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BLIND MULTI-USER RECEIVER FOR MIMO-OFDM SYSTEMS

Traian Abrudan *Marius Sirbu* *Visa Koivunen*

Helsinki University of Technology
Signal Processing Laboratory
P.O.Box 3000, 02015-FIN
e-mail: {tabrudan,marius,visa}@wooster.hut.fi

ABSTRACT

This paper addresses the problem of blind multi-user equalization for OFDM. A Vector Constant Modulus Algorithm (VCMA) is developed for a specific Multiple Input-Multiple Output (MIMO) system. The proposed algorithm relies on a *combined criterion*, to cancel both inter-symbol-interference (ISI) and inter-user-interference (IUI). ISI is minimized by using a constant mean block energy criterion, while IUI is reduced by using a decorrelation criterion. Reliable performance is achieved with relatively fast convergence and small steady-state error, as well as low computational complexity.

1. INTRODUCTION

An OFDM signal consists of a relatively very large number of independently modulated subcarriers. From the central limit theorem it follows that for a large number of subcarriers modulated by independent and random data, the resulting signal tends to have a Gaussian probability distribution. The very popular Constant Modulus Algorithm (CMA) [1] fails for nearly Gaussian or super-Gaussian signal. Even if the input symbols belong to a constant modulus constellation, after IDFT operation at the transmitter, the CM property is lost. On the other hand, according to the Parseval's theorem IDFT operation preserves the constant mean block energy property. Therefore, if we have complex input symbols the block energy remains the same after IDFT operation. Vector CMA exploits this property. VCMA has been introduced in [2] for single user case, being applied for shaped constellation. Multi-user schemes have been considered in [4, 5], with the classical CMA, for constant modulus signals and with VCMA in [9], for DS-CDMA systems.

In this paper, we extend the VCMA algorithm for blind multi-user equalization in OFDM. The proposed algorithm operates in a block mode and the equalization is performed in time domain before the DFT operation at the receiver. The underlying VCMA penalizes the deviation of the equalized OFDM block energy from a given dispersion constant. In multi-user case, the problem becomes more difficult, because at the receiver we observe a mixture of user's signals and their delayed versions caused by the multi-path propagation channel. VCMA is not sufficient criterion for equalizing the desired signal in the presence of IUI. Therefore an additional decorrelation criterion is needed to separate the independent data streams. This criterion minimizes the cross-correlation between the output corresponding to one user and the output corresponding to any other user, with its delayed versions caused by the channel ISI. VCMA and the decorrelation criterion are combined to cancel both ISI and IUI, and equalizer coefficients are adjusted according to a stochastic gradient algorithm.

This paper is organized as follows. In Section 2 we define the system model. The algorithm is introduced in Section 3 and simulation results are presented in Section 4. Finally, conclusions are given in Section 5.

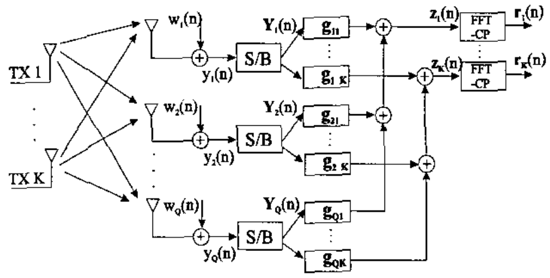

Figure 1. MIMO-OFDM system model

2. SYSTEM MODEL

We consider the MIMO-OFDM system shown in Figure 1. where K users transmit independent and identically distributed (i.i.d.) data streams through a linear spatio-temporal channel. The signals are captured by Q receive antennas. Assuming the IDFT length M, and cyclic prefix of length L, the OFDM block length is $N = M + L$. The sample index is denoted by $(\cdot)$, and the block index by $[\cdot]$. Let us consider the complex data symbols of the k^{th} user, stacked in a vector of length M:

$$\mathbf{s}_k[n] = [s_k(nM), \ldots, s_k(nM + M - 1)]^T, \tag{1}$$

and the $(M \times M)$ normalized IDFT matrix, with entries: $\{\mathbf{F}\}_{m,p} = \frac{1}{\sqrt{M}} e^{j\frac{2\pi}{M}mp}, \quad m, p = 0, \ldots, M-1.$ Then we can write the transmitted OFDM block of the k^{th} user, assuming the multirate filterbank representation [6]:

$$\mathbf{u}_k[n] = \mathbf{T}_{CP}\mathbf{F}\mathbf{s}_k[n], \tag{2}$$

where $\mathbf{T}_{CP}$ is $(N \times M)$ matrix that transforms the $(M \times 1)$ vector $\mathbf{F}\mathbf{s}_k[n]$, into a $N \times 1$ vector:

$$\mathbf{u}_k[n] = [u_k(nN), \ldots, u_k(nN + N - 1)]^T, \tag{3}$$

copying the last L OFDM symbols in the beginning of the block, according to the cyclic prefix addition [7].
The channel impulse responses, between the k^{th} user and the q^{th} receive antenna are denoted by:

$$\mathbf{h}_{kq} = [h_{kq}(0), \ldots, h_{kq}(L_{\text{h}} - 1)]^T. \tag{4}$$

In terms of block transmission [7], the $(N \times N)$ channel convolution matrices $\mathcal{H}^0_{kq}$,$\mathcal{H}^1_{kq}$ between k^{th} user and q^{th} antenna, are:

$$\mathcal{H}^0_{kq} = \begin{bmatrix} h_{kq}(0) & 0 & 0 & \ldots & 0 \\ \vdots & h_{kq}(0) & 0 & \ldots & 0 \\ h_{kq}(L_{\text{h}}-1) & \ddots & \ddots & \ldots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \ldots & h_{kq}(L_{\text{h}}-1) & \ldots & h_{kq}(0) \end{bmatrix} \tag{5}$$

$$\mathcal{H}^1_{kq} = \begin{bmatrix} 0 & \ldots & h_{kq}(L_{\text{h}}-1) & \ldots & h_{kq}(1) \\ \vdots & \ddots & 0 & \ddots & \vdots \\ 0 & \ldots & \ddots & \ldots & h_{kq}(L_{\text{h}}-1) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \ldots & 0 & \ldots & 0 \end{bmatrix}. \tag{6}$$

The matrix $\mathcal{H}^0_{kq}$ models the convolution of the channel with the current transmitted block $\mathbf{u}_k[n]$ and $\mathcal{H}^1_{kq}$ models the effect of the previous OFDM block $\mathbf{u}_k[n-1]$ to the current one, i.e., the inter-block interference. If the guard band interval L is larger than the FIR channel order $L_{\text{h}} - 1$, we do not have any inter-block interference.
In this setup, the noise-free $(N \times 1)$ OFDM block, received at the q^{th} antenna from the k^{th} user, can be written as:

$$\mathbf{y}_{kq}[n] = \mathcal{H}^0_{kq}\mathbf{u}_k[n] + \mathcal{H}^1_{kq}\mathbf{u}_k[n-1]. \tag{7}$$

The superposition of the K users at the q^{th} receive antenna is:

$$\mathbf{y}_q[n] = \sum_{k=1}^{K} \mathbf{y}_{kq}[n] + \mathbf{w}_q[n], \tag{8}$$

where $\mathbf{w}_q[n] = [w_q(nN) \ldots w_q(nN+N-1)]^T$ is the $(N\times 1)$ additive noise vector at the q^{th} antenna. We can write (8) in a matrix form:

$$\begin{aligned} \mathbf{y}_q[n] &= \left[\mathcal{H}^0_{1q} \ldots \mathcal{H}^0_{Kq}\right]\left[\mathbf{u}_1^T[n] \ldots \mathbf{u}_K^T[n]\right]^T + \quad (9) \\ &+ \left[\mathcal{H}^1_{1q} \ldots \mathcal{H}^1_{Kq}\right]\left[\mathbf{u}_1^T[n-1] \ldots \mathbf{u}_K^T[n-1]\right]^T + \mathbf{w}_q[n]. \end{aligned}$$

The adaptive equalizer
VCMA involves a collection of input samples, arranged in a Toeplitz matrix structure (Hankel structure in [2]), which is equivalent to a serial to block conversion, shown in Figure 1. by S/B operation. Considering the current block $\mathbf{y}_q[n]$ and $L_{\text{g}} - 1$ samples from the previous block, we may build the $(L_{\text{g}} \times N)$ VCMA matrix:

$$\mathbf{Y}_q[n] = \begin{bmatrix} y_q(nN) & \ldots & y_q(nN+N-1) \\ y_q(nN-1) & \ldots & y_q(nN+N-2) \\ \vdots & \ldots & \vdots \\ y_q(nN-L_{\text{g}}+2) & \ldots & y_q(nN+N-L_{\text{g}}+1) \\ y_q(nN-L_{\text{g}}+1) & \ldots & y_q(nN+N-L_{\text{g}}) \end{bmatrix},$$

where L_{g} is the length of adaptive equalizer $\mathbf{g}_{qk}$, located in the k^{th} branch of the q^{th} receive antenna (Figure 1.).
The k^{th} user output from the q^{th} sensor is a $(N \times 1)$ vector:

$$\mathbf{z}_{qk}[n] = \mathbf{Y}_q^T[n]\mathbf{g}_{qk}[n], \tag{10}$$

where the equalizer coefficients at the block time instace $[n]$ are $\mathbf{g}_{qk}[n] = [g_{qk}(0) \ldots g_{qk}(L_{\text{g}}-1)]^T$.
The equalized output for the k^{th} user is:

$$\mathbf{z}_k[n] = \sum_{q=1}^{Q} \mathbf{z}_{qk}[n], \tag{11}$$

with $\mathbf{z}_k[n] = [z_k(nN), \ldots, z_k(nN+N-1)]^T$.
By using matrix notation $\mathbf{Z}[n] = \left[\mathbf{z}_1[n] \ldots \mathbf{z}_K[n]\right]$, $\mathbf{Y}[n] = \left[\mathbf{Y}_1^T[n] \ldots \mathbf{Y}_Q^T[n]\right]$ and

$$\mathbf{G}[n] = \begin{bmatrix} \mathbf{g}_{11}[n] & \ldots & \mathbf{g}_{1K}[n] \\ \mathbf{g}_{21}[n] & \ldots & \mathbf{g}_{2K}[n] \\ \vdots & \ldots & \vdots \\ \mathbf{g}_{Q1}[n] & \ldots & \mathbf{g}_{QK}[n] \end{bmatrix}, \tag{12}$$

the $(N \times K)$ equalizer output can be written:

$$\mathbf{Z}[n] = \mathbf{Y}[n]\mathbf{G}[n]. \tag{13}$$

For the k^{th} user, the equalized output, can be written:

$$\mathbf{z}_k[n] = \left[\mathbf{Y}_1^T[n] \ldots \mathbf{Y}_Q^T[n]\right] \begin{bmatrix} \mathbf{g}_{1k}[n] \\ \vdots \\ \mathbf{g}_{Qk}[n] \end{bmatrix} = \mathbf{Y}[n]\mathbf{G}_k[n], \tag{14}$$

where $\mathbf{G}_k[n]$ denotes the k^{th} column of the $(QL_{\text{g}} \times K)$ equalization matrix $\mathbf{G}[n]$.

3. PROPOSED ALGORITHM

The proposed algorithm involves a *composite cost function* which penalizes the deviations of the equalized outputs from VCM property, as well as the cross-correlation between the outputs.
In single user case, VCMA alone is able to equalize Gaussian signals, i.e. to cancel ISI [2, 8]. When multiple users transmit independent Gaussian signals, the resulting mixture has also a Gaussian distribution. The equalizer may converge to the desired signal mixed with copies of other user's signals. In this case the equalizer outputs are correlated to each other, and contain interference (IUI). This leads to a signal separation problem. The classical VCMA cost function can be combined with a decorrelation cost function to cancel both ISI and IUI. Consequently, we arrive to a constrained optimization problem, which will be explained in this section.
Two properties of OFDM signal allow us to apply VCM equalization algorithm: the *constant mean block energy* and the *Gaussianity*. Gaussian signals are completely defined by their two first moments. Hence, higher order cumulants and moments quantify the distance from Gaussianity. Assuming

the zero-mean i.i.d. complex symbols $u(n)$ and existence of the moments up to the fourth order, the kurtosis of $u(n)$, is defined as $\kappa = E[|u(n)|^4] - 2E^2[|u(n)|^2] - |E[u^2(n)]|^2$. For sub-Gaussian sources (negative kurtosis) CMA and VCMA share the same global minima. It has been shown that, when the source is Gaussian, CMA is equivalent to a power constraint and the CM cost function admits infinitely many minima. VCMA can equalize also Gaussian signals such as OFDM signal ($\kappa \approx 0$). A very good comparison between VCMA and CMA is given in [8].

3.1. VCMA applied in OFDM

VCMA minimizes the sum of energy penalties, over all users:

$$\mathcal{J}^{\mathrm{VCMA}}(\mathbf{G}[n]) = E\Big[\sum_{k=1}^{K}(|\mathbf{z}_k[n]|^2 - \mathcal{R}_2)^2\Big], \quad (15)$$

where $|\mathbf{z}_k[n]|^2 = \mathbf{z}_k^H[n]\mathbf{z}_k[n]$, and $\mathcal{R}_2$ is the block energy dispersion constant [2], defined as:

$$\mathcal{R}_2 = \frac{E[|\mathbf{u}_k[n]|^4]}{E[|\mathbf{u}_k[n]|^2]}. \quad (16)$$

If the user's symbols come from the similar modulation scheme, $\mathcal{R}_2$ is the same for all k users. The cost function $\mathcal{J}^{\mathrm{VCMA}}(\mathbf{G}[n])$ may be minimized iteratively using a stochastic gradient algorithm. We compute the gradient with respect to the equalizer coefficients:

$$\boldsymbol{\Delta}^{\mathrm{VCMA}}[n] = \nabla_{\mathbf{G}}\mathcal{J}^{\mathrm{VCMA}}(\mathbf{G}[n]). \quad (17)$$

By using (14), the gradient component for the k^{th} user is:

$$\boldsymbol{\Delta}_k^{\mathrm{VCMA}}[n] = \frac{\partial}{\partial \mathbf{G}_k[n]}E\big[(\mathbf{z}_k^H[n]\mathbf{z}_k[n] - \mathcal{R}_2)^2\big]. \quad (18)$$

Finally, we get:

$$\boldsymbol{\Delta}_k^{\mathrm{VCMA}}[n] = 4E\big[(|\mathbf{z}_k[n]|^2 - \mathcal{R}_2)\mathbf{Y}^H[n]\mathbf{z}_k[n]\big]. \quad (19)$$

By using the instantaneous values instead of expectation, a $(QL_g \times 1)$ vector is obtained:

$$\boldsymbol{\Delta}_k^{\mathrm{VCMA}}[n] = 4(|\mathbf{z}_k[n]|^2 - \mathcal{R}_2)\mathbf{Y}^H[n]\mathbf{z}_k[n], \quad (20)$$

and for all users, we obtain a $(QL_g \times K)$ matrix:

$$\boldsymbol{\Delta}^{\mathrm{VCMA}}[n] = \big[\boldsymbol{\Delta}_1^{\mathrm{VCMA}}[n] \ldots \boldsymbol{\Delta}_K^{\mathrm{VCMA}}[n]\big]. \quad (21)$$

The equalizer achieves the zero forcing solution (in the absence of noise), under the following conditions (see [3, 4, 5]):

1) Equalizer Minimum Length: The lenght of each equalizer $\mathbf{g}_{qk}$ must satisfy:

$$L_g \geq L_{\min} = \left\lceil \frac{K(L_h - 1)}{Q - K} \right\rceil, \quad (22)$$

where $\lceil\cdot\rceil$ denotes the integer part.

2) Common zeros condition: The virtual channel polynomials defined in the $\mathcal{Z}$-transform domain[1] as:

$$\bar{H}_q(\mathcal{Z}) = \sum_{k=1}^{K}\mathcal{Z}^{-k+1}h_{kq}(\mathcal{Z}^K), \quad q = 1, \ldots, Q \quad (23)$$

have no common roots. The channels are defined in $\mathcal{Z}$-transform domain, as: $h_{kq}(\mathcal{Z}) = \sum_{l=0}^{L_h-1}h_{kq}(l)\mathcal{Z}^{-l}$. A detailed stability analysis of zero forcing extrema is given by [8], considering the global channel-receiver impulse responses and the kurtosis bound.

If the transmitted symbols $u_k(n)$ are zero-mean, independent and identically distributed, they can be recovered at the receiver up to an arbitrary phase rotation. Such ambiguity is inherent in all blind equalization algorithms. This is due to the fact that such a rotation does not affect the statistics exploited by the criterion, i.e. the constant mean block energy constraint does not take into account the phase information. Therefore the equalized symbols of the k^{th} user are rotated and possibly time-delayed versions of the transmitted symbols: $z_k'(n) = u_k(n - d_k)e^{j\theta_k}$. The delay d_k depends on initialization and channel power delay profile, therefore the OFDM block boundaries must be synchronized after equalization (for example based on cyclic prefix, using the time domain autocorrelation). Because multiple users share the same statistical properties, it is not possible to predict which user's signal is recovered at a given equalizer output z_k' (permutation ambiguity).

The columns of equalization matrix $\mathbf{G}$ are adapted independently for each user. If they are identically initialized they will remain the same after any iteration. VCMA may converge, depending on its initialization, to any of the transmitted signals, usually to those that have a stronger power [4, 5]. In order to avoid this behaviour a decorrelation penalty must be imposed.

3.2. User decorrelation

Constant mean block energy is not a sufficient criterion to equalize multiple users in the presence of IUI [4, 5] because multiple copies of other user's signal may be present in the desired signal. The k^{th} user output $\mathbf{z}_k[n]$ may contain inteference signals corresponding to other users $\mathbf{z}_l[n]$ and their delayed replicas:

$$\mathbf{z}_l[n,\delta] = [z_l(nN - \delta), \ldots, z_l(nN - \delta + N - 1)]^T. \quad (24)$$

The interference is measured by the cross-correlation matrix $\mathbf{R}_{lk}(\delta)$, for a certain delay δ:

$$\mathbf{R}_{lk}(\delta) = E[\mathbf{z}_k[n]\mathbf{z}_l^H[n,\delta]] = E\Big[\mathbf{Y}[n]\mathbf{G}_k[n]\mathbf{z}_l^H[n,\delta]\Big]. \quad (25)$$

In this criterion, we minimize the squared Frobenius norm [10]:

$$\mathcal{N} = \Big\|\mathbf{R}_{lk}(\delta)\Big\|_F^2 = trace\Big\{\mathbf{R}_{lk}(\delta)\mathbf{R}_{lk}^H(\delta)\Big\}. \quad (26)$$

Using the instantaneous estimates of correlation matrices, we can write:

$$\mathcal{N} = trace\{\mathbf{Y}[n]\mathbf{G}_k[n]\mathbf{z}_l^H[n,\delta]\mathbf{z}_l[n,\delta]\mathbf{G}_k^H[n]\mathbf{Y}^H[n]\}. \quad (27)$$

[1]To avoid confusion we denote by $\mathcal{Z}$ the variable of the transform

Relying on the commutativity property inside the trace operator, we get:

$$\mathcal{N} = \mathbf{z}_l^H[n,\delta]\mathbf{z}_l[n,\delta]\mathbf{G}_k^H[n]\mathbf{Y}^H[n]\mathbf{Y}[n]\mathbf{G}_k[n]. \quad (28)$$

The cross-correlation cost function over all users is:

$$\mathcal{J}^{\text{xcorr}}(\mathbf{G}[n]) = \sum_{\substack{l,k=1\\l\neq k}}^{K}\sum_{\delta=\delta_1}^{\delta_2}\left\|\mathbf{R}_{lk}(\delta)\right\|_F^2. \quad (29)$$

The delays δ_1, δ_2 are chosen according to the maximum delay L_h-1 introduced by the channel, i.e., the integer δ spans the window of possible delays. To minimize $\mathcal{J}^{\text{xcorr}}(\mathbf{G}[n])$ we compute the gradient of this cost function with respect to the equalizer coefficients:

$$\mathbf{\Delta}^{\text{xcorr}}[n] = \nabla_{\mathbf{G}}\mathcal{J}^{\text{xcorr}}(\mathbf{G}[n]). \quad (30)$$

For the k^{th} user, the gradient column for G matrix, is:

$$\mathbf{\Delta}_k^{\text{xcorr}}[n] = \frac{\partial}{\partial\mathbf{G}_k[n]}\sum_{\substack{l,k=1\\l\neq k}}^{K}\sum_{\delta=\delta_1}^{\delta_2}\left\|\mathbf{R}_{lk}(\delta)\right\|_F^2 = \sum_{\substack{l=1\\l\neq k}}^{K}\sum_{\delta=\delta_1}^{\delta_2}\frac{\partial\mathcal{N}}{\partial\mathbf{G}_k[n]}. \quad (31)$$

Considering that in (28) $(\mathbf{Y}^H[n]\mathbf{Y}[n])$ is a symmetric Hermitian matrix, we get:

$$\frac{\partial\mathcal{N}}{\partial\mathbf{G}_k[n]} = 2|\mathbf{z}_l[n,\delta]|^2\mathbf{Y}^H[n]\mathbf{z}_k[n]. \quad (32)$$

The gradient $\mathbf{\Delta}_k^{\text{xcorr}}[n]$ is a $(QL_g \times 1)$ vector:

$$\mathbf{\Delta}_k^{\text{xcorr}}[n] = 2\sum_{\substack{l=1\\l\neq k}}^{K}\sum_{\delta=\delta_1}^{\delta_2}|\mathbf{z}_l[n,\delta]|^2\mathbf{Y}^H[n]\mathbf{z}_k[n]. \quad (33)$$

For the K users, the gradient is a $(QL_g \times K)$ matrix:

$$\mathbf{\Delta}^{\text{xcorr}}[n] = \left[\mathbf{\Delta}_1^{\text{xcorr}}[n]\ldots\mathbf{\Delta}_K^{\text{xcorr}}[n]\right]. \quad (34)$$

3.3. Composite criterion

Our goal is to cancel both ISI and IUI. VCMA constraint (15) may be improved by adding the extra-term (29), which penalizes the output cross-correlation. The novel multi-user VCMA cost function can be expressed as:

$$\mathcal{J}(\mathbf{G}[n]) = \lambda\mathcal{J}^{\text{VCMA}}(\mathbf{G}[n]) + (1-\lambda)\mathcal{J}^{\text{xcorr}}(\mathbf{G}[n]). \quad (35)$$

The composite function $\mathcal{J}(\mathbf{G}[n])$ is a sum of two non-negative terms, and its global minima set both terms in (21) and (34) to zero, respectively. In this case the outputs are uncorrelated to each other and IUI is reduced. The combined cost function combats both ISI and IUI. The weighting parameter $\lambda \in (0,1)$ balances the two constraints. The adaptation step $\mathbf{\Delta}[n]$ is:

$$\mathbf{\Delta}[n] = \lambda\mathbf{\Delta}^{\text{VCMA}}[n] + (1-\lambda)\mathbf{\Delta}^{\text{xcorr}}[n]. \quad (36)$$

The adaptive algorithm that minimizes the composite cost function is:

$$\mathbf{G}[n+1] = \mathbf{G}[n] - \mu\mathbf{\Delta}[n]. \quad (37)$$

The parameters involved in this algorithm are the tuning parameter λ, the convergence rate μ and the equalizer length L_g. The optimum value of λ will be derived in a forthcoming paper. The convergence factor μ can be chosen to guarantee the stability and to provide a reasonable convergence speed and stready-state error variance.

4. SIMULATION RESULTS

In this section, we study the performance of the proposed blind algorithm in computer simulations. We consider a MIMO OFDM scenario with two users, that transmit i.i.d. 4QAM symbols using $K = 2$ transmit antennas. The symbols are modulated by $M = 64$ subcarriers, and the cyclix prefix of length $L = 8$ is added. L is large enough to avoid the inter-block interference. The signals are transmitted through the channel and received by $Q = 3$ antennas. The channels have $L_h = 3$ complex taps:

$$\mathbf{h}_{11}(z) = 1.166e^{j0.5404} + 0.228e^{j0.6610}z^{-1} + 0.125e^{-j0.4993}z^{-2}$$
$$\mathbf{h}_{12}(z) = 0.447e^{j0.4636} + 0.111e^{j0.4636}z^{-1} + 0.111e^{j0.4636}z^{-2}$$
$$\mathbf{h}_{13}(z) = 1.131e^{j0.7854} + 0.412e^{j0.2450}z^{-1} + 0.123e^{-j0.2450}z^{-2}$$
$$\mathbf{h}_{21}(z) = 0.640e^{j0.6747} + 0.200e^{j0.0500}z^{-1} + 0.117e^{j0.3488}z^{-2}$$
$$\mathbf{h}_{22}(z) = 1.220e^{j0.6107} + 0.559e^{j0.4636}z^{-1} + 0.165e^{-j0.4366}z^{-2}$$
$$\mathbf{h}_{23}(z) = 1.131e^{j0.7854} + 0.269e^{j0.3805}z^{-1} + 0.158e^{-j0.3218}z^{-2}$$

We add Gaussian noise at the receiver. The transmitted OFDM signals are Gaussian, i.e., their kurtoses are practically equal to zero because M is large enough. The demodulated patterns at each antenna, and the equalized patterns, are shown in Figure 2. The SNR is assumed to be $E_b/N_0 = 15dB$ in this simulation. Figure 3 shows the evolution of symbol mean square error (MSE) versus the number of iterations. The inherent ambiguity [2] introduced by the algorithm has been removed in MSE computation. In general the initialization is critical for the VCMA convergence speed. In many cases "single-spike" initialization is preferred for each column of matrix $\mathbf{G}$, and the spike position is chosen according to the channel statistics. The equalizer length is $L_g = 5$ according to (22) resulting to a (15×2) equalization matrix $\mathbf{G}$. The columns of $\mathbf{G}$ have been initialized with non-zero values equal to one, on the positions $(1,1)$ and $(6,2)$. The convergence rate $\mu = 2.1 \cdot 10^{-6}$ and $\lambda = 0.714$ have been chosen to guarantee the convergence and the stability. To emphasize the contribution of each cost function in the composite criterion, the output MSE averaged by the two users versus the number of iterations is shown in Figure 4. The energy penalty alone ($\lambda = 1$) does not provide an acceptable symbol MSE in the presence of IUI, the constellation clusters being grouped in subclusters. The decorrelation criterion alone ($\lambda = 0$) tends to set the equalizer outputs to zero and is not sufficient for equalization. The block energy constaint establishes the equilibruim for an optimal λ, keeping the block energy constant. The dominating criterion is the constant mean block energy, but the decorrelation is necessary, to supress IUI. The algorithm behaviour at different signal to noise ratios is shown in Figure 5 and Figure 6, considering the output mean square error and the symbol error rate, respectively.

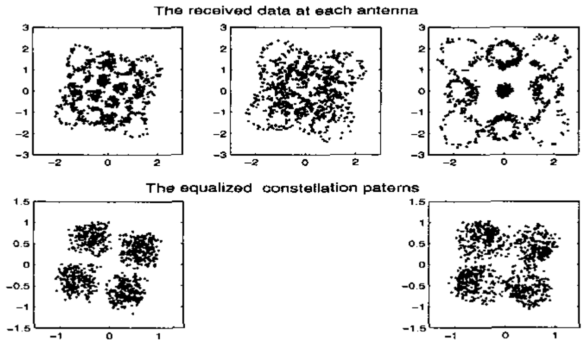

Figure 2. The symbols, before and after equalization, $E_b/N_0 = 15dB$

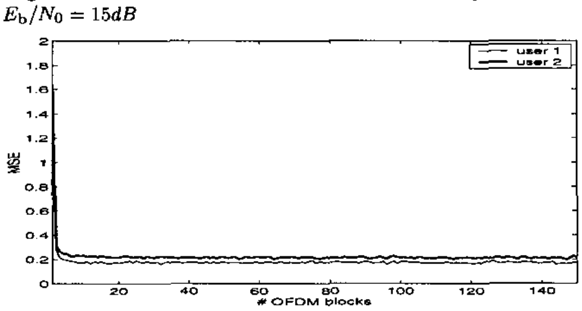

Figure 3. Symbol MSE versus # iterations, $E_b/N_0 = 15dB$

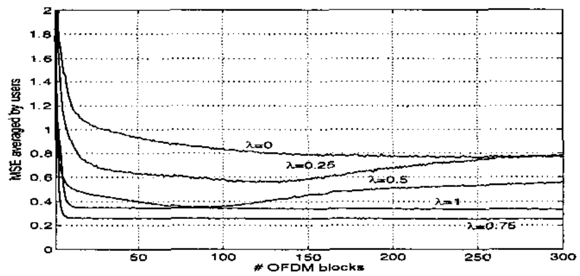

Figure 4. Symbol MSE for different balance factors λ, $E_b/N_0 = 15dB$

5. CONCLUSIONS

We have extended VCMA to MIMO OFDM systems. The proposed blind algorithm operates in a combined fashion to mitigate both ISI and IUI. The extra-term added to the VCMA cost function plays an important role for IUI cancellation and allows us to apply VCMA in the multi-user scenario. The blind algorithm is derived assuming quasi-stationary channel over block period. A semi-blind version for time-varying channels can be developed using limited training sequences.

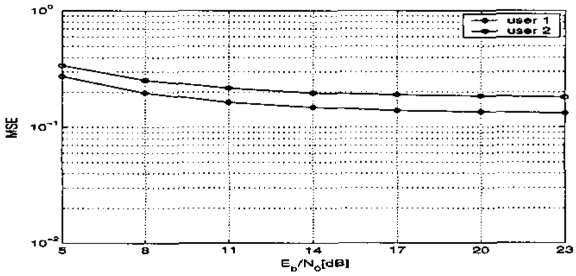

Figure 5. Symbol MSE at different SNRs

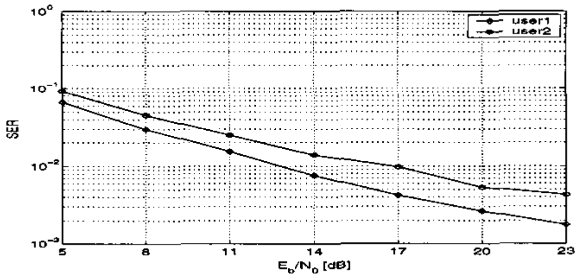

Figure 6. SER at different SNRs

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