-1)$, the constrain matrix $\mathcal{C}$ for this GSC is chosen as the $J \times 1$ matrix $[g_1]$. The signal blocking matrix $B = \mathcal{C}^H$ is the orthogonal complement of $\mathcal{C}$, which implies that $b(2i-1)$ is annihilated by $B$ and only interference passes through the lower branch of this GSC, and $w_q = \mathcal{C}(\mathcal{C}^H)^{-1}$. To determine the filters and the feedback taps, we consider the cost function given by

$$\Lambda = E\{|w^H y(i) - w^H b(2i) - w^H b(2i-1)|^2\}$$

(5)

where $w = w_q - B w_q$, $w_q$ and $w_c$ are the direct and cross feedback tap weights, respectively, and $b(2i-1)$ and $b(2i)$ are the detected symbols. In the following analysis, for brevity we assume that the decision is correct, i.e., $b(2i-1) = b(2i-1)$ and $b(2i) = b(2i)$, which are then independent by assumption. Therefore, the cost function in (5) can be re-written as

$$\Lambda = E\{e_c(i) e_c^H(i) \} - E\{e_c(i) b^H(2i-1) w_b \} - w^H_b E\{b(2i-1) y^H(i)\} w + w^H b^H \sigma_b^2 w_b$$

(6)

where $e_c(i) = w^H y(i) - w^H b(2i)$ and $\sigma_b^2 = E\{b(2i-1) b^H(2i-1)\}$. Substituting (4) into (6), $E\{b(2i-1) y^H(i)\}$ can be simplified as

$$E\{b(2i-1) y^H(i)\} = \sqrt{\rho_i} \sigma_b^2 b_i^H$$

(7)
Substituting (7) into (6), and setting the gradient of (6) with respect to \( w_b \) to zero yields
\[
\dot{w}_b = \sqrt{\rho_1} g_i^H w_q
\]
where we have used the facts that \( B^H R_b = 0 \) and (7).
To design the filter \( w_a \) and \( w_c \), by substituting \( w = w_q - B w_a \) into (5), the cost function can be re-written as
\[
\Lambda = E(\{e_a(i) - w_a^H z(i)\}^2)
\]
where \( e_a(i) = w_q^H y(i) - w_b^H b(2i - 1) \), \( w_a = [w_a, w_c] \), and \( z(i) = [B^H R_b b(2i)] \).
To solve for the optimum solution of \( w_{ac} \), setting the gradient of (9) with respect to \( w_{ac} \) to zero yields
\[
w_{ac,opt} = \left[ \frac{E(z(i) e_{ac}^H(i))}{\sigma_{ac}^2} \right]
\]
where \( R_z = E[\{z(i) \}^2] \) and after some manipulations can be re-expressed as
\[
R_z = \begin{bmatrix} \frac{B^H R_b B}{\sigma_{ac}^2} \frac{\sqrt{\rho_1} \sigma_b^2}{\sigma_{ac}^2} B^H \mathbf{g}_1 \end{bmatrix}
\]
where \( \sigma_b^2 = E\{b(2i) b^H(2i)\} \) and \( R_y = E\{y(i) y^H(i)\} = R_b + R_c + R_{ac} \), in which we have used the independence among transmitted symbols and noise. \( R_y = E\{(\sqrt{\rho_1} \mathbf{g}_1 b(2i - 1)) (\sqrt{\rho_1} \mathbf{g}_1 b(2i - 1))^H\} = \rho_1 \sigma_b^2 \mathbf{g}_1 \mathbf{g}_1^H \).
\( R_{ac} = E\{(\sqrt{\rho_1} \mathbf{g}_1 b(2i)) (\sqrt{\rho_1} \mathbf{g}_1 b(2i))^H\} = \rho_1 \sigma_{ac}^2 \mathbf{g}_1 \mathbf{g}_1^H \) and \( R_b = E\{v(1) v^H(1)\} \) and we have used the fact that \( E\{y(i) b^H(2i)\} = \sqrt{\rho_1} \sigma_b^2 \mathbf{g}_1 \) by (4). Consequently, \( E[\{z(i) e_{ac}^H(i)\}] \) can be re-written as
\[
E[\{z(i) e_{ac}^H(i)\}] = \begin{bmatrix} B^H R_b w_q - E\{B^H y(i) b^H(2i - 1)\} w_b \\ 0 \\ E\{b(2i) y^H(i)\} w_q - E\{b(2i) b^H(2i - 1)\} w_b \\ 0 \end{bmatrix}
\]
where we make use the fact that \( B^H y(i) \) and \( b(2i - 1) \) are independent, i.e., \( E\{B^H y(i) b^H(2i - 1)\} = 0 \), as \( b(2i - 1) \) has been blocked by \( B \).
Moreover, using the matrix lemma [11], the inverse of (11) can be expressed as
\[
R_z^{-1} = \begin{bmatrix} A^{-1} \\ -\sqrt{\rho_1} A^{-1} B^H \mathbf{g}_1 \\ -\sigma_{ac}^{-2} + \rho_1 \sigma_{ac}^2 B^H \mathbf{g}_1 \end{bmatrix}
\]
where \( A = B^H R_b B \), in which \( R_b = E\{v(1) v^H(1)\} \). Substituting (13) and (12) into (10) gives rise to
\[
w_{a,opt} = (B^H R_b B)^{-1} B^H R_b w_q
\]
and \( w_{c,opt} = \sqrt{\rho_1} \sigma_{ac}^2 w_q - B w_{a,opt} \)
To accommodate the nonstationary environment, \( w_a \) as well as the tap weights should be able to adaptively adjust according to the change of the outside environment. In light of this, based on the renowned LMS algorithm, they can be recursively updated by
\[
w_a(i + 1) = w_a(i) + \mu_2 B^H y(i) e_a^\ast(i)
\]
\[
w_b(i + 1) = w_b(i) + \mu_3 b(2i - 1) e_b^\ast(i)
\]
and \( w_c(i + 1) = w_c(i) + \mu_4 b(2i) e_c^\ast(i) \)
where \( e_a(i) = \sqrt{\rho_1} B y(i) - \sqrt{\rho_1} b(2i) b(2i - 1) e_c^\ast(i) = w_q^H y(i) - w_b^H b(2i) \), and \( \mu_2, \mu_3, \mu_4 \) are the corresponding step sizes.

### IV. Performance Analysis

In this section, we determine the MMSE of the proposed GSC-based Capon receiver with and without the CDF. Note that the resulting MMSE at the output of the lower branch of the GSC, MMSE\(^{DF} \), can be expressed as
\[
\text{MMSE}^{DF} = E\{|w_{opt}^H y(i) - w_{c,opt}^H b(2i)|^2\}
\]
\[
= w_{opt}^H R_y w_{opt} - w_{opt}^H E\{y(i) b^H(2i)\} w_{c,opt} - w_{c,opt}^H E\{b(2i) y^H(i)\} w_{opt} + 2 w_{opt}^H R_{yw} w_{c,opt}
\]
where the second term and the last term of which, with the substitution of (15), can be simplified, respectively, as
\[
w_{opt}^H E\{y(i) b^H(2i)\} w_{c,opt} = \text{MMSE}^{DF} R_{yw} w_{opt}
\]
\[
w_{c,opt}^H w_{opt} = w_{opt}^H R_{yw} w_{opt}
\]
Substituting (21) into (20), MMSE\(^{CDF} \) can be re-written as
\[
\text{MMSE}^{CDF} = w_{opt}^H R_y w_{opt} - w_{opt}^H R_{yw} w_{opt}
\]
Comparing (22) with (19), we then arrive at
\[
\text{MMSE}^{DF} = \text{MMSE}^{CDF} + w_{opt}^H R_{yw} w_{opt}
\]
where \( w_{opt}^H R_{yw} w_{opt} \) is the output power from the output signal from the upper GSC branch of the receiver and is always greater than zero. Therefore, we have
\[
\text{MMSE}^{CDF} \leq \text{MMSE}^{DF}
\]
which implies that the MMSE will be further reduced by incorporating such a new decision feedback and, as shown in the following simulation, provides the receiver with a better interference suppression capability.
V. SIMULATIONS AND DISCUSSIONS

Simulations are conducted in this section to assess the new receiver. Consider a five-user and uses the Alamouti STBC MIMO CDMA system equipped with 2 transmit and receive antennas. The length of the PN signature sequence, \( J \), is 16. The transmit symbol are based on BPSK modulation. The channel is complex Gaussian random variable with zero-mean and unit-variance and the noise is addition white Gaussian noise (AWGN). Three GSC-based Capon receivers are carried out for comparison, including the Capon receiver in [5] (non-blind and implemented using the GSC), the Capon receiver with the classical DF [9], and the proposed Capon receiver with the CDF. For all three receivers, the constraints are all based on the composite signature vectors of the desired user which are assumed to be known at the receiver.

First, we compare the convergence characteristics of these three receivers at SNR=10 dB by using the same step sizes int the LMS algorithms, as shown in Fig. 2, from which we can observe that the Capon receiver in corporation with the DF renders faster convergence rate. Using the CDF, the receiver can achieve fastest convergence rate. Moreover, as analyzed in Sec. IV, it also attains the smallest MMSE and thus better performance as discussed next.

Next, we compare the BER versus the SNR based on the aforementioned three receivers after convergence, as shown in Fig. 2. We can observe form Fig. 3 that with the DF, the performance of the Capon receiver can be enhanced by employing the time diversity to attain better interference cancellation. Also, the proposed Capon receiver with the CDF yields the most superior performance by combing the DF with the STBC to render more thorough interference cancellation at the output of the GSCs.

VI. CONCLUSION

This paper addresses a new GSC-based Capon multuser receiver for the Alamouti STBC MIMO CDMA systems, which exploits both the space diversity and the time diversity along with the transmit diversity by making using of both outputs of the GSCs as the decision feedback. As such, the desired signal will be annihilated more thoroughly after the blocking matrix to attain better interference suppression. Simulations show that the new receiver can not only attain superior performance compared with previous works, but also possess faster convergence characteristics.

REFERENCES