JOINT SELF AND MULTIUSER INTERFERENCE REDUCTION FOR RELIABLE SYNCHRONIZATION OF DS-CDMA SYSTEMS OVER FREQUENCY-SELECTIVE FADEING CHANNELS

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ABSTRACT

This paper deals with the reduction of both self interference (SI) due to multipath, and multiuser interference (MUI) due to multiple access for synchronous DS-CDMA communications over frequency-selective fading channels. We are concerned with the down-link where the base station transmits all the users information synchronously and any mobile receiver must perform a reliable demodulation. In this scenario, the user receiver’s tasks involving synchronization and single detection are severely degraded by the high interference level. Our proposal intends to reduce this error source by using subspace blind detectors with a structure similar to the Generalized Side Lobe Canceller (GSLC) exploiting the canonical representation for the desired user linear detector. The orthogonality condition between both components is imposed by the proper design of the blocking matrix in the unknown multipath environment. Working at chip rate rather than baud rate, a multirate structure at the lower branch provides an almost MUI/SI free signal for time synchronization and multipath optimum combining.

1. INTRODUCTION

Direct Sequence, Code Division Multiple Access (DS-CDMA) schemes offer an attractive alternative for sharing a transmission medium among many users, while requiring minimum cooperation among them. One challenging issue in these applications is to handle with the timing of the desired user taking account of the presence of many interferers which severely degrades the channel estimator performance. Some detection strategies are based on the transmission of training sequences with appropriate correlation characteristic for timing acquisition and channel estimation. On the other hand, many works are dealing with blind strategies for time and channel acquisition based on the knowledge of the signature waveform of the desired user and also its timing (bit-epoch) where the remainder users are unknown interferers without explicit knowledge of their signature waveforms [1]. Recall that in the downlink, other users must be considered as interferers and therefore it is not reasonable to exploit multiuser detection benefits.

Several methods are concerned with the improvement of the classical matched filter, dealing with the blind interference reduction for seeking the minimization of the output power subject to the constraint that a particular code is passed with no distortion (MOE: Minimum Output Energy). Also it was shown that it converges to the linear Minimum Mean Square Error (MMSE) receiver for arbitrary initialization [2]. The feasibility of blind effective signature waveform estimation has been shown recently by several researchers [3, 4]. However, most blind estimation algorithms proposed to date involve computationally intensive operations as the SVD, and thus may be prohibitive in practice. To overcome this difficult a constrained adaptive filter MOE criterion is proposed in [5]. Compared to subspace methods, the algorithm significantly reduces the total complexity without requiring additional information. Its main disadvantage is the assumption of the availability of timing information for the user of interest within a chip period.

2. OUR PROPOSAL

Our method is concerned with a multipath unknown scenario in the downlink where all the users signals arrive at a particular user (user 1 in the sequel) synchronously. The signal received from user \( k \in \{1, 2, …K\} \) over the symbol interval \([0, T_b]\) in an ideal scenario without multiple access neither multipath yields:

\[
e^{j\theta_k} A_k b_k s_k(t)
\]

where

\( A_k \) = received amplitude for user \( k \)

\( b_k \) = data symbol for user \( k \)

\( \theta_k \) = phase user \( k \)

\( s_k(t) \) = normalized signature waveform for user \( k \)

At chip rate, the normalized signature wave form can be represented as a \( N \) dimensional vector:

\[
s_k(t) \rightarrow s_k = [s_k(1), s_k(2), …, s_k(N)]^T
\]

where superscript \(^T\) means transpose.
Assuming the following model for the L-multipath channel for every user $k$:
\[ c_i(t) = \sum_{i=0}^{K} s_i(t-(l-i)T_s) \quad \text{where} \quad LT_s \ll T_s \]
where obviously in the down link $c_i(t)=c_i(t) \forall k \in \{1, 2, \ldots, K\}$ although we will maintain the general notation.

Assuming time synchronization, the observable signal at the $i$-finger yields as follows:
\[
\begin{align*}
    r_i(t) &= \sum_{i=0}^{K} A_i e^{j\theta_i} \left[ b_i[n] \sum_{l=1}^{L} c_i s_l(t-(l-i)T_s) \right] \\
    &+ b_i[n-1] \sum_{l=1}^{L} c_i s_l(t+T_s-(l-i)T_s) + \\
    &+ b_i[n+1] \sum_{l=1}^{L} c_i s_l(t-T_s-(l-i)T_s)] + n(t) \\
    \forall t &\in (i-1)T_s, (i+1)T_s 
\end{align*}
\]
(4)

where $n(t)$ means additive white Gaussian noise.

By the generalization of the representation of signature vectors (see eq.(2)) for arbitrary right-left shifting with respect to some finite dimensional basis, at the chip rate, we have:
\[
    s_i(t+t_0) \rightarrow s_i^N = \begin{bmatrix} n_i & 0 & \cdots & 0 \end{bmatrix}^T \quad \text{for} \quad n_i = \frac{t_0}{T_s} 
\]
(5)

where the zero-padding size matches the $N$ dimension vector. Recalling eq.(2), we have now:
\[
    s_i^N|_{n_i=0} = s_i \left[ \begin{array}{c} 1 \\ \vdots \\ 1 \end{array} \right] = s_i 
\]
(6)

Therefore, the discrete model for the received signal at the $i$-finger is:
\[
\begin{align*}
    r_i[n] &= \sum_{i=0}^{K} A_i e^{j\theta_i} \left[ b_i[n] \sum_{l=1}^{L} c_i s_l^{(i-l)} + b_i[n-1] \sum_{l=1}^{L} c_i s_l^{(i-l-1)} + \\
    &+ b_i[n+1] \sum_{l=1}^{L} c_i s_l^{(i-l+1)} \right] + n[n] \\
\end{align*}
\]
(7)

Let us make the following definitions in order to reach a more compact expression for eq.(7).
\[
    S_i^0 = \left[ s_i^{-(i-1)}, s_i^{-2}, \ldots, s_i^{-(L-i)} \right] \\
    S_i^{w_1} = \left[ 0_{N-x_i}, s_i^{1}, s_i^{2}, \ldots, s_i^{N-L} \right] \\
    S_i^{w_2} = \left[ s_i^{N-(i-1)}, s_i^{N-2}, \ldots, s_i^{-N} \right] \\
    S_i^{w_3} = \left[ s_i^{N-(i-1)}, s_i^{N-2}, \ldots, s_i^{N} \right] \quad \text{as a set of $LxN$ matrices.}
\]
(8)

Expression given by equation (9) provides an appropriate description of any detector behavior:
\[
    \begin{align*}
    &A_{DS} e^{j\theta_i} s_i b_i[n] \\
    &A_{SI} e^{j\theta_i} s_i^{*(i)} b_i[n] + A_{DS} e^{j\theta_i} s_i b_i[n+1] \\
    &\sum_{i=0}^{K} A_i e^{j\theta_i} \left[ b_i[n] s_i^0 + b_i[n-1] s_i^{1} + b_i[n+1] s_i^{w_3} \right] \\
    &n[n] 
    \end{align*}
\]
(9)

where first term is the desired signal ($DS$), second term is $SI$, third term is $MUI$ and the remainder is noise. Let us observe that DS contribution is determined by span $\{s_i^r\}$ collecting the user spreading code and all the possible shifting (and zero padding) versions of it due to the multipath characteristic; on the other hand, optimum combining must be performed by the knowledge of $c_i$. In this scenario, $SI$ is typically negligible in front of $MUI$ which severely degrades the expected performance of the matched filter receiver.

Let us discuss about a subspace interference canceller which intends interference reduction by a GSLC like structure assuming perfect knowledge of the multipath characteristic (channel weights and delays). This scheme, described for a two paths($a, b$ and delay $n_i$) channel in fig.1, performs single user detection working at baud rate ($T_s$) where blocking matrix $B$ must span the orthogonal subspace of $DS$ in each branch. If perfect timing is available, at sampling time the $DS$ is spanned by the signature matrix $\{S_i^r\}$. Adaptive filters $w_1$ and $w_2$ intend to decorrelate both branches with the main branch in order to suppress $MUI$ and $SI$. The update of both filters is a standard constrained optimization problem. Finally, optimum combining is performed before the detection procedure.

![Fig.1 Single user detector assuming perfect knowledge of channel parameters](image-url)
However, the situation described in fig.1 is not realistic because channel acquisition is in fact a keypoint depending on the MUI and SI, which may severely degrade the expected behavior. Let us recall that errors in timing or channel estimation are propagated dramatically to the detector stage. Our proposal deals with a more feasible approach to the single user detection by the incorporation of a previous MUI/ SI cancellation to improve the synchronization performance and channel acquisition. This interference reduction is implemented as a multirate canceller working at chip rate (acquisition). This interference reduction is implemented as a multirate canceller working at chip rate (acquisition). This interference reduction is implemented as a multirate canceller working at chip rate (acquisition). This interference reduction is implemented as a multirate canceller working at chip rate (acquisition).

Let us discuss the main ideas remarked in figure 2.

![Fig.2. Detection scheme for SI/MUI reduction for time synchronization and optimum combining.](image)

Blocking matrix B must be designed to span the orthogonal subspace of s_t and all the possible shifting and zero padding versions of it. This subspace is defined taking account of the maximum expected channel length L (it must be assumed that all the multipath signals arrive within several chips duration, L << L_c where L_c is the code length). We have found that this subspace must be orthogonal to 1+2L possible shifts (the unshifted s_t and the corresponding L shifts for the pre and post interference). In this situation, the channel characteristics appear almost MUI and SI free leading to a very accurate parameter acquisition.

Our approach shares the purpose of [7] where it is proposed a joint decorrelating multiuser detection and channel estimation but with a blind single user perspective exploiting subspace properties of different signals involved (DS, SI, MUI). Also, a relationship with [8] is evident in terms of the partitioned linear interference canceller structure, but incorporating the multirate scheme at chip rate. Let us remark that DS span is only achieved at the correct chip phase meanwhile for the remainder a general signal cancellation is provided. This behavior is quite interesting because the false alarm is reduced considerably because spurious peaks are significantly suppressed as it can be observed in the computer simulation section.

The sampling time can be performed optimally by the inspection of periodic peaks after the matched filter with the interference minimized. Also, it should be determined the number of resolvable paths.

Once number and position of significant paths are determined, optimum combining of the multipath will add coherently the contribution of different paths to improve the SNR [6]. Our approach in this topic is well known in matrix algebra. After sampling, a L-vector x(n) (remember L as the channel length at chip rate) is obtained at baud rate, that is:

\[ x(n) = c_i b_i(n) + \epsilon(n) \]  \hspace{1cm} (12)

where \( c_i \) is the channel response and \( \epsilon(n) \) represents the noise and residual MUI effect. The autocorrelation of \( x(n) \), assuming a satisfactory performance of the interference canceller can be approximated as follows:

\[ R_x = E\{x(n)x^*(n)\} = c_i c_i^* + R_w = c_i c_i^* \]  \hspace{1cm} (13)

because of the noise and interference decorrelation. This enables us to approximate the optimum combining vector using the principal eigenvector of \( R_x \), which can be obtained blindly using standard decomposition techniques [9]. However, let us mention that an ambiguous phase should appear inherent to the problem.

3. PERFORMANCE ANALYSIS

Several computer simulations have been conducted to support our proposal for different coding length and coders (Walsh-Hadamard and Gold) in terms of the number of users. In terms of the timing acquisition, Gold codes are more appropriate due to its inherent peak autocorrelation feature. The channel is a two-paths invariant system described by its impulse response c[n]:

\[ c[n] = \delta[n] + 0.6 \delta[n-4] \]  \hspace{1cm} (14)

Our experiments with BPSK modulation lead us to the conclusion that our method allows much accurate channel acquisition and time synchronization due to the suppression of the masking effect of the MUI and SI.

Fig.3 shows the output of the matched filter directly (a) and with the proposed interference canceller (b) described in fig.2 for a two-path environment, a 64 spreading factor and 25 active users with pseudo-random code. This simulation presents a block Least Squares solution where \( E_s/N_0 = 20 \) dB in terms of the received power corresponding to the desired user and a zero mean additive white Gaussian noise. In can be observed that the matched filter output is severely masked by the MUI with the consequent false alarm increase. In this situation, this system is unfeasible and would require an specific training sequence for timing acquisition. On the other hand, the canceller effect is quite significant providing an almost interference free sequence for the corresponding timing acquisition.
Finally, we have evaluated the error probability for both schemes for the previously described scenario with 25 active users and spreading factor 64 for several SNR values. In the case of the matched filter scheme we have selected the right sampling phase because it is unfeasible from data. The results are presented in figure 4 showing an interesting behavior; of course, the interference canceller presents a significant improved performance but also, the performance is limited by the noise power instead of the interference level. This fact is showed because the BER curve for the matched filter reaches a flat convergence even for very high SNR meanwhile for our proposal, it shows a continuously decreasing behavior.

4. CONCLUSIONS AND LINES OF FURTHER RESEARCH

In this paper we have presented a new scheme which enables almost free time synchronization, channel acquisition and optimum combining where only the desired user signature is required. The interference is significantly reduced by a GSLC like structure where the blocking matrix is designed according to the desired user signature and the maximum channel time span at chip rate rather than at baud rate, all the subsequent topics in the single user receiver are significantly improved. Several computer simulations support the feasibility of our proposal. Our present line of research is focused on the adaptive implementation of this scheme and the analysis of its convergence features.

5. REFERENCES