Iterative Frequency-Domain Detection for IA-Precoded MC-CDMA Systems

Adão Silva, *Member, IEEE*, Sara Teodoro, Rui Dinis, *Member, IEEE*, and Atílio Gameiro

Abstract—Interference alignment (IA) is a promising technique that allows high capacity gains in interfering channels. On the other hand, iterative frequency-domain detection receivers based on the IB-DFE concept (Iterative Block Decision Feedback Equalization) can efficiently exploit the inherent space-frequency diversity of the MIMO MC-CDMA systems. In this paper we combine iterative IA precoding at the transmitter with IB-DFE based processing at the receiver for MC-CDMA systems. The receiver is designed in two steps: first a linear filter is used to mitigate the inter-user aligned interference, and then an iterative frequency-domain receiver is designed to efficiently separate the spatial streams in the presence of residual inter-user aligned interference at the output of the filter. The matrices for this non-linear space-frequency equalizer are obtained by minimizing the overall mean square error (MSE) of all data streams at each subcarrier. Our receiver structure is explicitly designed taking into account the residual inter-user interference, allowing both an efficient separation of the spatial streams and a reduction in the number of iterations of the IA procedure. We also propose a simple, yet accurate analytical approach for obtaining the performance of the proposed receiver structure. Our scheme achieves the maximum degrees of freedom provided by the IA precoding, while allowing an almost optimum space-diversity gain, with performance close to the matched filter bound (MFB).

Index Terms—Interference alignment, interference channels, iterative block equalization, MC-CDMA systems.

I. INTRODUCTION

THE increasing demand for wireless services has created the need for cost effective transmission techniques that can exploit scarce spectral resources efficiently. To achieve the high bit rates needed to meet the quality of service requirements of future multimedia applications, multi-carrier code division multiple access (MC-CDMA) has been considered as good air-interface candidate, especially for the downlink [1], [2]. This scheme combines efficiently orthogonal frequency division multiplex (OFDM) and CDMA.

Therefore, MC-CDMA benefits from OFDM characteristics such as high spectral efficiency and robustness against multipath propagation, while CDMA allows a flexible multiple access with good interference properties [3], [4]. However, the user capacity of MC-CDMA system is essentially limited

by interference. This interference can be mitigated by employing precoding techniques [5], [6], iterative block decision feedback equalization (IB-DFE) based receivers [7], [8] and other efficient interference suppression techniques, proposed for different scenarios [9], [10], [11], [12].

Conventional frequency domain equalization (FDE) schemes employ a linear FDE optimized under the minimum mean square error (MMSE) criterion. However, the residual interference levels might still be too high, leading to performance that is still several dB from the matched filter bound (MFB) [13]. Nonlinear time-domain equalizers are known to outperform linear equalizers and conventional, time-domain DFEs are known to have good performance-complexity tradeoffs [14]. For this reason, there has been significant interest in the design of nonlinear FDEs in general and frequency-domain FDEs in particular, with the IB-DFE being the most promising nonlinear FDE [13]. IB-DFE was originally proposed in [15] and was extended for a wide range of scenarios in the last 10 years, ranging from diversity scenarios [16], [17], MIMO systems [18] and MC-CDMA systems [19], [20], among many other. Essentially, the IB-DFE can be regarded as a low complexity turbo equalizer implemented in the frequency-domain that does not require the channel decoder output in the feedback loop, although true turbo equalizers based on the IB-DFE concept can also be designed [21], [22]. An IB-DFE-based scheme specially designed for offset constellations (e.g. OQPSK, and OQAM) was also proposed in [23]. In the context of cooperative systems, an IB-DFE approach was derived to separate the quantized received signals from the different BSs [24].

Recently, analysis of interference channels has shown that each users' capacity on an interference channel is one half the rate of its interference-free capacity in the high transmit power regime, regardless of the number of users [25]. One interesting scheme to efficiently eliminate the inter-user interference and achieve a linear capacity scaling is interference alignment (IA) [25]. This recent technique allows the transmitters to align in the unwanted users' receive signals in any dimension, through the use of precoders. With this strategy more interferers can be completely cancelled than with other interference cancellation methods, thus achieving the maximum degrees of freedom (DoF) [26]. Applications of IA include cellular networks, two-way communication networks, cooperative communication networks, cognitive radio networks, etc. [27]. An explicit formulation of the precoding vectors achieving IA for time or frequency selectivity channels has been presented in [25]. A two-stage optimization of the precoding and decoding matrices in the 3-MIMO constant interference channels was proposed

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A. Silva, S. Teodoro, and Atílio Gameiro are with DETI, Instituto de Telecomunicações, University of Aveiro, Aveiro, Portugal (e-mail: {asilva, steodoro, atilio}@av.it.pt).

R. Dinis is with Instituto de Telecomunicações, Faculdade de Ciências e Tecnologia, University Nova de Lisboa, Lisbon, Portugal (e-mail: rdinis@fct.unl.pt).

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in [28]. As closed-form solution for constant channels is still unknown except with 3 users, iterative algorithms [29]–[31] have been proposed for an arbitrary number of transmitter-receiver pairs. In [29] some examples of iterative algorithms were presented, where advantage of the reciprocity of wireless networks to achieve interference alignment with only local channel state information (CSI) knowledge at each node is taken. An MMSE-based iterative IA scheme was proposed in [30]. Several iterative linear precoding designs using alternating minimization were proposed in [31]. Most of these iterative algorithms require significant number of iteration to align the inter-user interference and exchange of information between the transmitter-receiver pairs at each step [31]. An overview of practical issues including performance in realistic propagation environments, the role of CSI at transmitter, and the practicality of IA in large networks was given in [32].

In this paper we consider MIMO MC-CDMA systems with iterative IA precoding at transmitter and iterative frequency-domain receivers based on the IB-DFE concept. To the best of our knowledge joint IA-precoding and IB-DFE based equalizer for MC-CDMA systems has not been addressed in the literature. The main motivation to consider this combination, is that IA based techniques achieve the maximum DoF in MIMO interference channels. However, they cannot by themselves efficiently exploit the space-frequency diversity inherent of the MIMO MC-CDMA systems. On the other hand, IB-DFE based receivers are well known to be one of the most efficient techniques to exploit this space-frequency diversity. Therefore, this combination allows us to design a system that is able to achieve maximum DoF (number of spatial stream per subcarrier) and exploit the high diversity order inherent to these systems. In the proposed scheme the chips are IA-precoded instead of the data symbols as in narrowband or OFDM-based systems. The proposed receiver structure is designed in two steps: first a linear filter is used to mitigate the inter-user aligned interference, and then an IB-DFE based equalizer is employed to efficiently separate the spatial streams. The matrices for this non-linear space-frequency equalizer are obtained by minimizing the overall mean square error (MSE) of all data streams at each subcarrier. In the design of the equalizer, we explicitly take into account the residual inter-user interference, allowing not only an efficient separation of the spatial streams but also a reduction the number of iteration in the IA procedure, and thus also reducing the information needed to be exchanged between the different transmitter-receiver pairs. Furthermore, we propose a simple, yet accurate analytical approach for obtaining the performance of the proposed receiver structure.

The remainder of the paper is organized as follows: Section II presents the MIMO IA-precoded MC-CDMA system model. Section III, starts by briefly presenting the iterative IA-precoding considered in this paper. Then, the proposed receiver structure is presented in detail and an analytical approach for obtaining the performance is discussed. Section IV presents the main performance results, both numerical and analytical. The conclusions will be drawn in Section V.

Notation: Throughout this paper, we will use the following notations. Lowercase letters, boldface lowercase letters and boldface uppercase letters are used for scalars, vectors and

matrices, respectively. $(\cdot)^H$, $(\cdot)^T$, and $(\cdot)^*$ represents the complex conjugate transpose, transpose, and complex conjugate operators, $E[\cdot]$ represents the expectation operator, $\mathbf{I}_N$ is the identity matrix of size $N \times N$, $CN(\cdot, \cdot)$ denotes a circular symmetric complex Gaussian vector, $\{\alpha\}$ represents a L -length block, $\text{tr}(\mathbf{A})$ is the trace of matrix $\mathbf{A}$, and $v_{\min}^P(\mathbf{A})$ is the matrix whose columns are the eigenvectors corresponding to the P smallest eigenvalues of matrix $\mathbf{A}$.

II. SYSTEM MODEL

We consider a K -user MIMO interference channel with constant coefficients on a per-subcarrier basis. It comprises K transmitter-receiver pairs sharing the same physical channel, where a given transmitter only intends to have its P_k spatial data symbols on each subcarrier decoded by a single receiver. Without loss of generality, we consider a symmetric case where all transmitters and receivers have M antennas, and $P_k = P \forall k$, which is denoted by an (M, M, K) interference channel with P data symbols per-subcarrier. It has been shown that for $K \leq 3$, the number of spatial DoF achievable in an (M, M, K) interference channel is $KM/2$, while for $K > 3$ the overall spatial DoF achievable is only $P_t = \sum_{k=1}^K P_k < 2M - 1$ [33]. Therefore, our system achieves $KM/2$ and P_t spatial DoF per-subcarrier for $K \leq 3$ and $K > 3$, respectively. Fig. 1 shows the proposed k th MC-CDMA based transmitter. As can be seen, each one of the P L -length data symbols blocks, $\{d_{k,p,l}; k = 1, \dots, K, p = 1, \dots, P, l = 0, \dots, L - 1\}$, where the constellation symbol $d_{k,p,l}$ (with $E[|d_{k,p,l}|^2] = \sigma_d^2$) is selected from the data according to given mapping rule, is spread into L chips using orthogonal Walsh-Hadamard codes, leading to the block $\{s_{k,p,l}; p = 1, \dots, P, l = 0, \dots, L - 1\}$. Then, a set of P chips (one of each block) is weighted by an IA-precoding matrix. Note that here the IA-precoding is applied on a chip level instead of data level as in the conventional IA systems. The signal after the IA precoding at the k th transmitter subcarrier l can be written as

$$\mathbf{x}_{k,l} = \mathbf{W}_{k,l} \mathbf{s}_{k,l}, \quad (1)$$

where $\mathbf{W}_{k,l} \in \mathbb{C}^{M \times P}$ is the linear precoding matrix computed at the k th transmitter on subcarrier l , constrained to $\|\mathbf{W}_{k,l}\|_F^2 \leq T_p$ and T_p is the transmit power at the transmitters, with $\mathbf{s}_{k,l} = [s_{k,1,l} \ \dots \ s_{k,P,l}]^T$. Finally, the precoding signals are mapped into the OFDM symbol and the cyclic prefix (CP) is inserted.

The received frequency-domain signal (i.e., after cyclic prefix removal and FFT operation) for the k th receiver and the l th subcarrier is given by

$$\mathbf{y}_{k,l} = \mathbf{H}_{k,k,l} \mathbf{W}_{k,l} \mathbf{s}_{k,l} + \sum_{\substack{j=1 \\ j \neq k}}^K \mathbf{H}_{k,j,l} \mathbf{W}_{j,l} \mathbf{s}_{j,l} + \mathbf{n}_{k,l}, \quad (2)$$

provided that the cyclic prefix is long enough to account for different overall channel impulse responses between the transmitters and the receivers (i.e., including transmit and receive filters, multipath propagation effects and differences in the time-of-arrival for different transmitter-to-receiver links).