ADAPTIVE MULTI-SENSOR RECEIVERS FOR FREQUENCY SELECTIVE CHANNELS

IN DS-CDMA COMMUNICATIONS SYSTEMS

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ABSTRACT

The performance of two adaptive multi-sensor Least
Squares (LS) receivers for a frequency-selective fading
channel are evaluated. These two receivers are preceded by a
RAKE which combines the resolvable paths of each channel of
the desired user before further interference suppression. In
the first, a LS space-time filter is used to accomplish
despreading and interference rejection simultaneously. The
second is a spatial-temporal version of the partial
despreading LS (prds-LS) as proposed in [1]. For the partial
despreading structure, the number of coefficients are reduced
to the LS structure. If the desired user's channel
coefficients are known, the multi-sensor prds-LS is very
attractive for DS-CDMA systems with large processing gain
in terms of both complexity and tracking performance.

INTRODUCTION

The single sensor minimum mean squared error (MMSE)
receiver has been proposed for interference suppression for
direct sequence code-division multiple access (CDMA)
systems [2], [3], [4]. It possesses several advantages relative
to the matched filter such as near-far resistance, and it does not
require knowledge of the amplitudes, phases and spreading
codes of the other users.

However, in realistic multipath fading channels, the
adaptive version (stochastic gradient or least squares) must be
able to track the fading of the desired user as well as that of
the other users. Moreover, in frequency selective fading channels
the receiver must be able to combine the discrete paths of the
desired user and track the multipath fading of the interfering
users. Furthermore, the complexity of the receiver affects the
convergence and tracking capabilities of the adaptive

algorithm. Since the number of coefficients in the adaptive
linear MMSE detector must be equal to the processing gain,
the performance of the adaptive receiver can significantly
degrad when the processing gain is large.

In this paper, we examine the performance of two multi-
sensor receivers, the linear LS and the partial despread LS
(prds-LS), in frequency selective fading channels. The
channels are modeled with 3-paths, each assumed to exhibit
independent Rayleigh fading. The multi-sensor LS gives
better performance than the multi-sensor prds-LS for low
processing gain and small number of sensors (≤2). The
multi-sensor prds-LS is shown to be advantageous for the
case of large processing gain scenario, since the number of
adaptive elements is reduced. Knowledge of the desired
user's fading channel can be exploited to improve
performance in terms of path diversity and tracking of
dynamic multipath fading.

SYSTEM MODEL

The low pass equivalent transmitted signal for the k-th
user is given by

\[ s_k = A \sum_{i=-\infty}^{\infty} I_{k} e^{j\phi_k} p_c(t-iT_c-\Delta_k), \]

(1)

where \( p_c(t) \) is the chip pulse shape, \( A^2 \) represents the
transmitted signal power of each user, \( \Delta_k \) is a uniform
random delay between [0,T] due to the asynchronous
transmission between different users, and \( \phi_k \) is a uniformly
distributed carrier phase angle between [0,2\pi]. The i-th
transmitted chip, for the k-th user for a peer-to-peer DS-
CDMA system, assuming BPSK modulation, is given by
\[ I_k = a_k b_k \]. The user's data signal \( b_k \) is an iid. binary
\((-1\) or \(+1\)) sequence, where \([x]\) is the integer part of \(x\) and
\(N\) is the spreading gain, that is, the ratio of the spread
bandwidth and the data bandwidth. Finally, \(a_k\), \(i = 1, ..., N\),
represents the user's spreading sequence, which is also
binary.

The channel impulse response on the \(d\)-th sensor seen by
the \(k\)-th user is defined as
\[
h_k(t) = \sum_{l=1}^{L_n} \alpha_{kl} \delta(t - \tau_l) \quad \text{with} \quad \alpha_{kl} = |\alpha_{kl}| \cdot e^{j\phi_{kl}}, \tag{2}
\]
where \(|\alpha_{kl}|\) is the amplitude of the \(l\)-th path, having a Rayleigh
distribution, \(\phi_{kl}\) is a random phase, uniformly distributed
between 0 and \(2\pi\), and \(L_n\) is the total number of paths. The
channel model used in this paper is given in Table 1

<table>
<thead>
<tr>
<th>Path</th>
<th>Delay ((\mu s))</th>
<th>Amplitude (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>-2.6</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>-3.0</td>
</tr>
</tbody>
</table>

Table 1: Channel Model

The low pass equivalent received signal on the \(d\)-th
sensor, after the chip matched filter, can be expressed as
\[
r_d(t) = A \left( \sum_{k=1}^{K} \sum_{l=1}^{\infty} I_k e^{j\phi_k} \sum_{l=1}^{L_n} \alpha_{kl} p(t - iT_c - \Lambda_{kl}) \right) + \eta_d(t), \tag{3}
\]
where \( P(t) = P_c(t) \ast P_c(t) \) is assumed to be a raised cosine Nyquist filter, \( \Delta_t \) accounts for the multipath delay and the asynchronous delays corresponding to the \( k \)-th user and \( \eta_d(t) \) is AWGN with zero mean and single-sided power density given by \( N_0 \).

**MMSE ADAPTIVE RECEIVERS**

Consider first an MMSE adaptive receiver which consists of a tapped delay line with \( M \) coefficients spaced by the inverse of spread bandwidth \( (T_c) \). We assume perfect code synchronization for the desired user (user #1), i.e \( \Delta_t = 0 \). We can express the contents of the filter on the \( d \)-th sensor during the \( m \)-th symbol in vector form as

\[
\begin{bmatrix}
\tilde{r}_d(m) = \\
\end{bmatrix}
\begin{bmatrix}
\tilde{r}_{d_{(m-1)M+1}}(m) \\
\vdots \\
\tilde{r}_{d_{(m+1)M}}(m)
\end{bmatrix}
\]

(4)

The elements of the tap delay line, \( r_{d_j} \), depend on the receiver structure. Here we consider two structures and the elements are given as follows:

(i) for the MMSE adaptive receiver with \( M = N \), i.e. the processing gain,

\[
r_d = r_d(JT_c)
\]

(5)

(ii) for the partial despread over a duration of \( T_c/M \) and an MMSE adaptive receiver with \( M \) coefficients,

\[
r_d = \sum_{n=M}^{N} \alpha_{n}^* r_d(nJT_c - \tau_i)
\]

(6)

The output of the adaptive filter is given by

\[
y(m) = W(m)R^H(m)
\]

(7)

where

\[
R(m) = \begin{bmatrix}
\tilde{r}_1(m) & \cdots & \tilde{r}_D(m)
\end{bmatrix},
\]

(8)

\[
W(m) = \begin{bmatrix}
\tilde{w}_1^* (m) & \cdots & \tilde{w}_D^* (m)
\end{bmatrix}
\]


\[
W(m) = \begin{bmatrix}
\tilde{w}_1^* (m) & \cdots & \tilde{w}_D^* (m)
\end{bmatrix}
\]

is the tap weight vector of size \( MD \), \( M \) is the number of taps on each sensor and \( D \) is the number of sensors. In this paper, we consider the least squares (LS) algorithm to minimize the cost function

\[
J = \sum_{m=1}^{i-1} \lambda^{i-m-1} |e_m|^2,
\]

(9)

where \( \lambda \) is the forgetting factor and is close to one, and \( e_n = b_1(m) - y(m) \) is the error to be minimized. The optimum coefficient vector that minimizes \( J \) is given by

\[
W_{opt} = \Gamma^{-1} \xi,
\]

(10)

where

\[
\Gamma = \sum_{m=1}^{i-1} \lambda^{i-m-1} R^H(m)R(m)
\]

(11)

**PRE-RAKE and MMSE STRUCTURE**

In order to alleviate the tracking of the channel coefficients of the desired user, we consider a RAKE combiner on each sensor before further suppression of the MAI. In this case Equations (5) and (6) become, respectively,

\[
r_d = \sum_{i=1}^{L_n} \alpha_{n}^* r_d(nJT_c - \tau_i)
\]

(12)

\[
r_d = \sum_{n=M}^{j} \sum_{i=1}^{N} \alpha_{n}^* r_d(nJT_c - \tau_i) a_{1_d}
\]

(13)

**NUMERICAL RESULTS**

The performance of the two receivers is compared numerically via simulations. The system is shown in Figure 1. The channel was modeled with 3 paths as shown in Table 1. The users' data symbols were modulated by an augmented M-sequence of length 32 multiplied by a Walsh code. The pulse shape is a square-root-raised-cosine (SRRC) filter. Differential coding and decoding is used. The Recursive Least Squares (RLS) algorithm is used to update the LS detector coefficients [5, Table 13.1].

First consider the case where the receiver has no a priori knowledge of the desired user's channel coefficients. Figure 2 shows the bit error rate (BER) obtained with the two LS structures and a RAKE using perfect maximal-ratio combining (MRC). The number of coefficients in the LS structure is equal to 32 (processing gain). For the prds-LS, the signal is partially despread over 4 chips; that is, the number of coefficients of the LS structure is equal to 8. It can be observed that for the single sensor case, both adaptive LS receivers perform worse than the RAKE receiver. However, in the 2-sensor case, the adaptive LS provides a slight improvement compared to the RAKE receiver, but not the partial despread and LS scheme (prds-LS). It appears that
for the fade rate chosen (i.e., 50 Hz), the single sensor adaptive schemes are not able to track the fading of the desired user as well as the multi-access interference. Further, the prds-LS is not able to combine the multipath, in contrast to the full LS detector. As the receiver is synchronized to the first path, the partial despreads the other two paths and therefore path diversity is less effective than with the full LS detector. However, the performance of the LS with 3-sensors and number of coefficients equal to the processing gain exhibited very poor performance because the adaptive algorithm diverged (BER not shown on Figure 3). This is because the number of coefficients was too large ($96 = 3 \times \text{Processing Gain}$) to enable accurate tracking.

![Figure 1 - BER as function of number of users (No a priori knowledge of channel coefficients)](image1)

In order to alleviate the tracking of the desired user's multipath fading, we consider a pre-RAKE on each sensor before applying the two LS adaptive filters. The desired user's channel coefficients are assumed to be perfectly known; that is, the pre-RAKE is a perfect MRC.

The BER obtained as a function of the number of users when the two adaptive LS structures are preceded by a RAKE is shown in Figure 3. It is clearly seen that there is a significant improvement in performance. For both structures, the performance improves with the number of sensors. Furthermore, the LS outperforms the prds-LS for the single sensor and 2-sensor receivers.

![Figure 2 - BER as function of number of users with Pre-RAKE (MRC)](image2)

Next we consider the performance in a near-far scenario of 6 interferers with an average power 6 dB higher than that of the desired user. First, we consider the prds-LS receiver with different numbers of adaptive coefficients. Figure 4 shows the BER obtained when the partial despreads interval is $T_s/M$ where $M$ is the number of the coefficients in the prds-LS structure and the processing gain is 32. The results show that the best performance is obtained when $M=32$. However, in this case, the processing gain is low. If a higher processing gain had been used, the performance would probably degrade, because of the number of coefficients.

![Figure 3 - BER vs. partial desprearding parameter $M$](image3)
Second, we consider the performance of the prds-LS for two different Doppler frequencies of the fading process. The number of coefficients on each sensor is 8, that is the partial despread reading is done over 4 chips. Figure 5 shows the BER obtained for Doppler frequencies equal to 70 and 100 Hz respectively. The difference in performance for the two Doppler frequencies depends on the number of coefficients.

![Figure 4 - BER for the prds-LS receiver at 2 different Doppler frequencies](image)

**CONCLUSION**

The performance of two multi-sensor LS adaptive structures are comparatively evaluated in a frequency selective fading channel. The results obtained indicate that both structures can perform poorly in a such frequency selective channel because of tracking problems. However, if the channel coefficients of the desired user are known, their performance is significantly improved. In this paper, the two structures are preceded by a RAKE with MRC. A more appropriate way to implement the receiver if the desired user's channel coefficients are known is to incorporate them in the RLS algorithm instead of the pre-RAKE, because the pre-RAKE modifies the statistics of the MAI.

**REFERENCES**


