Interference Suppression with joint Pre-distortion filtering and Selective Transmit Diversity

Mário Marques da Silva, Américo M. C. Correia
ADETTI
IST, Torre Norte 11.10, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
marquesilva@mail.telepac.pt

Abstract

It is intended to specify the pre-distortion (PD) filtering technique, which can be used to combat the Multiple Access Interference (MAI), combined with a variation of the Selective Transmit Diversity (STD) for high data rate transmissions over frequency selective Rayleigh fading channels.

By pre-distorting the signals to be transmitted by the Base Station (BS) with a Minimum Variance (MV) algorithm, the orthogonality between the desired signal and all interfering signals can be improved. We combine the PD with a variation of the conventional STD, which is optimized for the proposed pre-distortion scheme, allowing an increase in the reduction of MAI and combating the fading. Both schemes are closed loop systems with Feedback Indication (FBI). The increase in performance is achieved with an increase in power processing in the BS, avoiding any need to increase complexity in the Mobile Station (MS).

Keywords – W-CDMA, MAI Cancellation, Pre-distortion filtering, Selective Transmit Diversity

I. INTRODUCTION

The current paper specifies the PD filter, combined with STD, which combats both MAI and fading.

With the aid of pre-distorting the signals to be transmitted by the BS, the orthogonality between the signals seen by the different users can be improved [1][2]. Additionally, the loss of orthogonality that happens in the reference user due to the Inter-Path Interference (IPI) can be reduced, thus, leading to an increase in performance. The PD is done taking into account the spreading sequences of the different users present in the cell and the Channel State Information (CSI) between the BS and the several MS, therefore, it is considered a closed loop system with FBI. For this reason, we combined this technique with a variation of the conventional STD, optimized to work with the PD, which is also a closed loop system, leading to a performance improvement over the PD alone.

This paper is structured as follows. Section II presents the system models for the PD filtering and STD. Section III presents the performance results and analysis for the proposed schemes. The key findings of this paper are then summarized in Section IV.

II. SYSTEM MODELS FOR THE PRE-DISTORTION FILTER AND STD

A. System Model for the Pre-distortion filter

It is considered a DS-CDMA network, in the downlink direction, where users are synchronous but whose signals suffers of frequency selective Rayleigh fading. It is considered a reference user receiving from the BS in the presence of several interfering users from the same BS, which originate MAI.

With this scheme, the loss of orthogonality in the MS due to different spreading sequences can be reduced, so as the loss of orthogonality due to IPI terms (both caused by the reference and interfering users). These are the cross-correlations that we intend to estimate and to minimize by pre-distorting the signals, before transmission, in the BS.

The PD is done taking into account the spreading sequences of the different users in the cell and the Channel Impulse Response (CIR) between the BS and the several MS.

The proposed system is shown in the Figure 1, where the PD filter is included in the CDMA-QPSK modulator of the BS, jointly with STD, which is also a closed loop system.

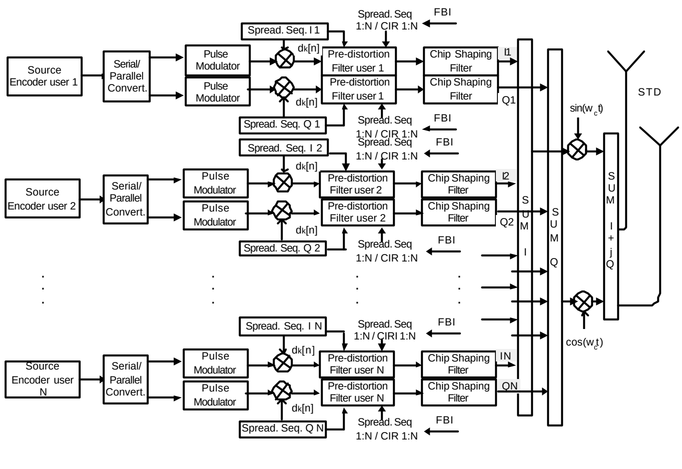

Fig. 1 Scheme of a CDMA-QPSK modulator with combined pre-distortion filter and STD

The PD filter is implemented based on the Finite Impulse Response (FIR) philosophy. Only a simple correlator is used for the receiver filter, in the MS, because the considered approach is based in avoiding cross-correlation. The proposed transmitter filter is:

$$g_q = \left[g_q[0]\, g_q[1] \cdots g_q\left[L_g - 1\right] \right]^T \qquad (1)$$

In order to find the filter coefficients we will develop the proper matrix-vector representation. The purpose of the transmitter filter is to change the CIR to combat the interference. The CIR matrix with the FIR vector $\mathbf{h_q} = \left[h_q[0] \cdots h_q[M-1] \right]^T$ is a Toeplitz matrix and is written as:

$$\mathbf{H_q} = \mathcal{T}\left(\mathbf{h_q};\mathbf{L_g}\right) \tag{2}$$

where $\mathcal{T}\left(\mathbf{h_q};\mathbf{L_g}\right)$ means the Toeplitz matrix with vector $x = \left[x_1\ x_2 \cdots x_r \right]$, which is defined as:

$$\mathcal{T}(x;L) = \begin{bmatrix} x_1 & & \mathbf{0}_{r+L-1} \\ \vdots & \ddots & x_1 \\ \vdots & & \vdots \\ \vdots & & \vdots \\ x_r & & \vdots \\ & \ddots & \\ \mathbf{0}_{r+L-1} & \cdots & x_r \end{bmatrix} \tag{3}$$

being $\mathbf{0}_r$ the $r \times 1$ column vector of all zero elements. We define the received signal $s_{q,k}[n]$ at the q[th] MS due to the k[th] transmission as [1]:

$$s_{q,k}[m] = \left[s_{q,k}[mN]\, s_{q,k}[mN+1] \cdots s_{q,k}\left[(m+1)N + L_0 - 2 \right] \right]^T \tag{4}$$

being $L_0 = M + L_g - 1$, and being M the maximum delay spread expressed in number of chips (or in number of samples per chip, in case of a sampled version of the filter) and L_g the length of the FIR. We assume that $N > L_0 = M + L_g - 1$, which means that the maximum delay spread should be smaller than the symbol duration, being true when the processing gain (N) is large enough.

The vector $s_{q,k}[m]$ can be decomposed as [1]:

$$s_{q,k}[m] = \mathbf{C}_k^{(0)}\mathbf{H}_q\mathbf{g}_k b_k[m] + \mathbf{C}_k^{(-1)}\mathbf{H}_q\mathbf{g}_k b_k[m-1] + \mathbf{C}_k^{(1)}\mathbf{H}_q\mathbf{g}_k b_k[m+1] \tag{5}$$

where the matrix $\mathbf{C}_k^{(0)}[m]$ of size $(N + L_0 - 1) \times L_0$ is written as:

$$\mathbf{C}_k^{(0)}[m] = \mathcal{T}\left(\mathbf{C}_k^{(0)};\mathbf{L}_0\right) \tag{6}$$

and where $c_k = \left[c_k[0]\ c_k[1] \cdots c_k[N-1] \right]^T$. In addition, the two matrices $\mathbf{C}_k^{(-1)}$ and $\mathbf{C}_k^{(1)}$ are written as:

$$\mathbf{C}_k^{(-1)} = \begin{bmatrix} 0 & c_k[N-1] & \cdots & c_k[N-L_0+1] \\ \vdots & & \cdots & \vdots \\ \vdots & & & c_k[N-1] \\ 0_N & 0_N & \cdots & 0_N \end{bmatrix} \tag{7}$$

$$\mathbf{C}_k^{(1)} = \begin{bmatrix} 0_N & \cdots & 0_N & 0_N \\ c_k[0] & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ c_k[L_0-2] & \cdots & c_k[0] & 0 \end{bmatrix}$$

When we consider a sampled version of the PD filter, the value N in (6) and (7) should be replaced by $N \times sampling\,rate$, to be in accordance with proper sampled version of the CIR, defined in (2). In (5) $\mathbf{C}_k^{(-1)}\mathbf{H}_q\mathbf{g}_k b_k[m-1]$ and $\mathbf{C}_k^{(1)}\mathbf{H}_q\mathbf{g}_k b_k[m+1]$ are IPI vectors. $\mathbf{C}_k^{(-1)}$ and $\mathbf{C}_k^{(1)}$ contain many zeros because the downlink transmissions are synchronized, and hence, we can usually ignore the two IPI vectors. Additionally, if N is not small, the IPI vectors cannot be ignored. If N is smaller than L_0, we need to take into account more IPI vectors.

Ignoring the IPI vectors, the received signal at the input of the q[th] MS, from all K transmissions, is defined as [1]:

$$s_q[m] = \sum_{k=1}^{K} s_{q,k}[m] + h_q[m] \tag{8}$$

being h_q the background noise seen by the MS. To find the impulse response of the filter, the BS should have knowledge about the spreading sequences of all MS. The received signal at the output of the q[th] MS (correlator) is:

$$\begin{aligned} y_q[m] &= \mathbf{c}_{q,(c)}^H\left(\sum_{k=1}^{K} s_{q,k}[m] + h_q[m]\right) \\ &= \sum_{k=1}^{K}\sum_{i=-1}^{1}\left(\mathbf{v}_{q,k}^{(i)}\right)^H \mathbf{H}_q g_k b_k[m+i] + \overline{h}_q[m] \end{aligned} \tag{9}$$

being the filter vector for the receiver filter $\mathbf{c}_{q,(c)}$ the c^{th} column (reference delay which affects the performance) of the vector $\mathbf{c}_q^{(0)}$. We define $\mathbf{v}_{q,k}^{(i)}$ as the cross-correlation between the spreading sequence of the reference q[th] user and the spreading sequence of some k[th] interfering user, without taking into account the CIR's as:

$$\mathbf{v}_{q,k}^{(i)} = \left(\mathbf{C}_k^{(i)}\right)^H \mathbf{c}_{q,(c)} \tag{10}$$

where $\overline{h}_q[m] = c_{q,(c)}^H h_q[m]$. Additionally, we define $\mathbf{w}_{q,k}^{(i)}$ as:

$$\mathbf{w}_{q,k}^{(i)} = \mathbf{H}_q^H \mathbf{v}_{q,k}^{(i)} \tag{11}$$

The received signal can be rewritten as:

$$y_q[m] = \sum_{k=1}^{K}\sum_{i=-1}^{1}\left(\mathbf{w}_{q,k}^{(i)}\right)^H \mathbf{g}_k b_k[m+i] + \overline{h}_q[m] \tag{12}$$

At the k[th] MS, the interfering signals due to the q[th] signals are given as $\left(\mathbf{w}_{k,q}^{(i)}\right)^H \mathbf{g}_q b_q[m+i],\ i = -1, 0, 1$. The total sum of interfering signals to other MS, including IPI terms due to the q[th] signals comes:

$$\mathbf{v}_q[m] = \sum_{k \neq q}\sum_{i=-1}^{1}\left(\mathbf{w}_{k,q}^{(i)}\right)^H \mathbf{g}_q b_q[m] + \left(\mathbf{w}_{k,q}^{(-1)}\right)^H \mathbf{g}_q b_q[m-1] + \left(\mathbf{w}_{k,q}^{(1)}\right)^H \mathbf{g}_q b_q[m+1] \tag{13}$$

In order to mitigate the interference, the filtering vector $\mathbf{g}_q$ should be calculated to minimize $E\left[\left\|\mathbf{v}_k[m]\right\|^2\right]$, while providing distortionless response to the q[th] MS (reference user). The optimization based on the Minimum Variance of Interfering Signals to Others (MVISO) algorithm is to find $\mathbf{g}_q$ with the following constraints:

$$\begin{aligned} &\min_{g_q}\ E\left[\left\|\mathbf{v}_q[m]\right\|^2\right] \\ &\textit{subject to}\ \mathbf{w}_q^H \mathbf{g}_q = 1 \end{aligned} \tag{14}$$

where $\mathbf{w}_q = \mathbf{w}_{q,q}^{(0)}$. There is a closed-form solution for the optimal filtering vector under the MVISO criterion in (14). From (13) it comes [1]:

$$E\left[\left\|\mathbf{v}_k[m]\right\|^2\right] = \mathbf{g}_q^H\left(\sum_{k \neq q}\sum_{i=-1}^{1}\mathbf{w}_{k,q}^{(i)}\left(\mathbf{w}_{k,q}^{(i)}\right)^H + \mathbf{w}_{q,q}^{(-1)}\left(\mathbf{w}_{q,q}^{(-1)}\right)^H + \mathbf{w}_{q,q}^{(1)}\left(\mathbf{w}_{q,q}^{(1)}\right)^H\right)\mathbf{g}_q \tag{15}$$

Considering

$$\overline{\mathbf{W}}_q = \left(\sum_{k \neq q} \sum_{i=-1}^{1} \mathbf{w}_{k,q}^{(i)} \left(\mathbf{w}_{k,q}^{(i)} \right)^H + \mathbf{w}_{q,q}^{(-1)} \left(\mathbf{w}_{q,q}^{(-1)} \right)^H + \mathbf{w}_{q,q}^{(1)} \left(\mathbf{w}_{q,q}^{(1)} \right)^H \right) \quad (16)$$

and using the method of Lagrange multiplier, the optimal vector under the MVISO criterion comes:

$$g_q = \frac{\overline{\mathbf{W}}_q^{-1} \mathbf{w}_q}{\mathbf{w}_q^H \overline{\mathbf{W}}_q^{-1} \mathbf{w}_q}, \; q = 1, 2, \ldots, K \quad (17)$$

B. *System Model for STD*

In typical frequency or time diversity the same signal is transmitted over different carrier frequencies or time slots. This results in a decrease of the number of bits per Hertz and a consequent loss in spectral efficiency. To maintain a high spectral efficiency, frequency or time diversity should be based on the transmission of different information symbols over the different frequencies or time slots. When the antennas are spaced sufficiently far apart, the transmission from each antenna undergoes independent fading, and thus, providing transmit diversity without reducing the spectral efficiency.

The block diagram of this scheme is presented in figure 2.

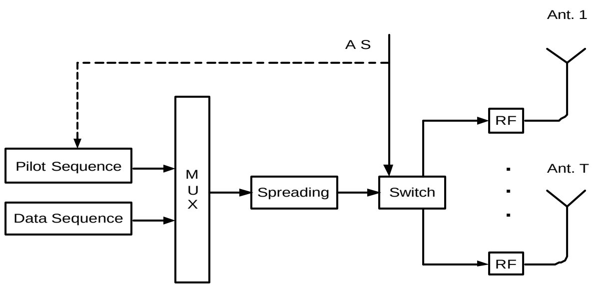

Fig. 2 Scheme of a Selective Transmit Diversity with FBI

The STD scheme has a low rate (750 Hz-3 kHz) feedback link from the receiver (MS) telling the transmitter (BS) which antenna should be used in transmission. There is a common or dedicated pilot sequence, which is transmitted. Different antennas with specific pilot patterns/codes enable antenna selection. Then, the transmitter has a link quality information about the T (number of antennas) links and it transmits a single symbol stream over the best antenna. The receiver is supposed to re-acquire the carrier phase after every switch between antennas. The Antenna Switch (AS) has the capability to switch every slot duration, i.e., 0.667 ms (rate 1.5 kHz).

After using STD from T antennas over the M-paths, each with equal average energy, then we have changed the probability density function for each link. The corresponding BER analytical expression is described in [3].

The decision for the antenna selection of the STD combined with the RAKE receiver (maximize multipath diversity) is done in order to select the channel which maximizes the sum of the square of the absolute values of the paths gains, i.e., to maximize the expression $\max\left(\sum_{m=1}^{M} |h_m|^2\right)$. However, when we deal with the PD filter, we focus on minimizing the cross-correlation, even that created by the multipath fading channel (IPI terms). In this sense, when we consider the PD filter, it makes sense to change the previous expression of the STD and choose one expression (to make the selection decision) where the relationship between the path with maximum power to the sum of the others is higher, and hence, minimizing the IPI terms. The chosen expression was $\max \frac{|h_{\max}|^2}{\left(\sum_{m=2}^{M} |h_m|^2\right)}$. When we combine the PD filtering with STD we conclude that the decision based on the later expression leads to better performance than the first expression because with this strategy we, for one side, select the antenna with maximum gain in the first multipath and, for the other side, avoid the channels where the reflected multipaths are deeper, and hence, it minimizes the cross-correlation caused by the multipath (IPI vectors). The exposed before is not demonstrated in the current paper but it was part of the research developed.

III. NUMERICAL RESULTS

The Monte Carlo approach is taken for the simulations, i.e., drawing a random independent sequence of channel parameters, in accordance with the distribution of these parameters. For each set of drawn parameters the BER (bit error rate) is evaluated and after a sufficiently large number of parameter states (in our case 2^{17}) the estimate of the BER distribution is constructed (we restrict ourselves to the signal to noise ratio interval $E_b / N_0 = [3,12]\,(dB)$).

All the simulation results in this section considered a frequency selective Rayleigh fading channel, namely the Pedestrian A propagation model of 3GPP. The number of antennas considered in the STD was always two. The simulations considered always the PD filter implemented as a FIR with a dimension eight (L_g=8). The processing gain (N) considered was 16, always with four samples per chip, and considering a root raised cosine chip shaping filter with roloff 0.22. The modulation scheme was QPSK.

In figure 3 it is shown the performance results for 12 interfering users. As can be seen both RAKE+STD and PD lead to a performance improvement over the RAKE. With 12 interfering users, the system achieves the best performance for the combination of the PD with STD. This happens because, while the PD avoids the MAI with the reduction of the cross-correlation seen by the reference MS, the STD provides an additional gain due to the transmit diversity, thus, allowing the receiver to select the antenna that presents lower fading. However, the performance improvement achieved with the PD filter is higher than the one achieved with the STD. Additionally, with the PD filter the implementation complexity of the scheme is transferred from the MS to the BS, while with RAKE+STD it considers some level of complexity in the MS because of the RAKE receiver.

When we compare the scheme with and without the PD filter, we conclude that the performance improvement achieved with the PD+STD (related to RAKE+STD) is higher than the performance improvement obtained only with the PD filter (related to the RAKE).

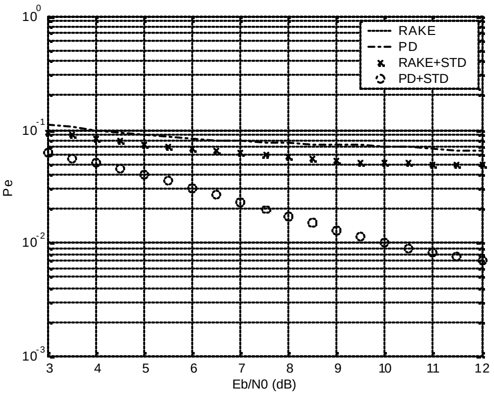

Fig. 3 BER performance with 12 interfering users

In figure 4 it is shown that, for 6 interfering users, the performance achieved with PD is lower than the performance of the RAKE. For the other side, when we consider the PD+STD, the system achieves the best overall performance for higher values of E_b / N_0. For lower number of users the system becomes fading sensitive, instead of MAI sensitive (higher number of users), and hence, the RAKE tends to perform better. The lack of gain achieved with the PD (related to the RAKE) is because the RAKE takes advantage of the multipath fading channel as a form of diversity, thus, recombining the energies in the several fingers. However, as with 12 interfering users, it is shown that the use of STD leads to a performance improvement over the corresponding schemes without.

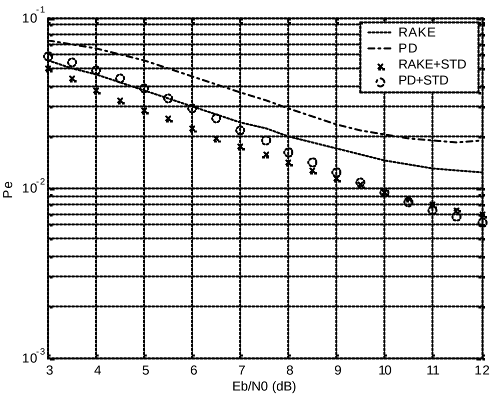

Fig. 4 BER performance with 6 interfering users

Figure 5 presents the results with 3 interfering users. It can be seen that when the number of interfering users is lower, the PD filter (or PD+STD) does not correspond to a performance improvement over the RAKE (or RAKE+STD). The reason for this is because the reference has always a RAKE receiver, and this scheme performs better with lower number of users. For lower number of users the predominant kind of interference is the fading, while for higher number of users the system becomes MAI dependent. For lower number of users the RAKE receiver takes advantage of the multipath environment to provide a kind of diversity, combating the fading effectively. When the number of users is high, the best approach to improve the performance consists in combating the MAI, and hence, the PD seems to provide best results. For the other side, the STD achieves always better performance than the corresponding schemes without STD.

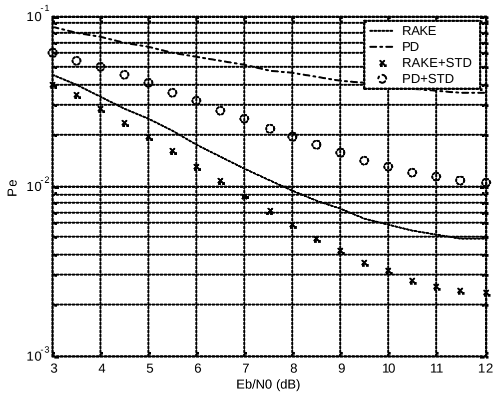

Fig. 5 BER performance with 3 interfering users

IV. CONCLUSIONS

In this document we have presented a combined scheme to combat MAI and fading, which is a power and bandwidth-efficient technique for the Rayleigh fading channel. Two specific schemes, namely, the PD scheme and the STD were introduced. The BER was taken as a figure of merit.

The PD leads to a performance improvement, for higher number for users. When we combine this scheme with the proposed STD (which is a variation of the conventional) the system achieves better performance because this kind of transmit diversity combat the fading and additionally it selects the channel where the IPI vectors are less intense, and hence, it decreases the MAI. Additionally, both PD filtering and STD are closed loop systems with FBI.

For lower number of users the RAKE performs better than the PD because the system is fading dependent, and hence, the RAKE provides a kind of diversity. When the system is MAI dependent (higher number of users), the PD combined with the proposed STD achieves the best performance.

V. REFERENCES

[1] J. Choi, "Interference Mitigation Using Transmitter Filters in CDMA Systems", IEEE Transactions on Vehicular Technology, nº4-Vol.51, July 2002, pp. 657-666;

[2] Stefano Buzzi, H. Vincent Poor, "A Multi-Pass Strategy for Data Detection in Long-Code Downlink CDMA Systems", Proc. of IEEE WPMC'02, 27-30 Oct 2002, Honolulu, Hawaii;

[3] Américo Correia, "Optimised Complex Constellations for Transmission Diversity", Wireless Personal Communications 20, March 2002, Journal of Kluwer Academic Pub, pp. 267-284;

[4] Mário M. Silva., Américo Correia, "MAI Cancellation with Commutation Signaling", Proc. IEEE VTC'00, Tokyo, Japan, Spring 2000;

[5] Mário M. Silva, Américo Correia, “Space Time Block Coding for 4 antennas with coding rate 1”, Proc. of IEEE ISSSTA’02, Sep. 2002, Prague, Check Republic, pp. 318-322;
[6] J. G. Proakis, “Digital Communications”, McGraw Hill 1995;