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A Blind Adaptive Decorrelating Detector Using Spatial Signature Estimation

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SUMMARY The decorrelating detector is one of the detecting methods in a direct sequence code division multiple access systems. We investigate the blind adaptive decorrelating detector (BADD) using only the signature of the desired user (DU) according to the assumption that the algorithm is used in downlink. When the BADD is constructed with an antenna array, both the spatial and temporal signature must be taken into consideration for signal detection. We propose the BADD incorporated with the blind estimation of spatial signature (SS) of the DU only from the received signals. As the estimation procedure of SS, the orthogonal projection approximation and subspace tracking algorithm is adopted. The proposed BADD presented the BER improvement with using antenna array. The BER performance has a lower limit with increasing the number of antenna array elements.
key words: *blind adaptive decorrelating detector, antenna array, spatial and temporal signature*

1. Introduction

The computation complexity of the optimum multiuser detector in a direct sequence code division multiple access (DS-CDMA) system increases exponentially with the number of active users [1]. Decorrelator is the quasi-optimum detector. On the construction of the decorrelator, not only the desired user's signature, but also all the interference users' ones are required. An implementation of the decorrelator inevitably requires the inverse of the correlation matrix of signature sequences. Therefore, recursive decoding algorithm is necessary to reduce computation complexity.

The blind adaptive decorrelating detector (BADD) reported in Ref. [2] meets the above conditions. However, the single input and single output (SISO) system in [2] treats only the temporal signature. To improve the signal to interference and noise ratio (SINR) characteristic, the antenna array is used, resulting necessity of the knowledge on spatial signature (SS) of the desired user (DU) for estimating the performances of the BADD. We propose the BADD incorporated with the blind estimation of SS of the DU only from the received signals, since SS varies with moving of a mobile station (MS), and is usually unknown to the MS. The unknown spatial signature is blindly estimated using the orthogonal projection approximation and subspace tracking algorithm. We show the substantial performance improvement of the BADD by using an antenna array [6].

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2. Blind Adaptive Decorrelating Detector

We assume a synchronous system at the downlink channel. In the downlink of the DS-CDMA system, the signature sequences of all active users cannot be utilized at a MS. For that reason, the BADD which assumes only the signature sequence of the DU is expected. The BADD should be operated under the same assumption as the conventional matched filter detection (CMFD), and is expected to have better performance than the CMFD. The timing of bit carrier phase and the signature sequence of the desired user are assumed to be known.

2.1 System Model

For simplicity, we assume an additive white Gaussian noise (AWGN) channel to consider the construction possibility of the BADD incorporated with SS estimator. The received complex baseband signal at the pth antenna element is expressed with vector form by collecting the outputs of chip-matched filtering followed by chip-rate sampling as

$$\boldsymbol{y}_p = \sum_{k=1}^{K} A_k b_k \boldsymbol{s}_k g_k^p + \boldsymbol{n}_p, \quad p = 1, 2, \cdots, P, \tag{1}$$

where $A_k, b_k, \boldsymbol{s}_k, g_k^p$ and P are the signal amplitude, information bit, temporal signature, spatial signature of the kth user, and the number of elements of an antenna array. The complex AWGN vector $\boldsymbol{n}_p$ has the covariance matrix $\sigma^2 \boldsymbol{I}$, and K is the number of total active users. The total received signal on an array is written as

$$\boldsymbol{y} = \sum_{k=1}^{K} A_k b_k \widetilde{\boldsymbol{s}}_k + \boldsymbol{n}. \tag{2}$$

The term $\widetilde{\boldsymbol{s}}_k$ is the spatial-temporal (S-T) signature sequence of the kth user which is the composite vector of the spatial signature $\boldsymbol{g}_k$ and temporal signature $\boldsymbol{s}_k$, and is expressed by using Kronecker product as $\boldsymbol{g}_k \otimes \boldsymbol{s}_k$, $\boldsymbol{g}_k = (g_k^1, \cdots, g_k^P)^T$. The element g_k^p has the form of

$$g_k^p = \frac{1}{\sqrt{P}} \exp\left(-j\frac{2\pi}{\lambda}(p-1)d\sin\theta_k\right), \tag{3}$$

where the uniform linear array is assumed, resulting the expression of g_k^p by setting the origin of the incident wave

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phase on the 1st element, λ is the wavelength of the carrier, d is the spacing of the elements, and θ_k is the direction of arrival (DoA) of the kth user's signal wave measured from the direction perpendicular of the broadside of the elements. In the following, the spacing d is assumed to be a half-wavelength of the carrier.

2.2 Algorithm for BADD with Spatial-Temporal Signature

The algorithm for the blind adaptive decorrelating detector is shown with using only the S-T signature of the DU. The algorithm is expressed with utilizing the iterative form on the decorrelator which operates on the received signal $\boldsymbol{y}_p$ on the pth antenna element as

$$\widetilde{\boldsymbol{c}}_p^{(k)}(n+1) = \widetilde{\boldsymbol{c}}_p^{(k)}(n) - \mu\left[\{\boldsymbol{y}_p(n)\boldsymbol{y}_p^H(n) - \sigma^2\boldsymbol{I}\}\widetilde{\boldsymbol{c}}_p^{(k)}(n) - \widetilde{\boldsymbol{s}}_{kp}\right], \quad (4)$$

where $\widetilde{\boldsymbol{s}}_{kp} = g_k^p \boldsymbol{s}_k$ is the S-T signature of the kth user characterized by the spatial signature on the pth antenna element. The expression in Eq. (4) is based on the approximation to correlation of the received signal vector $\boldsymbol{y}_p$. The variance of the ambient noise σ^2 is measured using the filter orthogonal to the temporal signature sequences of all users, and μ is the step size for iteration. The convergence property of the BADD using only the temporal signature is shown in [2]. Incorporating the S-T signature does not change the convergence property since the norm of the spatial signature vector is kept unity and the resulting magnitude of the S-T signature is not altered. The decorrelator with exploiting S-T signature is shown in Fig. 1. The parameter z is the decision statistic expressed as

$$z = \widetilde{\boldsymbol{c}}_1^{(k)H}\boldsymbol{y}_1 + \cdots + \widetilde{\boldsymbol{c}}_P^{(k)H}\boldsymbol{y}_P, \quad (5)$$

where $(\cdot)^H$ denotes complex conjugate.

2.3 BER Performance Comparison of BADD and CMFD

For the case of single receive antenna, we show the bit-error rate (BER) performances of BADD and compare them with those of the CMFD in Fig. 2. The single user bound means the case where no interference exists. SNR is signal to ambient AWGN ratio. The BERs of the BADD and CMFD are simulated for the case of relatively large correlation coefficients of the temporal signature due to channel distortion.

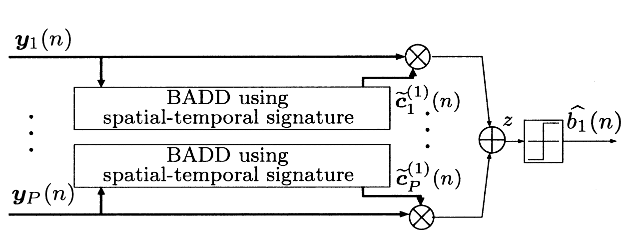

Fig. 1 Spatial-temporal blind adaptive decorrelating detector.

The Gold sequence with the length of 31 is used as the temporal signature. The magnitude of multiple access interference (MAI) is defined as

$$\mathrm{MAI} \overset{\mathrm{def}}{=} 10\log_{10}\left(\frac{A_i}{A_1}\right)^2, \quad i = 2, \cdots, K, \quad (6)$$

where $A_1, A_i (i = 2, \cdots, K)$ are the signal amplitudes of the DU and interference users, respectively. For high level interference, the BERs of the CMFD deteriorate severely, while those of the BADD do not. For the higher SNRs, the BADD outperforms CMFD in BERs performance. The correlation coefficients, ρ_{ij} between the ith and jth users are supposed to have relatively large values due to channel distortion. They are assumed to have $|\rho_{ij}|_{\max} = 9/31$ for $i \neq j$ throughout this paper.

2.4 BER Performance of BADD Using an Antenna Array for Known Spatial Signature

By taking into consideration of the SS of the DU on an antenna array, the BERs of the BADD are shown in Fig. 3. It is assumed that only the DoA of the DU is known and those of interference users are constant and distributed from −90 to 90 degrees. The severe condition is supposed that MAI is equal to 15 dB. The BERs characteristic of the BADD and

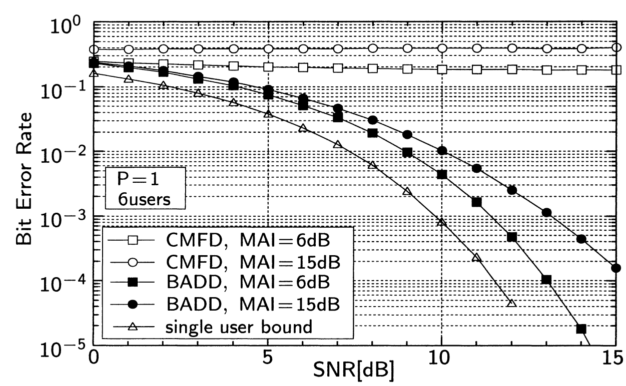

Fig. 2 Bit-error rate versus SNR for conventional and blind adaptive decorrelating detector (BADD) with 6 users and $P = 1$.

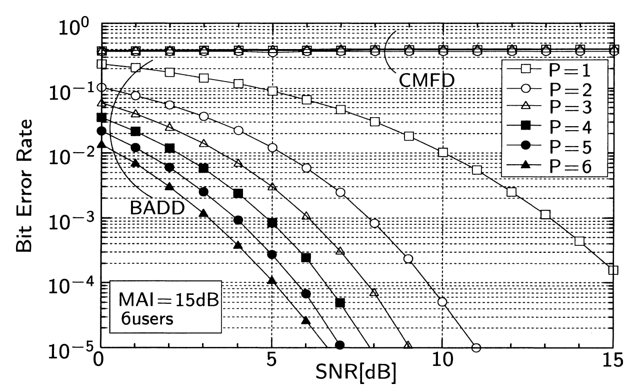

Fig. 3 Bit-error rate versus SNR for spatial-temporal BADD using antenna array with constant and known DoA.

CMFD have large differences. The CMFD presents no improvement of BERs and the high error level over the wide range of SNRs. However, the BADD presents improvement of BERs with augmentation of an antenna array, even for relatively large MAI due to the severe near-far condition. The effect of improvement on BER decreases with larger P and the BER reaches nearly to the lower limit with $P = 6$. This is caused by the accumulation of the residual of interference power at the outputs of decorrelators.

3. BADD Algorithm with Blind Adaptive Estimation of the Spatial Signature

In the previous section, the DoA of the DU is assumed to be known. However, the DoA is generally unknown, and in practice, it varies with moving of a MS, resulting the time-variant SS. Therefore, we propose the BADD incorporated with a blind adaptive estimator of the SS of the DU.

Figure 4 shows the block diagram of the proposed spatial-temporal BADD. In the first stage, the BADD using only temporal signature is constructed, and then decorrelated outputs at antenna elements are collected into vector $\boldsymbol{u}_1$ as

$$\boldsymbol{u}_1 \triangleq \left[\boldsymbol{c}_1^{(1)H}\boldsymbol{y}_1, \boldsymbol{c}_2^{(1)H}\boldsymbol{y}_2, \cdots, \boldsymbol{c}_P^{(1)H}\boldsymbol{y}_P\right]^T, \quad (7)$$

where $\{\boldsymbol{c}_1^{(1)}, \cdots, \boldsymbol{c}_P^{(1)}\}$ denote the BADD at antenna elements using only temporal-signature of the DU. The complex vector $\boldsymbol{u}_1$ has the mean $A_1 b_1 \boldsymbol{g}_1$ and the covariance matrix $\sigma^2(\boldsymbol{R}^{-1})_{11}\boldsymbol{I}_P$, where $\boldsymbol{R}$ is the correlation matrix of temporal-signature sequences, and $\boldsymbol{I}_P$ is a unit matrix of size P. The correlation matrix [3] of $\boldsymbol{u}_1$ is expressed as

$$\boldsymbol{C} \triangleq E[\boldsymbol{u}_1\boldsymbol{u}_1^H] = A_1^2\boldsymbol{g}_1\boldsymbol{g}_1^H + \sigma^2(\boldsymbol{R}^{-1})_{11}\boldsymbol{I}_P. \quad (8)$$

Equation (8) shows that $\boldsymbol{g}_1$ is the principal eigenvector of the matrix $\boldsymbol{C}$. The vector $\boldsymbol{g}_1$ is the optimum solution of the minimization problem, whose objective function $\mathcal{J}(\boldsymbol{g}_1)$ is shown as

$$\mathcal{J}(\boldsymbol{g}_1) = E(\|\boldsymbol{u}_1 - \boldsymbol{g}_1\boldsymbol{g}_1^H\boldsymbol{u}_1\|^2). \quad (9)$$

In the second stage of the proposed BADD, the spatial signature vector $\boldsymbol{g}_1$ is searched. The solution of optimization problem is derived with utilizing the projection approximation and subspace tracking (PAST) method [4]. The orthogonal version of the PAST (OPAST) algorithm [5] is adopted here, since the OPAST has the advantage of linear complexity of matrix size and global convergence. The process of blind estimation of the SS of the DU is shown in Table 1. The estimated results for the 2nd component of the SS are shown for time-variant DoA in Fig. 5. The DoAs of all users are assumed to be time-variant. The DoA $\theta_i(n)$ for the ith user is assumed to be expressed by the function of the number of symbols n as

$$\theta_i(n) = a_i\left(\frac{n}{1000}\right) + b_i, \quad (10)$$

where a_i and b_i denote the variable rates of DoA and initial value, respectively. From the results in Fig. 5, it is found that the estimation algorithm has tracking capability for the time-variant DoA, because estimation delay and deviation from the true values are small. The transient SINR characteristics of the BADD incorporated with the estimated SS for time-variant DoA are shown in Fig. 6 under the same multiuser environment in Fig. 5. In the mobile communication systems, it is generally prescribed that the BER of the DU is less 10^{-3} for voice transmission and the level is obtained with SNR=10 dB under the single user condition as

Table 1 Blind estimation algorithm for spatial signature of the desired user.

$\{\boldsymbol{u}_1(n)\}$: Output sequences of the decorrelator bank in Fig. 4, $n = 1, 2, \cdots$.

$n := 0,\quad \boldsymbol{g}_1(0) = (1, 0, \cdots, 0)^T, Z(0) = 1$

$Z(n)$:Inverse of autocorrelation of $y(n)$

$n := n + 1,\quad y(n) = \boldsymbol{g}_1^H(n-1)\boldsymbol{u}_1(n)$

$q(n) = \frac{1}{\beta}Z(n-1)y(n)$, β: Forgetting factor

$\gamma(n) = \frac{1}{1 + y^*(n)q(n)}$, $*$: Complex conjugate

$Z(n) = \frac{1}{\beta}Z(n-1) - \gamma(n)q(n)q^*(n)$

$\boldsymbol{p}(n) = \gamma(n)(\boldsymbol{u}_1(n) - \boldsymbol{g}_1(n-1)y(n))$

$\tau(n) = \frac{1}{|q(n)|^2}\left[\frac{1}{\sqrt{1 + \|\boldsymbol{p}(n)\|^2|q(n)|^2}} - 1\right]$

$\boldsymbol{p}'(n) = \tau(n)\boldsymbol{g}_1(n-1)q(n) + (1 + \tau(n)|q(n)|^2)\boldsymbol{p}(n)$

$\boldsymbol{g}_1(n) = \boldsymbol{g}_1(n-1) + \boldsymbol{p}'(n)q^*(n)$

$\boldsymbol{g}_1(n) = \frac{\boldsymbol{g}_1(n)}{\|\boldsymbol{g}_1(n)\|}$

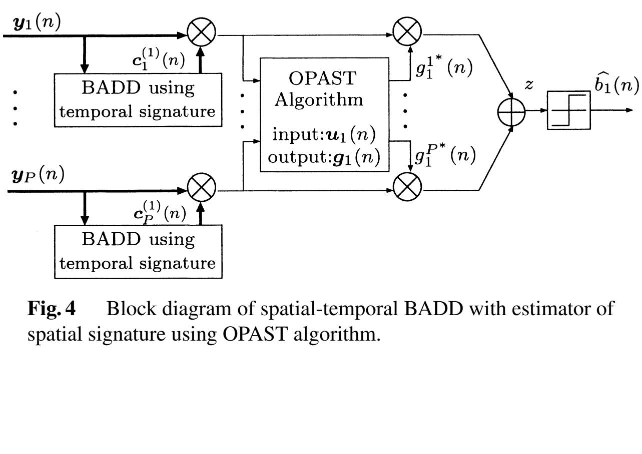

Fig. 4 Block diagram of spatial-temporal BADD with estimator of spatial signature using OPAST algorithm.

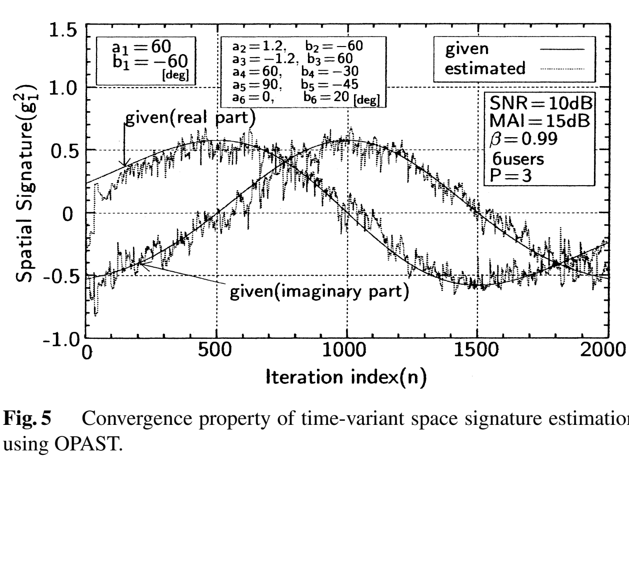

Fig. 5 Convergence property of time-variant space signature estimation using OPAST.

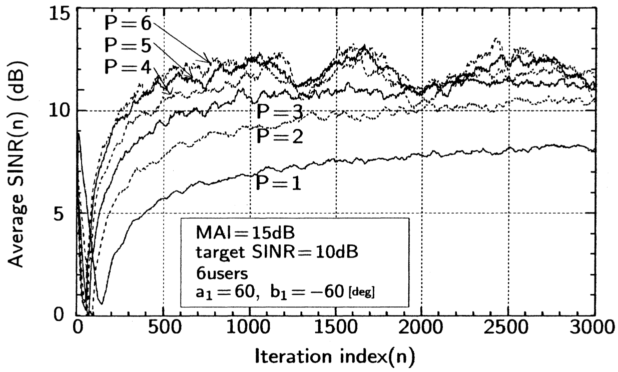

Fig. 6 Convergence property of SINR for spatial-temporal BADD using estimated SS.

shown is Fig. 1. For the multiuser condition, it is desirable for the BER to have value close to the single user bound by eliminating interference. Therefore, the target SINR is assumed to be 10 dB in Fig. 6. The SINR is defined as SINR $= E[z^2]/\mathrm{var}(z)$, where z is the decision statistic at the input of decoder and var(z) means the sum of interferences and noise components. The SINR after convergence can be improved with using an antenna array. However the SINR is upper-limited for P nearly equal to 6. The averaged BERs for the time-variant DoA are shown in Figs. 7(a) and (b) which correspond with the cases for slow and fast variation of DoA, respectively. The condition of the latter case is same as the multiuser environment in Fig. 5 and Fig. 6. The BER performance can be improved with increasing the number of array elements for both cases. However, there exists lower limit for the improvement of BER, and the limit appears especially for the case of fast variation of DoA. This fact may be attributed to the DoA estimation error with OPAST, because the SS components become smaller for larger P and consequently the relative estimation errors of them increase.

4. Conclusions

The blind adaptive decorrelating detector (BADD) which incorporates the process of estimating the spatial signature of the DU has been proposed as the signal detection filter for the DS-CDMA. The unknown spatial signature is blindly estimated with using the orthogonal projection approximation and subspace tracking algorithm. The proposed BADD presented the BER improvement with using antenna array. The BER approaches a lower limit with increasing the number of antenna array elements. The extension for the fading channel is left for the future study.

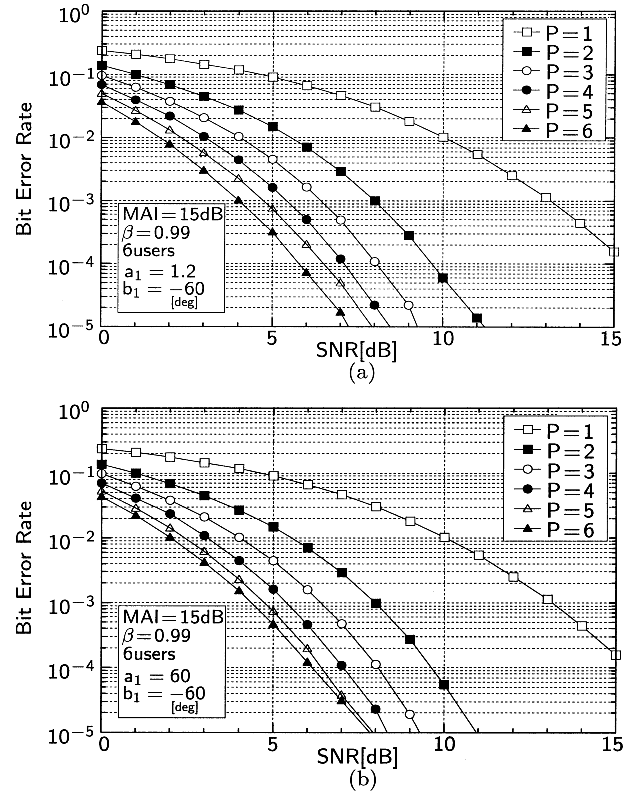

Fig. 7 Bit-error rate of spatial-temporal BADD for time-variant DoA using estimated SS. (a) Case for slow variation of DoA. (b) Case for fast variation of DoA.

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