Journal of Southeast University (English Edition) Dec. 2001 Vol.17 No.2 ISSN 1003—7985

A Decorrelating DOA Estimation Based on the Principal Eigenvector for CDMA Frequency-Selective Fading Channels

Yang Wei* Jiang Zhucheng Cheng Shixin

(National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, China)

Abstract: A novel decorrelating DOA estimation algorithm of multipath signals for CDMA frequency-selective fading channels based only on the principal eigenvector of its corresponding covariance matrix is proposed. The proposed algorithm has the advantages that the DOAs of the multipath signals can be estimated independently and all the other resolved multipath signal interference is eliminated. Simulation results show that this algorithm estimates the DOAs of multipath signals efficiently and accurately.

Key words: decorrelating, DOA estimation, antenna array, CDMA system, eigenvector

Code division multiple access (CDMA) is seen as one of the generic next-generation signal access strategies for wireless communications. CDMA possesses many intrinsic advantages over the early access techniques such as time-division multiple access (TDMA) and frequency-division multiple access (FDMA). Furthermore, as in other multiple access system, the use of antenna array in CDMA is expected to improve system capacity, quality and coverage promisingly[1]. One of the key techniques in antenna array CDMA system is the direction of arrival (DOA) estimation of the objective multipath signals. A number of DOA estimation algorithms were proposed during the last decade[2-4]. Since in CDMA, the users operate in the same frequency and time channel, and multiple access interference (MAI) arises from other users. The conventional DOA estimation algorithms such as multiple signal classification (MUSIC) and estimation of signal parameter via rotational invariance technique (ESPRIT) algorithms need that the elements of antenna array outnumber the signal source number. However, generally there are several tens of users and several sub-paths per user within a cell for a typical CDMA system. The cross-correlation from the multipath co-channel signals causes that the conventional DOA estimation algorithms such as MUSIC and ESPRIT algorithms cannot be used directly in CDMA system.

Unlike the general antenna array system, there is abundant prior knowledge of effective signature waveforms in CDMA system. The spread code is known *a priori*. In CDMA system every user processes its particular spread code, therefore in principle one can extract the desired signal one by one from each direction. The decorrelating DOA estimation algorithm proposed exploits knowledge of the desired user's spreading code and accomplishes decorrelating estimation without multiuser interference.

1 System Model

In this section, we consider the decorrelating detector[5,6] with antenna array. We only concern a synchronous CDMA channel with slow frequency-selective fading. In practice, the channels are generally asynchronous and the detection problem in an asynchronous channel is more complicated than in a synchronous channel. However, once the detection problem in a synchronous channel has been formulated, the extension to the detection problem in an asynchronous channel is straightforward. So we only consider a synchronous channel. In practice, the channel is subject to multipath fading, generally the difference between delays of sub-path signals is longer than the chip period, i.e., the channel is subject to frequency-selective fading. For this reason we concern this situation.

Assume that there are N users and each has L resolvable multipath signals when impinging on the antenna array. The base station receivers employ a linear antenna array of M uniformly spaced receiving elements, separated by a distance d, and, typically is chosen to be $\lambda/2$, where λ is the wavelength corresponding to the carrier frequency f as shown in Fig. 1.

The received signals from the base station antenna

Received 2001-03-03.

* Born in 1964, male, postdoctor.

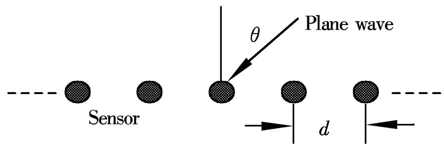

Fig. 1 Array geometry

array can be written as

$$\boldsymbol{x}(t) = \sum_{i=1}^{N}\sum_{i=1}^{L}\sqrt{P_{i,l}}b_i(t-\frac{l}{Bw}) \times c_i(t-\frac{l}{Bw})e^{j\varphi_{i,l}}\boldsymbol{a}_{i,l} + \boldsymbol{n}(t) \quad (1)$$

where $P_{i,l}, \varphi_{i,l}, b_i(t), c_i(t), Bw$, $\boldsymbol{a}_{i,l}$ are the signal power, carrier phase, information sequence, spreading sequence, channel bandwidth, and array response vector of the l-th sub-path signal of the i-th user's, respectively. $\boldsymbol{n}(t)$ denotes the zero mean spatially and temporally white Gaussian noise vector of the antenna array, i.e., $E[\boldsymbol{n}(t)\boldsymbol{n}^H(t)] = \sigma^2\boldsymbol{I}\delta(t-\tau)$, where $\delta(t)$ denotes the Dirac delta function. For synchronous system only a symbol period T_s needs to be considered. From (1) the received signals from the antenna array can be rewritten as matrix form

$$\boldsymbol{x}(t) = \boldsymbol{ABP\Phi C}(t) + \boldsymbol{n}(t) \quad 0 \leqslant t \leqslant T_s \quad (2)$$

where

$$\boldsymbol{A} = [\boldsymbol{a}_{1,1}, \boldsymbol{a}_{1,2}, \cdots, \boldsymbol{a}_{1,L}, \cdots, \boldsymbol{a}_{N,L}]$$

$$\boldsymbol{B} = \mathrm{diag}[\underbrace{b_1, b_1, \cdots, b_1}_{L}, b_2, \cdots, b_N]$$

$$\boldsymbol{P} = \mathrm{diag}[\sqrt{P_{1,1}}, \sqrt{P_{1,2}}, \cdots, \sqrt{P_{1,L}}, \cdots, \sqrt{P_{NL}}]$$

$$\boldsymbol{\Phi} = \mathrm{diag}[e^{j\varphi_{1,1}}, e^{j\varphi_{1,2}}, \cdots, e^{j\varphi_{1,L}}, \cdots, e^{j\varphi_{N,L}}]$$

$$\boldsymbol{C}(t) = [c_1(t), c_1(t-\frac{1}{Bw}), \cdots, c_1(t-\frac{L}{Bw}), \cdots, c_N(t-\frac{L}{Bw})]^{\mathrm{T}}$$

Among $\boldsymbol{C}(t)$, $c_q(t) = \sum_{n=0}^{G-1} r_q(n)g(t-nT_c)$, where G is the spreading factor or processing gain, $T_c(=T_s/G)$ is the chip period, $\{\gamma_q(n)|_0^{G-1}\}$ is the q-th user's spreading code, and $g(t)$ is the chip waveform.

To extract every resolvable sub-path signals, in conventional detector $N \times L$ correlators need to be used. The performance of the conventional detector depends on the correlation matrix that is defined by

$$\boldsymbol{R}_c = \int_0^{T_s}\boldsymbol{C}(t)\boldsymbol{C}^{\mathrm{T}}(t)\mathrm{d}t$$

From the $N \times L$ correlators with each spreading sequence, the outputs sampled at the bit epochs are given by the matrix

$$\boldsymbol{Y} = \int_0^{T_s}\boldsymbol{x}(t)\boldsymbol{C}^H(t)\mathrm{d}t = \boldsymbol{ABP\Phi R}_c + \boldsymbol{N} \quad (3)$$

where $\boldsymbol{N} = \int_0^{T_s}\boldsymbol{n}(t)\boldsymbol{C}^H(t)\mathrm{d}t$.

To eliminate the multipath signal interference and decouple the information of the user's data, the decorrelating detector applies the inverse of correlation matrix to the conventional detector output. The decoupled output matrix from the decorrelator is given by

$$\boldsymbol{Z} = \boldsymbol{YR}_c^{-1} = \boldsymbol{ABP\Phi} + \boldsymbol{N}_z = [\boldsymbol{z}_{1,1}, \boldsymbol{z}_{1,2}, \cdots, \boldsymbol{z}_{1,L}, \cdots, \boldsymbol{z}_{N,L}] \quad (4)$$

where $\boldsymbol{N}_z = [\boldsymbol{n}_{z_{1,1}}, \boldsymbol{n}_{z_{1,2}}, \cdots, \boldsymbol{n}_{z_{1,L}}, \cdots, \boldsymbol{n}_{z_{N,L}}]$.

Obviously, each column vector of the matrix $\boldsymbol{Z}$ contains a single resolved sub-path signal and has not interference from all the other resolvable mutipath signals. So every resolvable sub-path signal is detected independently.

Therefore the decoupled vector of the l-th path signal of the i-th user's can be written as

$$\boldsymbol{z}_{i,l} = \boldsymbol{a}_{i,l}\sqrt{P_{i,l}}e^{j\varphi_{i,l}}b_i + \boldsymbol{n}_{z_{i,l}} \quad 0 \leqslant l \leqslant L \quad (5)$$

where b_i is the symbol of the i-th user's signal and $\boldsymbol{n}_{z_{i,l}}$ is the corresponding noise vector. From (5) the covariance matrix of $\boldsymbol{z}_{i,l}$ is given by

$$\boldsymbol{R}_{z_{i,l}} = E[\boldsymbol{z}_{i,l}\boldsymbol{z}_{i,l}^H] = P_{i,l}\boldsymbol{a}_{i,l}\boldsymbol{a}_{i,l}^H + \tilde{\sigma}_{i,l}^2\boldsymbol{I}$$

where $\tilde{\sigma}_{i,l}^2 = \sigma^2[\int_0^{T_s}\boldsymbol{C}^H(t)\boldsymbol{v}_{i,l}\boldsymbol{v}_{i,l}^H\boldsymbol{C}(t)\mathrm{d}t]$ and $\boldsymbol{v}_{i,l}$ is the $i \times l$-th column vector of the matrix $\boldsymbol{R}_c^{-1}$. The noise vector $\boldsymbol{n}_{z_{i,l}}$ is also spatially white besides temporal white[5,6].

2 Proposed DOA Estimation Algorithm

Now we concern the DOA estimation of a desired sub-path signal. After a desired sub-path signal is decoupled based on the decorrelating algorithm above we can apply the conventional MUSIC algorithm to estimate the DOA of the desired sub-path signal based on the principal eigenvector of the covariance matrix $\boldsymbol{R}_{z_{i,l}}$.

The proposed decorrelating DOA estimation algorithm based on the principal eigenvector can be summarized as follows:

1) From finite observations of $\boldsymbol{z}_{i,l}$, estimate its covariance matrix $\hat{\boldsymbol{R}}_{i,l}$

$$\hat{\boldsymbol{R}}_{i,l} = \frac{1}{N}\sum_{n=1}^{N}\boldsymbol{z}_{i,l}(n)\boldsymbol{z}_{i,l}^H(n)$$

2) Perform an eigendecomposition of the sample covariance matrix $\hat{\boldsymbol{R}}_{i,l}$, to reveal the largest eigenvalue $\hat{\lambda}_1$ and its corresponding principal eigenvector $\hat{\boldsymbol{e}}_1$.

3) Construct the spatial spectrum function as

$$P_{mu}(\theta_{i,l}) = [1 - \| \boldsymbol{a}_{i,l}^H(\theta_{i,l}) \hat{\boldsymbol{e}}_1 \|^2]^{-1} \quad (6)$$

where for uniformly spaced antenna array

$$\boldsymbol{a}_{i,l}^H(\theta_{i,l}) = \left[1, \exp\left(-\mathrm{j}\frac{2\pi d}{\lambda}\sin(\theta_{i,l})\right), \cdots, \exp\left(-\mathrm{j}\frac{2\pi d}{\lambda}(M-1)\sin(\theta_{i,l})\right)\right] \Big/ \sqrt{M}$$

4) Search the peak of the spatial spectrum function P_{mu} that provides the DOA estimation of the decoupled sub-path signal. The estimation of $\theta_{i,l}$ is given by

$$\hat{\theta}_{i,l} = \arg\max_{\theta_{i,l}} \{[1 - \| \boldsymbol{a}_{i,l}^H(\theta_{i,l}) \hat{\boldsymbol{e}}_1 \|^2]^{-1}\} \quad (7)$$

Compared with the conventional MUSIC method, the proposed decorrelating DOA estimation algorithm processes several main advantages. First it requires only the principal eigenvector to be solved, consequently the corresponding computation is decreased. Secondly, the proposed algorithm needs not to detect the gemination number of minimum eigenvalue and the number of signal sources because of the decorrelating process. Thirdly the proposed algorithm needs only to search the maximum spectrum peak, and the corresponding search algorithm is simple and reliable. Finally, also because of the decorrelating process the cross-correlation interference caused by multipath propagation is decreased greatly and make the proposed algorithm accurate.

3 Simulation Results

We present a simulation result to illustrate the performance of the proposed algorithm. In this simulation, we employ an 8-element liner array for reception of BPSK multipath signals. The sub-path signal power and carrier phase of the desired user's signal are assumed to be 1 and 0, respectively. The spreading sequence is 31 Gold codes. Suppose that there are five users within a cell and each has two resolvable sub-path signals. The directions of arrival, 20° and 30°, is from a user, and the directions of arrival, 22° and 50°, is from another user. The average performance of 100 Monte-Carlo simulations with the proposed algorithm is shown in Fig.2. Though the DOA of different sub-path signals are estimated respectively, for simplification and comparison, they are shown in the same figure. From Fig.2, it is easy to see that the proposed algorithm estimates DOAs of the desired sub-path signals accurately even though for signals which may be superposition spatially.

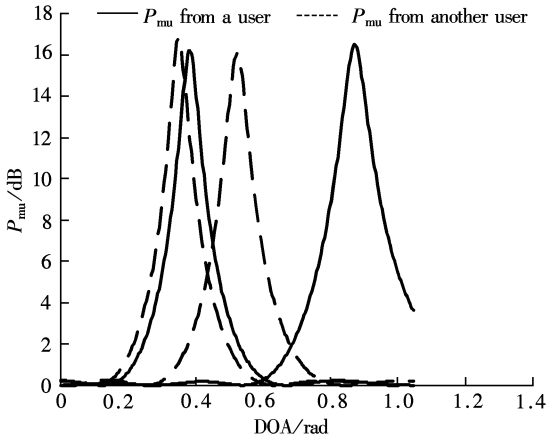

Fig.2 Directions of arrival through the proposed algorithm

4 Conclusion

In this paper, a novel decorrelating DOA estimation algorithm for CDMA frequency-selective fading channels is proposed. Making full use of the prior knowledge and signature of the spreading sequence of CDMA system, the proposed algorithm has the advantages that need not detect the eigenvalues and their corresponding eigenvectors other than the principal eigenvector corresponding to the maximum eigenvalue. Furthermore the proposed algorithm does not require that the array elements outnumber the multipath signal numbers that is required in conventional MUSIC like DOA estimation algorithm. The proposed algorithm has simple, accurate and robust quality. All of these makes the proposed algorithm quite suitable for the DOA estimation of synchronous CDMA systems.

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一种基于主特征矢量的 CDMA 频率选择性衰落信道解相关 DOA 估计算法

杨 维 蒋朱成 程时昕

（东南大学移动通信国家重点实验室，南京 210096）

摘 要 提出了一种新的只基于所对应协方差矩阵主特征矢量的同步 CDMA 频率选择性衰落信道的多径信号的解相关 DOA 或 AOA 估计算法．所提出的算法具有能消除其他多径信号干扰独立地估计期望信号到达角的优点．仿真结果表明该算法可高效、精确地估计出多径信号的到达角．

关键词 解相关，DOA 估计，天线阵，CDMA 系统，特征矢量

中图分类号 TN929.53