Deterministic semi-blind detection of quasi-synchronous DS/CDMA signals using antenna arrays

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ABSTRACT

A deterministic semi-blind detector for quasi-synchronous DS/CDMA signals is proposed. The detector makes use of an antenna array for semi-blind separation and detection of the various users' signals in multipath environment. It is shown , through computer simulations, that the detector performs efficiently over small block sizes which is an advantage over statistical type detectors. Therefore, this deterministic detector is a suitable candidate for DS/CDMA signal detection in time-varying channels, such as in the mobile channel.

1. INTRODUCTION

Blind multiuser (MU) detection for DS/CDMA signals, has been a subject of ever increasing interest in the past few years. However, most of the work done in this area employs statistical methods [1,2,3,4], requiring a large number of symbols for proper operation. On the other hand, deterministic methods, are able generally to work with small sample sizes. However, in MU situations such as those associated with the DS/CDMA signal, deterministic methods are not easily implemented. Use of multiple antennas helps in deriving a better structure for the received signal that could lead to a MU separation and detection. In a recent paper [6], it was shown that by using antenna arrays, the signal parameters can be uniquely determined by a tri-linear least squares fitting technique.

In this paper, we propose a new deterministic semi-blind detector for quasi-synchronous DS/CDMA signals for operation in time-varying multipath environment. This detector does not need to know any user code in its detection process including the desired user code. The detector uses a linear antenna array to separate and detect the MU signals. It is shown through computer simulations, that the detector works efficiently over small sample sizes (33-66 bits) and significantly outperforms statistical methods for this case, thus making it ideally suitable for the dynamic mobile channel environment.

2. THE SIGNAL MODEL

A quasi-synchronous DS/CDMA signal of K-users is assumed using binary phase signaling (BPSK), and an array of M-antennas is used for signal detection. A short spreading code is used i.e., the code period is taken to be one bit or symbol period. The number of paths for each user are assumed to be equal to L, and the assumption of quasi-synchronocity is meant to imply that all the multipath signals arrive within a few chip durations Hence, it will be possible (with negligible loss in performance) to carry out symbol detection using only the code chips that are free of intersymbol interference (ISI). The number of ISI-free chips shall be denoted by P. After down-conversion, the received signal is chip match-filtered and sampled at the chip rate to give (in the absence of noise)

$$x_m(n,p) = \sum_{k=0}^{K-1} s_k(n) \sum_{l=0}^{L-1} a_l(m,k)\, c_{k,l}(p) \quad (1)$$

where $a_l(m,k)$ denotes the complex gain of the l^{th}-path of the k^{th}- user channel including the path attenuation and the array response at the m^{th} antenna, $c_{k,l}(p)$ denotes the p^{th} chip of the k^{th} user's code arriving through the l^{th}-path, taking into consideration the code delay in that path, $s_k(n)$ denotes the k^{th} user symbol at time instant n, P denotes the process gain considering ISI-free chips only. The problem of interest here is to determine the symbol sequence $\{s_k(n)\}$ for each user in the absence of the knowledge of all the users' codes.

3. THE DETECTION METHOD FOR THE SINGLE PATH CASE

The assumption made for this part of the detection is that each user signal arrives at the receiving array via a single path and a distinct DOA'. Define $\mathbf{X_m}$ to be the m[th] antenna output signal matrix (for an N-symbol block) as

$$\mathbf{X_m} = \begin{bmatrix} x_m(0,0) & x_m(0,1)\cdots x_m(0,P-1) \\ \vdots & \vdots & \vdots \\ x_m(N-1,0)\cdots x_m(N-1,P-1) \end{bmatrix} \quad (2)$$

Using (1), this matrix can be expressed in terms of the symbol and code matrices as follows (dropping the path subscript *l)*

$$\mathbf{X_m} = \mathbf{S_m C}, \quad m = 1,.....,M, \quad (3)$$

where

$$\mathbf{S_m} = \begin{bmatrix} a(m,0)s_0(0) & \cdots & a(m,K-1)s_{K-1}(0) \\ \vdots \quad \vdots & & \vdots \\ a(m,0)s_0(N-1)\cdots a(m,K-1)s_{K-1}(N-1) \end{bmatrix} \quad (4)$$

$$\mathbf{C} = \begin{bmatrix} c_0(0) & c_0(1) & \cdots\cdots & c_0(P-1) \\ \vdots & \vdots & & \vdots \\ c_{K-1}(0) & & \cdots\cdots & c_{K-1}(P-1) \end{bmatrix} \quad (5)$$

We can write the two antenna outputs as

$$\mathbf{X_1} = \mathbf{S_1 C} \qquad \mathbf{X_2} = \mathbf{S_2 C} \quad (6,7)$$

respectively. Assuming **C** to be full rank and that K<P) and from (6) and (7) we get

$$\mathbf{X_1 C^+} = \mathbf{S_1} \qquad \mathbf{X_2 C^+} = \mathbf{S_2} \quad (8,9)$$

where $\mathbf{C}^+$ is used here to denote the psuedo-inverse of **C**.But, from the definition of signal matrices $\mathbf{S_m}$ given in (4), it can be seen that the i^{th} columns of $\mathbf{S_1}$ and $\mathbf{S_2}$ are given by

$$\mathbf{s_2}(i) = \mathbf{s_1}(i) * a(2,i)/a(1,i), \; i = 0,.,K-1 \quad (10)$$

where the small bold letters **s**(i) denote here the i^{th} column of the corresponding symbol matrix. Denoting the i^{th} column of $\mathbf{C}^+$ with $\mathbf{c}^+$(i) and using (10), it follows that

$$\lambda_i \, \mathbf{X_1} \, \mathbf{c}^+(i) = \mathbf{X_2} \, \mathbf{c}^+(i), \; i = 0,.,K-1 \quad (11)$$

where λ_i is an appropriate scalar. In other words, each column of $\mathbf{C}^+$ satisfies

$$\lambda \, \mathbf{X_1} \, \mathbf{v} = \mathbf{X_2} \, \mathbf{v} \quad (12)$$

or $$\lambda \, \mathbf{v} = (\mathbf{X_1}^+ \, \mathbf{X_2}) \, \mathbf{v} = \mathbf{Z} \, \mathbf{v} \quad (13)$$

where $\mathbf{Z} = \mathbf{X_1}^+ \, \mathbf{X_2}$

It is clear from (6) and (7), and under the assumption of persistence of excitation, that the maximum rank of $\mathbf{X_1}$ and $\mathbf{X_2}$, and hence of **Z**, can be K. In fact, under the assumption of single path propagation, and distinct DOA's for each user, there will be K distinct values of λ that satisfy (13), since **Z** would have exactly K distinct non-zero eigen values. The corresponding eigenvectors of **Z** would yield the columns of $\mathbf{C}^+$. In the presence of noise, $\hat{\mathbf{C}}^+$ = {set of eigenvectors of the K-largest eigenvalues of matrix **Z** }.We can get the estimated symbol matrix directly from $\mathbf{C}^+$ as

$$\hat{\mathbf{S}}_1 = \mathbf{X_1} \, \hat{\mathbf{C}}^+ \quad (14)$$

In practice, since K is not accurately known, we will include all the eigen values of magnitude>.6. In order to identify each user's symbol column we use the concept of identity numbers (ID) for user identification, where each user symbol sequence has a certain portion of it for labeling its identity.

4. THE MULTIPATH CASE

Our approach to the extension of the results described above to the multipath case has been motivated by the desire to obtain a receiver detector, which implicitly resolves the various multipath components and the symbol sequence estimate for each user is obtained as the best of the estimates from all the paths. In the presence of multipaths, the matrix **S** will have repeated columns and hence its rank will remain K as also the rank of $\mathbf{X_1}$. The rank of **Z** can take a maximum value of K, which is less than the total number of signals (viz. KL). This will clearly make it impossible to detect signals from all the paths of each user even in the noiseless case.

To solve this problem, we restore the rank of **S** by staking several $\mathbf{X_m}$ matrices to form larger matrices, using signals from additional antennas. We stack L such matrices, and to illustrate, for the two-path case, we define the stacked matrices $\mathbf{X}_1'$ and $\mathbf{X}_2'$ in terms of the data matrices from 3 antennas, as follows:

$$\mathbf{X_1}' = \begin{bmatrix} \mathbf{X_1} \\ \mathbf{X_2} \end{bmatrix} \quad \mathbf{X_2}' = \begin{bmatrix} \mathbf{X_2} \\ \mathbf{X_3} \end{bmatrix}$$

Assuming the 3 antennas to form a linear array with a spacing of ($\lambda/2$), it is easy to see that, once again, we have

$$\mathbf{X_1}' = \mathbf{S_1}' \mathbf{C}' \qquad \mathbf{X_2}' = \mathbf{S_2}' \mathbf{C}' \qquad (15,16)$$

$$\mathbf{S_1}' = \begin{bmatrix} a_0(1,0)s_0(0) & a_1(1,0)s_0(0)\cdots & a_0(1,K-1)s_{K-1}(0) & a_1(1,K-1)s_{K-1}(0) \\ \vdots & \vdots & \vdots & \vdots \\ a_0(1,0)s_0(N-1) & a_1(1,0)s_0(N-1) & \cdots\cdots & a_1(1,K-1)s_{K-1}(N-1) \\ e^{j\phi_{0,0}}a_0(1,0)s_0(0) & e^{j\phi_{0,1}}a_1(\cdots\cdots & \cdots\cdots & e^{j\phi_{K-1,1}}a_1(1,K-1)s_{K-1}(0) \\ \vdots & \vdots & & \vdots \\ e^{j\phi_{0,0}}a_0(1,0)s_0(N-1) & e^{j\phi_{0,1}}a_1(\cdots & \cdots\cdots & e^{j\phi_{K-1,1}}a_1(1,K-1)s_{K-1}(N-1) \end{bmatrix} \quad (17)$$

$$\mathbf{C}' = \begin{bmatrix} c_{0,0}(0) & c_{0,0}(1) & \cdots & c_{0,0}(P-1) \\ c_{0,1}(0) & c_{0,1}(1) & \cdots & c_{0,1}(P-1) \\ \vdots & \vdots & & \vdots \\ c_{K-1,0}(0) & c_{K-1,0}(1) & \cdots & c_{K-1,0}(P-1) \\ c_{K-1,1}(0) & c_{K-1,1}(1) & \cdots & c_{K-1,1}(P-1) \end{bmatrix}$$

Here we have the electrical angle $(\phi_{k,l} = \pi \sin\theta_{k,l})$ where $\theta_{k,l}$ is the angle of arrival of the l^{th}-path of the k^{th} –user. The matrix $\mathbf{S}'_2$ will be the same as $\mathbf{S}'_1$ but with each column multiplied by $\exp(j\phi_i)$ (where $\phi_i = \pi\sin\theta_i$ and θ_i**:** is the angle of arrival of the signal of the i^{th} column). Assuming different DOA's, both $\mathbf{S}'_1$ and $\mathbf{S}'_2$ are full rank matrices, each having a rank of KL, as desired. From these comments, it follows that the relation (13) (with $\mathbf{X}'_1$ and $\mathbf{X}'_2$ replacing $\mathbf{X}_1$ and $\mathbf{X}_2$) holds, and **Z** will have KL non-zero eigenvalues.

However, due to the multipath signals, the matrix $\mathbf{C}'$ will become tall resulting in a non-unique solution for (8) and (9). In order to make the matrix fat again, we stack the matrices $\mathbf{X_m}$ horizontally as follows:

$$\mathbf{X}''_1 = \begin{bmatrix} \mathbf{X_1} & \mathbf{X_2} \\ \mathbf{X_2} & \mathbf{X_3} \end{bmatrix} \qquad \mathbf{X}''_2 = \begin{bmatrix} \mathbf{X_2} & \mathbf{X_3} \\ \mathbf{X_3} & \mathbf{X_4} \end{bmatrix}$$

It is easy to see that the relations given in (15) and (16) still hold, with $\mathbf{C}'$ replaced with $\mathbf{C}''$ given as

$$\mathbf{C}'' = \begin{bmatrix} c_{0,0}(0) \cdots\cdots c_{0,0}(P-1) & \cdots e^{j\phi_{0,0}}c_{0,0}(0) \cdots\cdots e^{j\phi_{0,0}}c_{0,0}(P-1) \\ c_{0,1}(0) \cdots\cdots c_{0,1}(P-1) & \cdots e^{j\phi_{0,1}}c_{0,1}(0) \cdots\cdots e^{j\phi_{0,1}}c_{0,1}(P-1) \\ \vdots \qquad \vdots & \vdots \qquad \vdots \\ c_{K-1,0}(0) \cdots\cdots c_{K-1,0}(P-1)\cdots & e^{j\phi_{K-1,0}}c_{K-1,0}(0)\cdots e^{j\phi_{K-1,0}}c_{K-1,0}(P-1) \\ c_{K-1,1}(0) \cdots\cdots c_{K-1,1}(P-1)\cdots & e^{j\phi_{K-1,1}}c_{K-1,1}(0)\cdots e^{j\phi_{K-1,1}}c_{K-1,1}(P-1) \end{bmatrix} \quad (18)$$

It can be argued that the matrix $\mathbf{C}''$ (18) will be full rank with probability one, and the solution given in (14) remains valid with these changes. With this method of stacking, the number of antennas needed will be twice the number of multipaths (which is usually small in quasi-synchronous systems) and this number will accommodate nearly P.

5. DETECTION IN THE CASE OF SIMILAR DOA'S

Even though, the probability of having two different signals having the same DOA may be rather small, it would be, nevertheless, desirable to modify the proposed method to remove the need for this assumption. In section 3, it was shown that if DOA's are distinct, then the eigenvalues will be distinct. From (10), (11) and the definition of a(m,k) we have $\lambda_i = a(2,i)/a(1,i) = \exp(j\pi\sin\theta_i)$**,** where θ_i is the angle of arrival of the i^{th} user/column signal**.** Therefore, if two signals have the same DOA then there will be two columns of $\mathbf{C}^+$ (say, $\mathbf{c}^+$(i) and $\mathbf{c}^+$(j)) that satisfy (11) for the same value of λ_i , i.e. $\lambda_i = \lambda_j$. This specific eigenvalue will clearly have two independent eigenvectors spanning the subspace containing $\mathbf{c}^+$(i) and $\mathbf{c}^+$(j). Correspondingly, there will be two columns of the estimated symbol matrix, viz., $\hat{\mathbf{s}}_1(i)$ and $\hat{\mathbf{s}}_1(j)$ which span the subspace containing the real symbol columns of the two users in direction θ_i.These relations suggest that by using a suitable linear combination of the detected symbol columns resulting from the eigenvectors whose eigenvalues (λ_i's) correspond to similar (or close) DOA's (θ_i's) or (ϕ_i's) it would be possible to estimate the desired user symbol column. The concept of ID bits can be employed usefully again to determine the optimum linear combination in the least square sense. Based on these ideas, we propose the following detection algorithm:

The total electrical view angle is divided into several sectors of equal widthsTo detect the desired user, a search is done in steps:

1. For each sector, identify all the eigenvalues (λ_i's) of matrix **Z** having magnitude (>.6) and giving (ϕ_i's) within that sector. The corresponding eigenvectors are premultiplied by the matrix $\mathbf{X_1}$ to form an estimate of the symbol columns in that sector, and then stacked as columns of a matrix **F.**

2. A matrix $\mathbf{F_s}$ is formed by truncating the columns of **F** to the first ID elements.

3. Denoting by $\mathbf{i_d}$ the column vector comprising the identity bits, the vector **w** which satisfies $\mathbf{F_s\, w} = \mathbf{i_d}$ in the least squares sense is found via $\mathbf{w=F_s^+\ i_d}$ under the assumption that $\mathbf{F_s}$ is tall with a probability close to one.

4. The estimated desired user symbols are

$$\hat{\mathbf{s}}_{\mathbf{d}} = \mathbf{F\,w}$$

5. Operation is repeated for all the sectors.

6. The detected data is chosen as the one that best satisfies the finite alphabet property.

In practice,the procedure can be implemented efficiently, as a search/track procedure.

6. COMPUTER SIMULATIONS

In our simulations, we assume a quasi-synchronous scenario with a process gain of 16 (ISI free chips) employing Gold codes. The combined impulse response of the transmitter pulse shaping filter and the receiver chip matched filter is assumed to be a raised cosine pulse with roll off factor of (0.5). The channel is assumed to provide 3-paths for each user, with the total power of each user's signal is held fixed.Performance comparison is done with the method in [5] as a statistical method using antenna arrays.

Fig.1 shows our message format in which each block of data is composed of 2-units (of symbols) for the identity part followed by q/2 -units of information. Each ID is used twice, once with the previous block, and again with the next block. The purpose of this reuse is to have an overall throughput of nearly twice the information percentage in the block. For our experiments, the value of q was taken to be 18, resulting in a throughput of 90%. The spatial view angle is assumed to be 120^o.

For all experiments, a system of 12-users (*P*=16) is assumed and performance is shown for the weakest user. For each block, a new set of DOA's, path amplitudes, delays are generated. Figure(2) shows the performance of the proposed detector and the statistical detector of [5].when the SNR for the desired user is 7 dB and the SIR (signal to interference ratio) of this user is -18 dB. This figure shows the significant advantage of the deterministic detector over the statistical one for block lengths as short as 33-66 symbols.The advantage increases with the increase of the block length. Figures (3) and (4) show performance comparisons under the same conditions above but fixing the block length of 55-symbols and varying the SNR for SIR of (-18 dB) and for equal power users case respectively. As it is expected from the deterministic nature of the proposed detector, its performance significantly improves as the SNR increases, while this is not so for the statistical detector. The figures also show that under good power controll, the proposed detector shows even a larger advantage.

7. CONCLUSIONS

In this paper, we have proposed a new semi-blind deterministic detector for quasi-synchronous DS/CDMA signals in time-varying multipath channels. The detector makes use of an antenna array to detect any or all of the user signals even without the knowledge of the users codes. ID numbers are used to identify different users as well as to make the detection process for each user more robust to noise and other perturbations. Due to its deterministic nature, the new receiver performs significantly better than statistical detectors for the range of small block lengths. This property is very useful in a dynamically changing channel such as those encountered in wireless mobile communications.

8. REFERENCES

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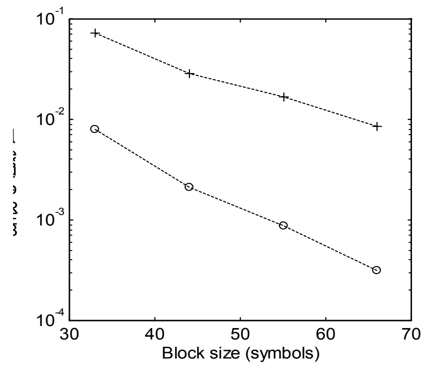

Fig.-2 BER (for user-1) verses block size; K=12, SNR(for user-1)=7dB, SIR=-18dB. (+++): statistical detector, (ooo): deterministic detector.

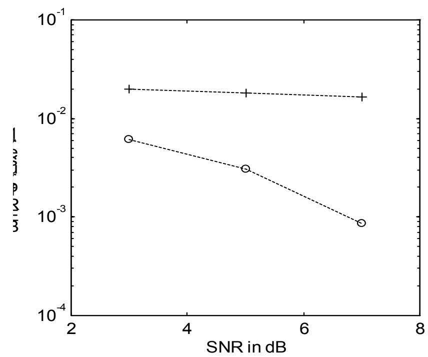

Fig.-3 BER (for user-1) versus SNR; K=12, SIR=-18 dB; block size=55 symbols.

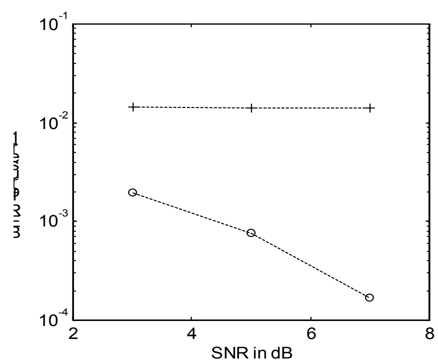

Fig.-4 BER (for user-1) versus SNR , block size=55 symbols; K=12, all users have equal powers.

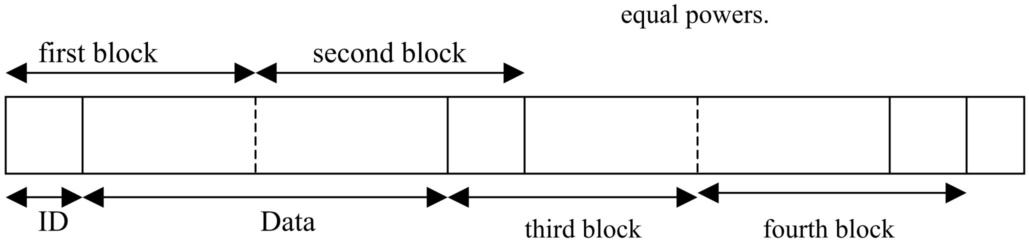

Fig.-1 User message format, and the processed blocks at the receiver.