Blind Adaptive Multiuser Detection and Integrated Channel Estimation in Multipath CDMA Channels

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Abstract- In this paper a blind, adaptive multiuser receiver for CDMA channels with integrated channel estimation is considered. The proposed receiver requires only the signature code of the user of interest (UOI) and does not require any training sequences, the channel parameters and signature codes of the interfering users. In a dynamic channel scenario, the tracking of the channel is done adaptively with reduced computational complexity. Though the channel parameters of the UOI are not explicitly calculated, the energies of multiple paths are advantageously combined as done in a conventional RAKE receiver. After removing the multiple access interference (MAI), the signal to noise ratio (SNR) of the system is further improved using the min-max criterion. The performance of the receiver matches that of a non-adaptive, non-blind MMSE receiver and its performance in a mobile, fading environment is found to be encouraging. In a high SNR scenario, no up-dation of the receiver filter is needed when the channels of the interfering users change and only a few computations are required for the up-dation of the receiver filter when channel of the UOI changes.

Key-Words-Blind adaptive multiuser detection, integrated detection and channel estimation, min-max criterion, fading channels, MOE criterion, LMS algorithm.

1.Introduction

In a conventional CDMA system, the matched filter is used for the detection of the data of the user of interest (UOI) and interference from other users is treated as additive, white noise. When number of users increases, due to the near-far effect, the signal of UOI get lost in the signals of interfering users and this effect is termed as multiple access interference (MAI). Using the multiuser detection [1], MAI can be mitigated and the performance of the system can be drastically improved. In a fading multi-path scenario, the channel characteristics are time variant and the signal reaches the receiver via different paths. In such a situation, the gains of individual paths are estimated and then used for the detection of data [2]. The channel parameters are usually estimated with the help of training sequences and this method consumes a sizable bandwidth.

In order to accomplish multiuser detection different methods have been proposed [1]. The optimal multiuser detector for CDMA systems has exponential computational complexity and because of this, sub-optimal detectors like decorrelating detectors and minimum mean squared error (MMSE) detectors are more popular. In a conventional decorrelating or MMSE detector, the knowledge of the signature codes/signal amplitudes of all the users is necessary for the detection of a particular user's data. However, the signature codes of the interfering users are not usually available at the detector of the UOI, and this requirement is relaxed in the blind detectors. There are several schemes for blind detection [1], [3], [6]. In the subspace based blind method, the received signals, after demodulation and chip-matched filtering are subjected to singular value decomposition (SVD) or autocorrelation matrix of the received signals are subjected to eigen value decomposition (EVD) [3]. In the batch processing version of the subspace method, the received signals are processed en-bloc and are not suited to a dynamic channel. The online (symbol by symbol adaptation) version of subspace scheme is suited to dynamic channels and is recursive in nature. The channel parameters also can be estimated blindly. The subspace method mentioned above is used for blind channel estimation also [4], [5]. In order to cope with the changing channel scenario, iterative methods for channel estimation also, are available. Another adaptive, blind method is based on the criterion of minimum output energy (MOE) [1].

If channel estimation and data detection are combined, a good amount of hardware/computations can be saved. In this paper we are proposing an integrated method for channel estimation and data detection. The paper [3] discusses an integrated method for channel estimation and data detection and there, the effective signature code of the UOI is first determined as the intersection of the subspace spanned by the signature code of UOI (and its delayed versions) and received signal subspace. Once the effective signature code is obtained, the decorrelating detector or MMSE detector is formed using the subspace method, as stated earlier. Here the drawbacks are that, the channel estimation has to be done separately and when the channels of the interfering users change, the receiver filter is to be updated. Moreover errors in the estimation of the channel results in cancellation of the desired signal due to signature mismatch.

In the proposed method the decorrelating or MMSE filters, corresponding to each path of the UOI is first determined in a blind, adaptive manner using the MOE criterion. The received signal is then projected on to the subspace spanned by these filter vectors to obtain the final detector filter. By adopting differential encoding, performance matching the non-adaptive, non-blind MMSE receiver is obtained without explicitly estimating the channel, at a reasonable computational complexity. In the following, column vectors and matrices are indicated through boldface lowercase and uppercase letters respectively. Here $\langle \mathbf{x}_1, \mathbf{x}_2 \rangle$ represents the dot product of vectors $\mathbf{x}_1$ and $\mathbf{x}_2$, $(\cdot)^T$ transpose, $(\cdot)^{\mathbf{H}}$ conjugate transpose and $\mathrm{R}(\cdot)$ real part of a complex number.

2. Signal Model

Consider a base-band synchronous direct sequence CDMA system with K active users. The received signals can be modeled as

$$r(t) = s(t) + \sigma n(t) \tag{1}$$

where $n(t)$ is white, Gaussian noise with unit power spectral density, σ^2 is the variance of noise and $s(t)$ is the superposition of the data signals of K users, given by

$$s(t) = \sum_{k=1}^{K} A_k \sum_{i=-M}^{M} b_k(i) s_k(t - iT - \tau_k) \tag{2}$$

where $2M+1$ is the number of data symbols per user per frame, T is the symbol interval and $A_k, \tau_k, \{b_k(i); i = 0, \pm1, \ldots\ldots \pm M\}$ and $\{s_k(t); 0 \le t \le T\}$ denote respectively, the received amplitude, delay, symbol stream, and normalized signaling waveform of the k^{th} user. For the DS-CDMA multiple access format, the user signaling waveform are of the form

$$s_k(t) = \Sigma_{j=0}^{N-1} \beta_j^k \varphi(t - jT_c), \quad t \in [0, T] \tag{3}$$

where, N is the processing gain, $(\beta_0^k, \beta_1^k, \ldots\ldots\ldots\ldots\ldots \beta_{N-1}^k)$ is the signature sequence of $\pm 1s$ assigned to the k^{th} user, f is a normalized chip waveform of duration T_C, with $NT_C = T$.

In this paper we restrict our attention to the synchronous CDMA, in which, $\tau_1 = \tau_2 = ...\tau_K = 0$. It is then sufficient to consider received signal during one symbol interval, and the received signal model becomes

$$r(t) = \Sigma_{k=1}^{K} A_k b_k s_k(t) + \sigma n(t), \quad t \in [0, T] \tag{4}$$

At the receiver, chip matched filtering followed by chip rate sampling yields an N-vector of chip filter output samples, within a symbol interval T as shown bellow

$$\mathbf{r} = \Sigma_{k=1}^{K} A_k b_k \mathbf{s}_k + s\,\mathbf{n} \tag{5}$$

where, $\mathbf{s}_k = 1/\sqrt{N}[\beta_0^k, \beta_1^k, ...\beta_{N-1}^k]^T$,is the normalized signature vector of the k^{th} user, and $\mathbf{n}$ is a white Gaussian noise vector with mean zero and covariance matrix $\mathbf{I}_N$.

When the signal is transmitted over a multi-path channel, at the receiver end, the effective signature wave form is the multi-channel response to the original signature waveform. Suppose that K users are transmitting synchronously over a multi-path channel, the number of resolvable paths for each user is L= [WTm], where W is the signal bandwidth & Tm is the multi-path spread of the channel. The impulse response of such a multi-path channel for the k^{th} user can be represented by a tapped delay line format:

$$h_k(t) = \Sigma_{l=1}^{L} h_{k,l}\,\delta(t - (l-1)T_c) \tag{6}$$

Where T_c =1/W, is the chip period and the coefficients $h_{k,l}$ are complex channel gains. The complex N-vector of chip matched filter output within a symbol interval is

$$\mathbf{r} = \Sigma_{k=1}^{K} A_k b_k \Sigma_{l=1}^{L} h_{k,l}\mathbf{s}_{k,l} + s\,\mathbf{n}$$
$$= \Sigma_{k=1}^{K} A_k b_k \tilde{\mathbf{s}}_k + s\,\mathbf{n} \tag{7}$$

where $\mathbf{s}_{kl}$ is the vector representation of the delayed user signature waveform, $\mathbf{s}_k(t-(l-1)T_c)$ and $\tilde{\mathbf{s}}_k = \mathbf{S}_k\mathbf{h}_k$, is the received composite signature wave form of the k^{th} user, where $\mathbf{S}_k = [\mathbf{s}_{k1}\mathbf{s}_{k2}............\mathbf{s}_{kL}]$ and $\mathbf{h}_k = [h_{k1}\, h_{k2}..........h_{kL}]^T$

3. Blind Adaptive Multiuser Detection

Assume that the user of interest is the first user. A blind, adaptive method for detecting the energy of the first path of the first user, using the MOE criterion is discussed first. This scheme is then extended for the detection of the energies of other paths of the first user. It can be shown that this method belongs to the class of MMSE detector and when noise is zero this reduces to a decorrelating detector. In this method the output variance is minimized using the gradient descent algorithum as follows:

The output variance is minimized with respect to $\mathbf{x}_1$, where $\mathbf{x}_1$ is a vector orthogonal to $\mathbf{s}_1$.

$$\text{MOE}(\mathbf{x}_1) = E[(\langle \mathbf{r}, \mathbf{s}_1 + \mathbf{x}_1 \rangle)^2] \tag{8}$$

The gradient of the above function lies in the same direction as the observed signal:

$$\nabla \text{MOE} = 2\langle \mathbf{r}, \mathbf{s}_1 + \mathbf{x}_1 \rangle \mathbf{r} \tag{9}$$

The component in (9) orthogonal to $\mathbf{s}_1$ is a scaled version of the component of $\mathbf{r}$ orthogonal to $\mathbf{s}_1$:

$$\mathbf{r} - \langle \mathbf{r}, \mathbf{s}_1 \rangle \mathbf{s}_1 \tag{10}$$

Therefore, the projected gradient (orthogonal to $\mathbf{s}_1$) is

$$2\langle \mathbf{r}, \mathbf{s}_1 + \mathbf{x}_1 \rangle [\mathbf{r} - \langle \mathbf{r}, \mathbf{s}_1 \rangle \mathbf{s}_1] \qquad (11)$$

The adaptive algorithm updation proceeds at the data rate. The observed wave form r (t) is slotted into waveforms of duration T, and the orthogonal component at the i^{th} iteration is $\mathbf{x}_1[i]$. Denote the responses of the matched filters for $\mathbf{s}_1$ and $\mathbf{s}_1 + \mathbf{x}_1[i-1]$ respectively by

$$Z_{MF}[i] = \langle \mathbf{r}[i], \mathbf{s}_1 \rangle \qquad (12)$$

$$Z[i] = \langle \mathbf{r}[i], \mathbf{s}_1 + \mathbf{x}_1[i-1] \rangle \qquad (13)$$

according to the stochastic gradient adaptation rule,

$$\mathbf{x}_1[i] = \mathbf{x}_1[i-1] - \mu Z[i] \\ .(\mathbf{r}(i) - Z_{MF}[i]\mathbf{s}_1) \qquad (14)$$

where, μ is the step-size parameter. Finally the MOE detector for the first path is given as

$\mathbf{m}_1 = \mathbf{s}_1 + \mathbf{x}_1$. Using identical steps, the filter coefficients of different paths of the first user are given as

$$\mathbf{m}_{11} = \mathbf{s}_{11} + \mathbf{x}_{11}$$
$$\mathbf{m}_{12} = \mathbf{s}_{12} + \mathbf{x}_{12}$$
$$\ldots\ldots\ldots\ \ \ldots\ldots\ldots\ \ \ldots$$
$$\mathbf{m}_{1L} = \mathbf{s}_{1L} + \mathbf{x}_{1L} \qquad (15)$$

3.1 Decorrelating Detector

When SNR is high $\mathbf{m}_{11}, \mathbf{m}_{12} \ldots\ldots\ldots \mathbf{m}_{1L}$ are the decorrelating detectors corresponding to L paths of the UOI. So according to [3],

$$\mathbf{m}_{1l} = \sum_{i=1}^{KL} [\mathbf{R}^{-1}]_{li} \mathbf{s}_i \qquad (16)$$

where $\mathbf{R}$ is the correlation matrix of the user signature codes and its delayed replicas. The linear combination of these decorrelating detectors and its inner product with signature code (or its delayed versions) of the users ($\mathbf{s}_p$) is as shown.

$$[c_1 \mathbf{m}_{11} + \ldots\ldots\ldots c_L \mathbf{m}_{1L}]^T \mathbf{s}_p$$
$$= c_1 \sum_{i=1}^{KL} [\mathbf{R}^{-1}]_{1i} \mathbf{s}_i{}^T \mathbf{s}_p + \ldots c_L \sum_{i=1}^{KL} [\mathbf{R}^{-1}]_{Li} \mathbf{s}_i{}^T \mathbf{s}_p$$

$$= c_1 \sum_{i=1}^{KL} [\mathbf{R}^{-1}]_{1i} [\mathbf{R}]_{ip} + \ldots c_L \sum_{i=1}^{KL} [\mathbf{R}^{-1}]_{Li} [\mathbf{R}]_{ip}$$

$$= c_1 [\mathbf{R}^{-1}\mathbf{R}]_{1p} + \ldots\ldots\ldots\ldots c_L [\mathbf{R}^{-1}\ \mathbf{R}]_{Lp}$$

$$= \{c_1, \text{for}, \ p = 1; \ldots\ldots\ldots; c_L, \text{for}, p = L;$$
$$\{0, \text{for}, p = L + 1 \ldots\ldots\ldots KL. \qquad (17)$$

where c_1 - - - c_L are constants and p varies from 1 to KL. So it can be seen that when the received signal is filtered using any linear combination of the obtained decorrelating detectors, the interference from other users is completely removed and only the energy corresponding to UOI appears at the output. Each filter vector obtained as above is orthogonal to the subspace spanned by the signals of the interfering users and signals corresponding to other paths of the UOI [6]. Hence the subspace spanned by the filter vectors will be orthogonal to the signals of the interfering users i.e., any linear combination of $\mathbf{m}_{11}, \mathbf{m}_{12} \ldots\ldots\ldots \mathbf{m}_{1L}$ will be orthogonal to the interfering signals.

3.2 MMSE Detector

It is shown in [1] that MOE detector is equivalent to an MMSE detector. So in the presence of noise the filter vectors $\mathbf{m}_{11}$, $\mathbf{m}_{12} \ldots\ldots\ldots \mathbf{m}_{1L}$ represents the MMSE detector corresponding to different paths of the UOI. As per MOE criterion,

$$E[(\mathbf{m}_{11}{}^T\mathbf{r})^2] = \min., \text{ s.t } \mathbf{m}_{11}{}^T\mathbf{s}_{11} = 1$$

i.e.,

$$E[(\mathbf{m}_{11}{}^T\mathbf{r})^2] = \min., \text{ s.t } \mathbf{m}_{11}{}^T\mathbf{s}_{11} = 1$$

$$-------------------$$

$$E[(\mathbf{m}_{1L}{}^T\mathbf{r})^2] = \min., \text{ s.t } \mathbf{m}_{1L}{}^T\mathbf{s}_{1L} = 1$$

Combining all the paths,

$$E[\|\mathbf{M}^T\mathbf{r}\|^2] = \min.,$$

$$\text{s.t Diag}(\mathbf{M}^T\mathbf{S}_1) = \text{Ones}(Lx1) \qquad (18)$$

Where, $\mathbf{M} = [\mathbf{m}_{11}\,\mathbf{m}_{12}\,..........\mathbf{m}_{1L}]$ and

$\mathbf{S}_1 = [\mathbf{s}_{11}\,\mathbf{s}_{12}.........\mathbf{s}_{1L}]$

For the MMSE detector, it can be shown [8] that it is immune to interferers having large power.

4.Integrated Data Detection and Channel Estimation

Any linear combination of $\mathbf{m}_{11},$ $\mathbf{m}_{12}.........\mathbf{m}_{1L}$ will not guarantee maximum SNR. In order to maximize the signal power, the received signal is projected on to this filter vector subspace to get the final filter, $\mathbf{m}_1$. Thus in order to remove MAI the energy is minimized using the MOE criterion and after the removal of MAI the energy is maximized to improve the SNR. This min-max principle is successfully applied here. In the case of the decorrelating detector an orthogonal basis for $\mathbf{m}_{11},$ $\mathbf{m}_{12}.........\mathbf{m}_{1L}$ is first formed, and $\mathbf{r}$ is then projected over this subspace. The proposed receiver is neither dependent on estimated channel parameters nor on training sequences and hence the modulation format cannot be a plain BPSK. We thus assume differential encoding and decoding, implying that the information of the pth signaling interval is contained in the signal $b_1(p)$ and $b_1(p\text{-}1)$ where $b_1(p)$ and $b_1(p\text{-}1)$ are the bits of UOI in the pth and (p-1)th symbol interval, respectively. Thus, the decision rule is

$$d(p) = \text{sgn}[\, R\{(\mathbf{m}_1{}^H\mathbf{r}(p))(\mathbf{m}_1{}^H\mathbf{r}(p-1))^*\}]$$

where d(p) is the incremental phase between $b_1(p)$ and $b_1(p\text{-}1)$.

For time varying channels, the final filter vector obtained as above should be updated frequently. In this case the decision rule is modified as,

$$d(p) = \text{sgn}[\, R\{\mathbf{m}_1(p)^H\,\mathbf{m}_1(p-1)^*\}],$$

where $\mathbf{m}_1(p)$ is the filter vector corresponding to the pth symbol interval and $\mathbf{m}_1(p\text{-}1)$ corresponds to that in the (p-1)th symbol interval.

5. Simulation Results

The proposed receiver is simulated for three users (K=3), each user having two paths (L=2). The channel vector, $\mathbf{h}$ is assumed to be real and $\|\mathbf{h}\| = 1$. The processing gain, N=8. At first the filter vector $\mathbf{m}_{11}$ corresponding to the first path of the first user is estimated in a blind adaptive manner using the MOE criterion, applying least mean square (LMS) algorithm [1]. Even though the convergence rate of this algorithum is slower, the computational complexity is less compared to recursive least square (RLS) algorithm. It takes around 300 runs to attain convergence. After this, the filter vector $\mathbf{m}_{12}$ corresponding to the second path of the first user is estimated, adopting similar procedures.

The received signal vector $\mathbf{r}$ is now projected on to the subspace spanned by the filter vectors $\mathbf{m}_{11}$ and $\mathbf{m}_{12}$, the resulting vector, $\mathbf{m}_1$ will be free from interfering signals (Decrrelating detector) and large amplitude interferers (MMSE detector). At the same time energies of two paths of the first user are combined as is done in a conventional RAKE receiver

When compared to a single path receiver the bit error rate (BER) is found to be lesser by an order of two (10^2). While the single path error rate is highly variable, the combined error rate was found to be stable also. When compared to the subspace tracking algorithm [3] for blind multiuser detection, the complexity of this receiver is less while error performance matches and in some cases excels that of the subspace tracking method. Moreover in our method the updation of the filter vector is not needed, when the channels of the interfering users change (for high SNR), unlike in the subspace tracking scheme. In the proposed scheme when the channel of UOI changes the updation of the filter vector is done without much computational complexity and any lapses in the updation of the filter vector only affect the SNR but the data detection is not disrupted. The system was also tested in a mobile, fading channel and the performance is found to suffer with the speed of the vehicle. Important results are shown in the table below.

Table 1

Et-Error two paths.
Es-Error single path.
Ec-Error single user channel.

Bit error out of 1000 for different channel configurations of UOI at SNR=10.5 dB.	Et	Es	Ec
	1	218	9.1027×10^{-4}
	3	27	
	5	5	
	3	7	
	7	460	
	7	484	
	7	9	
	1	1	
	3	3	
	3	21	

6. Conclusion

A blind, adaptive, integrated method for multiuser detection and channel estimation is implemented for a multi-path CDMA channels. Multi-path signals are advantageously combined, MAI eliminated and SNR improved. The complexity of the receiver is very much reduced. The receiver is tested in a mobile, fading channel and the performance is found to degrade with the speed of the vehicle. Modification of the algorithm, when new users enter the scene or existing users exit the scene is under investigation. Removal of noise from the derived filter vector using eigen value techniques is also under consideration.

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