PRE-COMBINING ADVANCED BLIND MULTIUSER DETECTOR FOR TIME AND FREQUENCY SELECTIVE WIRELESS CHANNEL

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ABSTRACT

This paper deals with an adaptive multiuser detector for DS-CDMA (Direct Sequence Code Division Multiple Access) wireless communication systems, whose main features are low complexity and joint utilization of the time diversity and blind adaptive processing techniques.

The proposed multiuser detector, defined as Pre-combining Advanced Blind Adaptive Multiuser Detector (PABA-MUD), a window reprocessing technique together with an original adaptation rule is used in order to improve performance for time varying environment. In particular, pre-combining of different replicas allows deriving a unique adaptive sequence even for multipath signals. The proposed detector shows remarkable near-far resistance and requires knowledge of the desired user's signature waveform, timing and phase. No training sequence is needed. Receiver performance is expressed in terms of bit error rate (BER), which has been derived by simulations under the assumption of a time and frequency-selective Rayleigh fading channel.

I - INTRODUCTION

Recently wireless communication standardization process has led to choose Direct Sequence Code Division Multiple Access (DS-CDMA) technique for 3rd generation wireless system. Major hurdles of DS-CDMA systems are the near-far problem and the multiple-access interference (MAI) that limits the number of active users in relation to a specified Bit Error Rate (BER) [2]. Conventional Rake receiver that is optimum in the case of single-path single-user AWGN channel, suffers performance degradation when the number of interfering users (MAI) or their received power level (near-far problem) increases.

These problems and other wireless channel shortcomings drive to consider more robust but still simple receivers like blind adaptive multiuser detector [1]. Main benefit lies in its property to support completely asynchronous and uncoordinated transmissions due to its intrinsically near-far resistant and MAI mitigation capability. As it is known in the literature, the blind adaptation rule is optimum in time invariant environment, but it prevents drawbacks in a multipath fading scenario: in real communication systems, spreading waveform is not exactly known by the detector because of signal distortion introduced by the wireless fading channel. In fact, it is not possible to assume original spreading waveform knowledge for the signal despreading since the actual received waveform may include additional multipath components or other channel damages: this phenomenon is known as mismatch and can prevent from adaptive blind algorithm correct convergence. Therefore, it is important to obtain a blind multiuser detector that is robust against imperfect knowledge of desired user waveform.

The blind MUD proposed in this paper, defined as Pre-combining Advanced Blind Adaptive MUD (PABA-MUD) is derived from *orthogonal anchored* minimum energy adaptive equalizer. It uses a very simple cost function (OE) and doesn't need any training sequence [1].

The basic idea underlying this detector is to exploit the maximum information than can be achieved from a data bit stream: the modification of the blind algorithm is obtained through two distinct steps. First, each replica of user of interest is delayed and time aligned before equal gain combining like in a RAKE structure (Fig. 5).

Hence, proposed recursive procedure aims to achieve an adaptive sequence orthogonal to the combined signal instead of nominal spreading waveform. As a consequence, precombined approach helps obtaining convergence for the whole-received signal of user of interest. In particular weaker received replicas, e.g. the ones corresponding to deep fading propagation, are considered as a part of the overall signal and not as an individual informative stream, so yielding a more reliable decision variable and a more robust convergence procedure. Moreover, pre-combining of different replicas allows deriving only one adaptive sequence for multipath signals aiming to maintain a low complex structure even in realistic channel.

In order to mitigate the increasing cross-correlation level among the signature waveforms due to the frequency-selective fading channel, data stream is divided and processed more than once in order to decorrelate the interference and the information in each data window. This algorithm aims to obtain a faster convergence in fading channel.

II - SYSTEM MODEL

The equivalent baseband received signal $r(t)$ for a CDMA system with K users can be represented as:

$$r(t) = \sum_{l=1}^{L}\sum_{n=0}^{N_b}\sum_{k=1}^{K} c_l^{(n)} A_k b_k^{(n)} s_k(t - nT - \tau_l) + n(t) \qquad (1)$$

where

- L is the number of resolvable paths,
- N_b is the number of transmitted symbols,
- $n(t)$ is the white Gaussian noise with double side power spectral density $N_o/2$,
- T is the symbol interval,
- A_k is the amplitude of the k-th user,
- $b_k^{(n)}$ is the n-th bit of k-th transmission: they are i.i.d. random values in {-1, 1} with equal probability 0.5,
- $c_l^{(n)}$ and $\tau_l^{(n)}$ are the channel coefficient and delay characterizing the l-th path.

Channel coefficients $c_l^{(n)}$ are defined as:

$$c_l^{(n)} = \left|c\right|_l^{(n)} \cdot e^{j\phi_l^{(n)}} \tag{2}$$

where $\left|c\right|_l^{(n)}$ are i.i.d. Rayleigh distributed random values and $\phi_l^{(n)}$ are i.i.d. Uniform random values in [0, 2π).

User k signature waveform $s_k(t)$ is defined, upon one symbol interval, as in the following:

$$s_k(t) = \sum_{m=1}^{N} p_k(m) u(t - mT_c) \tag{3}$$

where $N=T/T_c$ is the processing gain, T_c is the chip interval, $p_k(m) \in \{\pm 1\}$ is the m-th chip of the k-th spreading code and $u(t)$ is the baseband waveform. Assuming user of interest to be the first ($k=1$), the associated bit sequence $\{b_1^{(n)}\}$ has to be demodulated only by means of the signature waveform and timing. No hypothesis is made about interfering users.

III - PRE-COMBINING BLIND ADAPTIVE MUD

The received continuos-time signal is sampled at the rate N/T, so the vector at the input of the composed filter $s_1+\underline{x}_1$, in a single observation interval, is:

$$y_{tot} = \sum_{j=1}^{L} y^j = \sum_{j=1}^{L} \sum_{i=1}^{L} \sum_{k=1}^{K} a_{k,i}^{(d)} w_k b_k^{(d)} s_{k,i-j}^{(d)} + n \qquad for \quad d = m-1, m, m+1 \tag{4}$$

where n is the AWGN vector and $s_{k,i-j}^{(d)} = s_k^{(d)}\left(t - mT - \tau_k - \tau_{k,i} + \tau_{k,j}\right)$ represents the part of the *i-th* replica of *k-th* spreading waveform, after its time alignment to *j-th* replica (as in a RAKE structure), that modulates the *d-th* bit falling in the decision interval $[mT,(m+1)T]$. For simplicity we suppose, without loss of generality, that $\tau_1=0$.

Detector output is:

$$\begin{aligned}
< y_{tot}, s_1 + \underline{x}_1 > &= w_1 b_1^{(m)} \sum_{i=1}^{L} a_{1,i}^{(m)} < s_1, s_1 + \underline{x}_1 > + \\
&+ \sum_{j=1}^{L} \sum_{\substack{i=1 \\ i \neq j}}^{L} a_{1,i}^{(m-1)} w_1 b_1^{(m-1)} < s_{1,i-j}^{(m-1)}, s_1 + \underline{x}_1 > + \\
&+ \sum_{j=1}^{L} \sum_{\substack{i=1 \\ i \neq j}}^{L} a_{1,i}^{(m+1)} w_1 b_1^{(m+1)} < s_{1,i-j}^{(m+1)}, s_1 + \underline{x}_1 > + \\
&+ \sum_{d=m-1}^{m+1} \sum_{j=1}^{L} \sum_{k=2}^{K} \sum_{i=1}^{L} a_{k,i}^{(d)} w_k b_k^{(d)} < s_{k,i-j}^{(d)}, s_1 + \underline{x}_1 > + \\
&+ n'
\end{aligned} \tag{5}$$

The first term is the decision variable, the second and the third term are the self-interference due to the disarranged replicas of the desired signal, the forth term is the multiple access interference and the latter term is the background noise contribute at the output of the detector.

The self-interference term, in the latter equation, increases as the number of channel paths increase. In order not to loose performance due to this added noisy term and in order to avoid the desired signal cancellation problem caused by signature waveform mismatch, the adaptive vector $\underline{x}_1$ is generated orthogonal to the space spanned by the desired signal significant paths. Since received signal of the desired user must lie in the space spanned by its replicas, mismatch negative effect is mitigated and the filter energy limitation can be avoided. Indeed, an energy limitation must be maintained, in multipath fading channel, because of its high variability and not exact estimation of channel parameters.

A modified steepest descent stochastic gradient algorithm is used to update $\underline{x}_1$:

$$\begin{aligned}
&\underline{x}_1(i) = \underline{x}_1(i-1) - \\
&\mu < y_{tot}(i), s_1 + \underline{x}_1(i-1) > \cdot [y_{tot}(i) - < y_{tot}(i), \tilde{s}_{1tot} > \tilde{s}_{1tot}]
\end{aligned} \tag{6}$$

with

$$\tilde{s}_{1tot} = \frac{s_{1tot}}{\left\| s_{1tot} \right\|} \tag{6a}$$

$$s_{1tot} = \sum_{i=1}^{L} \sum_{j=1}^{L} \beta_i s_{1,i-j}^{(d)} \tag{6b}$$

where $\beta_i = \hat{a}_{1,i}^*$ should be the estimated channel coefficients associated to each received replica of the user of interest. Here we have supposed perfect phase compensation, i.e., $\arg\{\beta_i\} = \arg\{a_{1,i}\}$, but no channel amplitude compensation is assumed, i.e., $\left|\beta_i\right| = 1$. Intentionally, we have not performed a maximal ratio combining in order to investigate receiver resistance against amplitude fluctuations.

Denoting as Γ_d the subspace spanned by the basis vectors associated to the orthonormal signals constructed by means of the Gram-Schmidt procedure starting from the received desired signal significant paths after multipath recombination, we constraint $\underline{x}_1$ to be orthogonal to Γ_d. Let $\Psi_d \in \Re^{N \times N}$ be the projection matrix onto the subspace orthogonal to Γ_d, the component of the multipath combiner output vector (y_{tot}) orthogonal to Γ_d can be taken into account by simply replacing y_{tot} with $\hat{y}_{tot} = \Psi_d \cdot y_{tot}$ in the updating algorithm rule.

Although it is known [1] that a constant step μ can assure convergence and stability, we are also interested, in real environments, in facing the MOE minimum point displacements. Hence, step μ has been chosen as:

$$\mu = \frac{0.1}{\overline{E}_b \cdot f(i)} \tag{7}$$

where i is the iteration number and $\overline{E}_b$ is the mean output power of the matched filter calculated upon 10 bit epochs interval:

$$\overline{E}_b = \frac{1}{10T} \sum_{n=1}^{10} \left(\int_{(n-1)T}^{nT} y_{tot}(t) s_1(t - nT) dt \right) \tag{8}$$

This value is used to calculate step μ by (7) for the next 10 bit intervals and so on. Index $f(i)$ is chosen as:

$$f(i) = \begin{cases} 1 \quad i = 0 \\ i \bmod f_M \quad 1 < i < f_M / 2 \\ i \bmod f_M \quad k \cdot f_M / 2 \le i < k \cdot f_M \quad k = 1,2,... \\ f_M \quad i = f_M \end{cases} \tag{9}$$

The updating rule of the algorithm (6) starts from initial condition $\underline{x}_1=0$, then it let $\boldsymbol{x}_1$ energy grow until threshold χ_1 is reached and energy constraint $\|\underline{x}_1\|^2 \le \chi_1$ is applied.
Threshold χ_1 is estimated as:

$$\chi_1^{opt} = \frac{\alpha^{opt}(K-1) \cdot L}{N - \alpha^{opt}(K-1) \cdot L} \tag{10}$$

where K is the number of active users, L is the number of paths and α is a parameter experimentally optimized for the considered contest. Eq. 10 represents the comparison term on $\underline{x}_1$ energy to assure energy constraint at each step of gradient algorithm, i.e., if $\|\underline{x}_1\|^2 < \chi_{1opt}$, adaptive algorithm is carried on, otherwise the detector imposes a new $\boldsymbol{x}_1$ equal to:

$$\underline{x}_1^{\,new} = \frac{\underline{x}_1^{\,old}}{\left\|\underline{x}_1^{\,old}\right\|} \cdot \sqrt{\chi_I^{\,opt}} \tag{11}$$

Optimum solution can be easily calculated if we consider, without loss of generality, the case of K synchronous users. The constrained MOE function is:

$$\begin{aligned} J = J(c_1) &= E\left\{\left(y^T c_1\right)\cdot\left(y^T c_1\right)^*\right\} + \\ &+ \nu_1\left[\left(c_1^H \cdot c_1\right) - 1 - \chi_I^{opt}\right] + \nu_2\left[\widetilde{s}_{1tot}^{\,T} s_1 - \widetilde{s}_{1tot}^{\,T} c_1\right] \end{aligned} \tag{12}$$

taking the gradient $\nabla(J) = \dfrac{\partial J}{\partial c_1^*}$ we have,

$$E\left\{y^T c_1 \cdot y\right\} + \nu_1 c_1 - \nu_2 \widetilde{s}_{1tot} = 0 \tag{13}$$

So the optimum solution is:

$$c_{1opt} = \left(R_y + \nu_1 I_N\right)^{-1} \cdot \left[\nu_2 \widetilde{s}_{1tot}\right] \tag{14}$$

where $R_y = E\left\{y_{tot}\, y_{tot}^{\,T}\right\}$ and ν_1, ν_2 are the Lagrangian multipliers to assure the constraints $\left(\underline{x}_1^H\, \underline{x}_1\right) = \chi_I^{opt}$ and $\left(\widetilde{s}_{1tot}^{\,T}\, \underline{x}_1\right) = 0$ respectively.

Thus, the Lagrangian multiplier ν_2 can be calculated form (14) by taking into account the condition $\left(\widetilde{s}_{1tot}^{\,T}\, \underline{x}_1\right) = 0$:

$$\nu_2 = \left(\widetilde{s}_{1tot}^T\left[\widetilde{s}_{1tot}^T\left[R_y + \nu_1 I_N\right]^{-1}\widetilde{s}_{1tot}\right]^{-1} s_1\right)^{-1} \tag{15}$$

Here we have not considered the background noise. Its consideration, however, leads to replace ν_1 with $\gamma = \nu_1 + \sigma^2$ where σ^2 is the variance of the AWG noise.

The well-known convergence speed problem suffered by the standard blind receiver in fast fading channel can be mitigated using a reprocessing window algorithm [5].

A faster convergence of the blind algorithm can be achieved by iterating steepest descent algorithm more than once over the same informative bit frame (Fig. 1). The number of iterations upon the frame has to be chosen as a trade-off between two opposite issues. In particular, a too little number of iterations would not allow an efficient minimum output energy pursuit, but a too large value would mean the appearing of the effects of the correlation properties between two consecutive iterations so that the equivalence between Minimum Mean Square Error (MMSE) and Minimum Output Energy (MOE) detectors, demonstrated in [1], would not be verified and performance degradation would be introduced.

IV - NUMERICAL RESULTS

The considered propagation environment is the suburban wireless communication channel as described in GSM Recommendations [6]: six paths are assumed with their distinctive features, delay, phase and attenuation, the formers (the first and the second) with uniform distribution, the latter with a Rayleigh statistics.

In performing our simulations the following conditions have been assumed:

- Symbol rate for the BPSK modulation equal to 31.496 KSymbols/sec;
- Spreading obtained through Gold sequences with processing gain equal to 127;

Different communication contests are considered: in particular both up-link and down-link channels are taken into account with different interfering user configurations. The PABA-MUD detector has been tested and compared with the other two receivers, i.e., the classical rake receivers and BA-MUD, with different level of multiple access interference (MAI), i.e., for different values of the power unbalance between the desired user signal and the interfering signals. The performance obtained for a classical Rake receiver with only one user is also reported for comparison purposes. PABA-MUD improves BA-MUD performance (Fig. 3, 4), especially for high Signal-to-Noise ratios, even in the most hostile time varying environments. In particular, in extremely bad near-far situation (Fig. 4), the gain on performance allows thinking of a remarkable reduction of the BER irreducible floor with a consequent capacity improvement for CDMA wireless systems. Gain respect CRD is more evident in asynchronous transmission case and in near-far condition (Fig. 2), but even in the downlink it is observable a strong dependence of CRD by inter-cell interfering signal delay (Fig. 6). The proposed detector is not affected by this drawback.

Finally, it is worth stressing that the BER curves of the proposed blind receiver have been calculated considering even the errors coming from training period before blind algorithm convergence. So they have to be considered as a worse case.

V - CONCLUSIONS

In this paper a blind adaptive multiuser detector for DS-CDMA wireless communication systems has been discussed. It has been demonstrated by means of computer simulations that the proposed receiver is able to mitigate the problems which afflict the standard blind detector, previously proposed in [1], in particular in the case of a time-varying environment. A blind algorithm based on a window re-processing technique, and on a projection constraint approach, has been introduced in order to achieve better near-far resistance and convergence rapidity in fast fading channel. The numerical results presented in the paper clearly demonstrate that the proposed approach help obtaining a more robust receiver against near-far and multipath-fading drawbacks with a relatively low complexity scheme.

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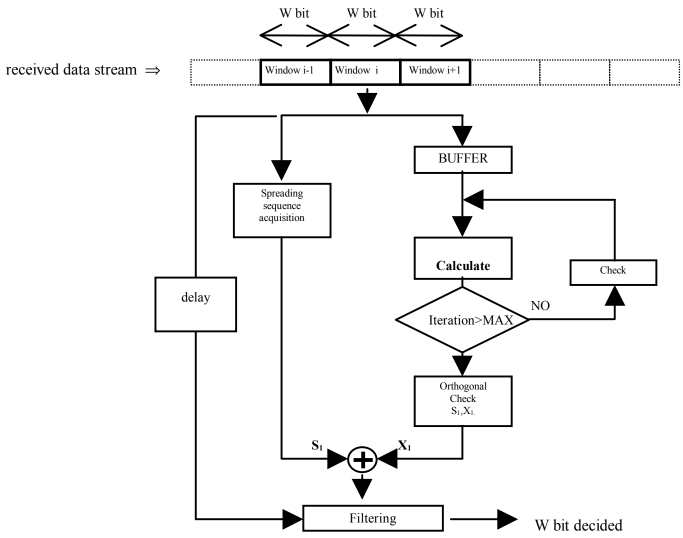

Fig. 1 Flow-chart of the advanced blind adaptive algorithm for fast fading environment.

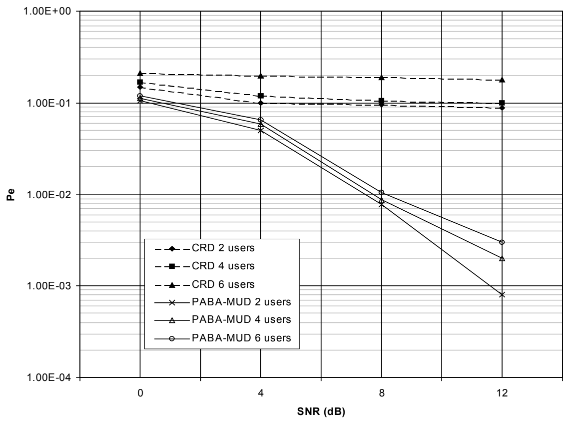

Fig. 2 Performance comparison between conventional RAKE detector (CRD) and pre-combining advanced blind adaptive multiuser detector (PABA-MUD) in the uplink GSM sub-urban channel with different number of asynchronous interfering users each one with a 10 dB stronger received power level than desired

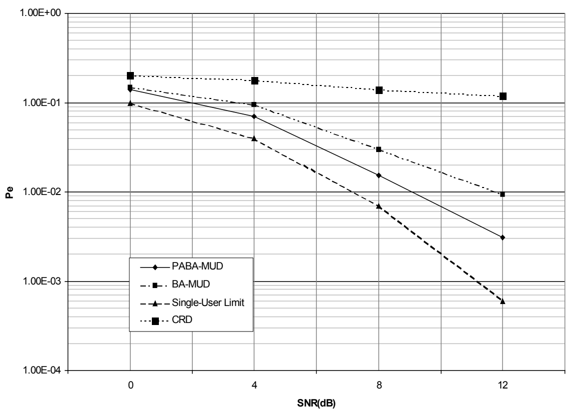

Fig. 3 Performance comparison between conventional RAKE detector (CRD), standard blind adaptive multiuser detector (BA-MUD) and pre-combining advanced blind adaptive multiuser detector (PABA-MUD) in the downlink GSM sub-urban channel with 10 interfering users and a co-cell interfering equivalent signal

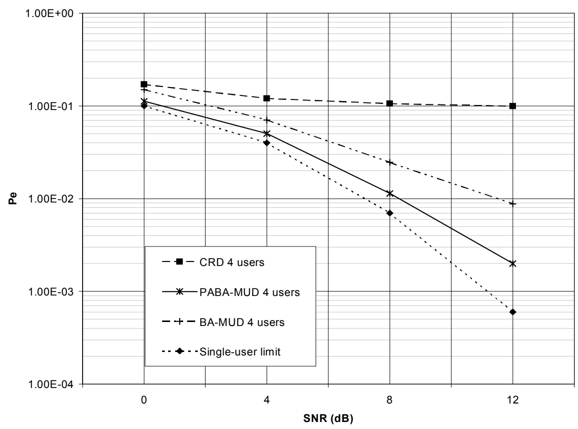

Fig. 4 Performance comparison between conventional RAKE detector (CRD), standard blind adaptive multiuser detector BA-MUD and pre-combining advanced blind adaptive multiuser detector (PABA-MUD) in the uplink GSM sub-urban channel with 4 asynchronous interfering users each one with a 10 dB stronger received power level than desired.

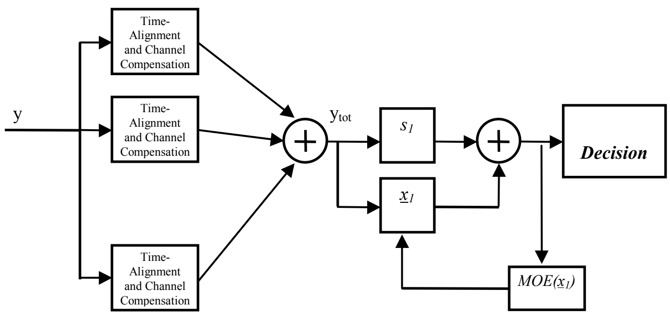

Fig. 5 Pre-combining blind adaptive detector scheme.

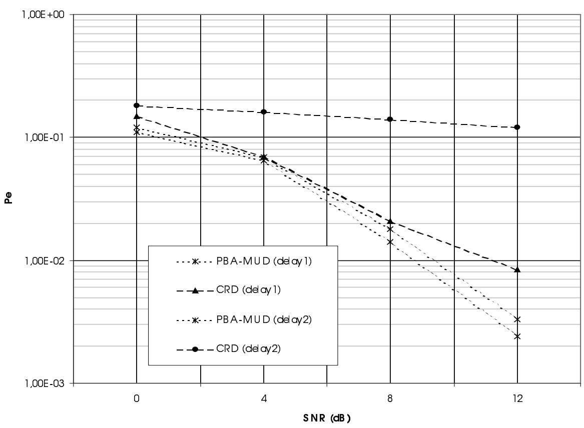

Fig. 6 Error probability comparison between PBA-MUD and CRD in the downlink GSM sub-urban channel with ten interfering users plus an inter-cell asynchronous interfering signal with different time delay (delay1>delay2).