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An orthogonalized blind algorithm for hybrid of adaptive array and equalizer

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SUMMARY

The problems generated by the interference will be more complicated in the future. A combination of adaptive array and equalizer has been employed to solve the problems of interference when an adaptive array alone cannot suppress all the interferences. A constant modules algorithm (CMA) of the combination system was proposed to solve the problems of insufficient degrees of freedom and main-beam multipath interference when no training signal is transmitted. The limitation of the CMA for combination systems is due to its slow rate of convergence. In this paper, an orthogonalized blind algorithm for hybrid of array and equalizer (OBHAE) is proposed to combat the problems of the interference. Because the modified input vector of the adaptive array is orthogonalized by the OBHAE in advance, the convergent rate of the CMA system can be improved by the OBHAE. When the coherent interference presents, the performance of the system will be degraded. In this paper, an orthogonalized spatial smoothing blind (OSSB) algorithm is proposed to further enhance the cancellation of the coherent interference. In the OSSB, we combine the OBHAE with the spatial smoothing method to combat the coherent interference problem. Simulation results are presented to demonstrate the merits of the OBHAE and the OSSB. Copyright © 2012 John Wiley & Sons, Ltd.

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KEY WORDS: adaptive array; equalizer; constant modulus algorithm; degrees of freedom; main-beam multipath interference; orthogonalized blind algorithm

1. INTRODUCTION

The number of mobile phone users will increase in the future. Therefore, the co-channel interferences (CCI), which are generated by other users, may decrease the performance of the system. In addition, the multipath signal with intersymbol interference (ISI) may disturb the reception of the desired signal. For the past two decades, the adaptive array has been employed to suppress these interferences [1–8]. However, the training sequence is assumed available in the adaptive array system. The constant modulus algorithm (CMA) of the adaptive array has been proposed to cancel the interferences when the training sequence is absent [9–11]. Although the CMA array can suppress the interferences, its performance will degrade when the degrees of freedom of the array are insufficient to suppress all the interferences [12, 13]. Besides, the CMA array also suffers the problem of main-beam multipath interference. When the multipath interference falls in the main-beam region, the reception of the desired signal will be significantly affected [14, 15]. One can use an equalizer following the array output to enhance the capability of canceling the multipath interferences [16, 17]. The CMA array followed with a CMA equalizer (CMA-AE) can perform better than a CMA array alone for suppressing the ISI. The CMA-AE, like the CMA array, may suffer the problem of insufficient degrees of freedom. This is because the weights of adaptive array in the

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CMA-AE is trained by the output of the array instead of the equalizer. Thus, the weight vector of the adaptive array in the CMA-AE is the same as using an adaptive array only. When the CMA array cannot suppress all the interferences, the residual CCI in the array output cannot be removed by the CMA equalizer. Therefore, the CMA-AE will suffer the problem of insufficient degrees of freedom as the CMA array. Besides, the performance of the CMA adaptive array and CMA-AE will degrade when the multipath ISI is in the main-beam region. In [18], a novel CMA for a hybrid adaptive array and equalizer (CMA-HAE) was proposed to combat the problems of interference. The CMA-HAE employed the constant modulus property of the output signal of the HAE to train both the array and the equalizer simultaneously. Therefore, the co-channel interferences can be suppressed by the array and the multipath interferences can be removed by the equalizer successfully. Although the CMA-HAE can combat the problems of insufficient degrees of freedom and main-beam multipath interference, the limitation of the CMA-HAE is its slow convergent rate. Moreover, the performance of the CMA-HAE will decrease in case of coherent interference present.

In this paper, we propose an orthogonalized blind algorithm for hybrid of adaptive array and equalizer (OBHAE) to improve the convergent performance of the CMA-HAE and combat the problems of interference. The optimum weights of the CMA array and equalizer for the CMA-HAE has been found by a gradient descent method. Because the cost function of the CMA is not a quadratic function, it has many saddle points. Thus, the convergent rate of the CMA-HAE is slow. Some recursive CMA algorithms of adaptive array have been proposed to improve the convergent rate of the CMA array [19–21]. However, those methods using array only cannot solve the problems of interference. In this paper, a hybrid of the adaptive array and equalizer with orthogonalized blind algorithm is introduced to combat the problems of insufficient degrees of freedom and main-beam multipath interference. The input vector of adaptive array for OBHAE is multiplied by the inverse of the modified input covariance matrix, which is tantamount to pre-orthogonalizing the modified input vector [19]. Therefore, the OBHAE will have better convergent performance than CMA-HAE. When the coherent interference presents, the input covariance matrix of the adaptive array becomes singular. The performance of the system will degrade by the coherent interference [22–24]. In this paper, an orthogonalized spatial smoothing blind (OSSB) method is used to cancel the coherent interference. In the OSSB method, the adaptive array is partitioned into some subarrays to generate the smoothing modified input vector of the adaptive array. The smoothing modified input vector can be multiplied by an orthogonalized matrix to generate the new smoothing input vector. Thus, the spatial smoothing adaptive array in OSSB algorithm can suppress coherent interference successfully. An equalizer follows the subarrays system is used to further suppress the multipath interferences in the OSSB. Therefore, the OSSB method can combat all the problems of interference and improve the convergent performance of the system.

This paper is organized as follows. In Section 2, the CMA array, CMA-AE and CMA-HAE are briefly introduced. In Section 3, the OBHAE, which multiplies the modified input vector with the inverse of the modified input covariance matrix, is proposed and presented in detail. The OSSB algorithm, which constructs the modified input vector with a spatial smoothing method, is proposed in this section also. Computer simulation results are presented in Section 4. Finally, the conclusion is given in Section 5.

2. PROBLEM FORMULATION

The structure of the CMA array is shown in Figure 1. Consider an N elements antenna array illuminated by M sources. Let the first $\tilde{m}$ sources contain the transmission signal and/or its multipath signals. The other $M - \tilde{m}$ sources are CCI. The base-band output signal of the n-th array element at time $t = kT$ (T is the symbol period) can be expressed by

$$x_n(k) = \sum_{m=1}^{M} \mathbf{h}^{\mathrm{T}}{}_m \mathbf{a}_m(k) e^{jk_{\mathrm{c}}(n-1)l \sin\theta_m} + n_n(k). \tag{1}$$

The T denotes the transpose, $\mathbf{a}_m(k)$ is complex waveform vector of the m-th source. $\mathbf{h}_m$ is impulse response vector of the m-th source, which is determined by the channel and the transmission system

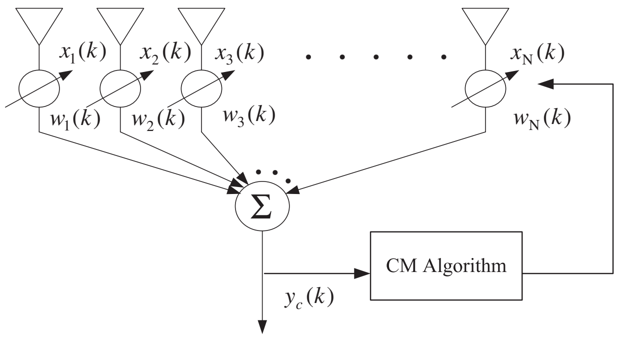

Figure 1. The structure of CMA array.

response, θ_m is the arrival angle of the m-th source, l is the distance between the adjacent array elements, k_c is the wave number of the carrier frequency and $n_n(k)$ is the additive white Gaussian noise. The vectors $\mathbf{h}_m$ and $\mathbf{a}_m(k)$ can be denoted as

$$\mathbf{h}_m = [h_{m0}\ ,\ h_{m1}\ ,\ \cdots\ ,\ h_{md}]^T \tag{2}$$

$$\mathbf{a}_m(k) = [a_m(k)\ ,\ a_m(k-1)\ ,\ \cdots\ ,\ a_m(k-d)]^T\ , \tag{3}$$

where d is maximum delay length of the M sources. The components of $\mathbf{h}_m$ are nonzero only for those existing delayed terms. Let $\mathbf{a}(k)$ be the waveform vector of the signal. We have

$$\mathbf{a}(k) = \mathbf{a}_j(k) = [a(k)\ ,\ a(k-1)\ ,\ \cdots, a(k-d)]^T, \quad \text{for } j = 1\ ,\ 2\ ,\ \cdots\ ,\ \tilde{m}, \tag{4}$$

because the first $\tilde{m}$ sources contain the signal and/or its multipath signals.

The output of the adaptive array in Figure 1 can be expressed as

$$y_c(k) = \mathbf{w}_c^H(k)\mathbf{x}(k)\ , \tag{5}$$

where H denotes the transpose conjugate, $\mathbf{w}_c(k)$ is the weight vector of the CMA array and $\mathbf{x}(k)$ is the input vector of adaptive array.

$$\mathbf{w}_c(k) = [w_1(k)\ ,\ w_2(k)\ ,\ \cdots\cdots\cdots\ ,\ w_N(k)]^T \tag{6}$$

$$\mathbf{x}(k) = [x_1(k)\ ,\ x_2(k)\ ,\ \cdots\ \cdots\ ,\ x_N(k)]^T\ . \tag{7}$$

The CMA array can be beam-formed toward the desired signal and steered nulls in the directions of the interference by using the constant modulus property of the array output. Assume the signal $a(k-j)$ has maximum power among signal $a(k-i)$ for $1 \leqslant i \leqslant d$ in the quiescent array output. Then, the output of the CMA array can be used to estimate the desired signal $a(k-j)$. The weight vector of the CMA array can be found by minimizing the power of cost function $\left(J_c(k) = E\left[\left|\mathbf{w}_c^{\mathbf{H}}(k)\mathbf{x}(k)\right| - C\right]\right)$, which is the difference between the amplitude of the array output and a constant. The signal $a(k-j)$ is a constant modulus transmitted signal, assumed to be scaled so that $|a(k-j)| = 1$. Thus, we can set the constant C to 1. For computation simplicity, the weight vector of the CMA array can be found by the steepest descent algorithm and is written as

$$\mathbf{w}_c(k+1) = \mathbf{w}_c(k) + \mu_1\mathbf{x}(k)e_c^*(k), \tag{8}$$

where * denotes the conjugate, μ_1 is the step size and error term $e_c(k)$ equals

$$e_c(k) = \left(\frac{y_c(k)}{|y_c(k)|}\right) - y_c(k). \tag{9}$$

Through the CMA array can solve the problems of interference without training signal, its performance is decreased in the cases of insufficient degrees of freedom and main-beam multipath

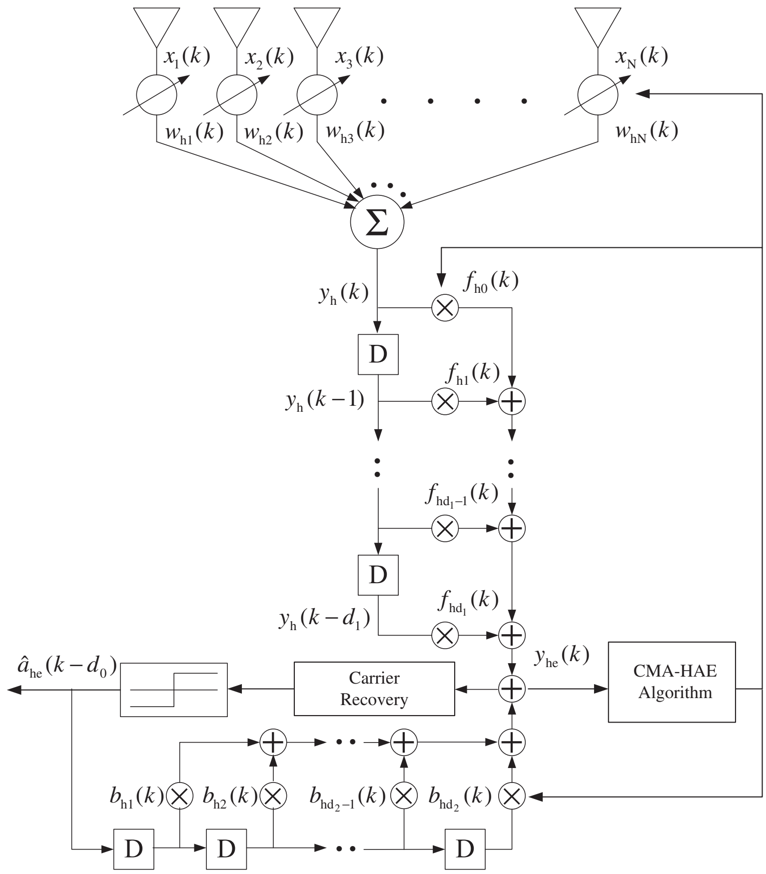

Figure 2. The structure of CMA-HAE system.

interference. The weight vector of adaptive array in the CMA-AE is same as using adaptive array only. Therefore, the CMA-AE will also suffer the above interference problems.

In Figure 2, the CMA-HAE uses the constant modulus property of the output signal for the HAE to train the weight vectors of adaptive array and equalizer simultaneously. The CCI can be canceled by the adaptive array and the ISI is removed by the equalizer following the array. Thus, the problems of insufficient degrees of freedom and main-beam multipath ISI can be solved successfully in the CMA-HAE. The output of the array for the CMA-HAE is

$$y_{\mathrm{h}}(k) = \mathbf{w}_{\mathrm{h}}^{H}(k)\mathbf{x}(k) \quad , \tag{10}$$

where the input vector $\mathbf{x}(k)$ of adaptive array is expressed as Equation (7) and the weight vector $\mathbf{w}_{\mathrm{h}}(k)$ of adaptive array for the CMA-HAE is

$$\mathbf{w}_{\mathrm{h}}(k) = [w_{\mathrm{h}1}(k)\ ,\ w_{\mathrm{h}2}(k)\ ,\ \cdots\cdots\cdots\ ,\ w_{\mathrm{h}N}(k)]^{\mathrm{T}}. \tag{11}$$

By feeding the array output $y_{\mathrm{h}}(k)$ into the decision feedback equalizer (DFE), the output of the DFE for the CMA-HAE can be expressed as

$$y_{\mathrm{h}e}(k) = \mathbf{w}_{\mathrm{h}e}^{H}(k)\mathbf{x}_{\mathrm{h}e}(k)\ , \tag{12}$$

where $\mathbf{w}_{\mathrm{h}e}(k)$ and $\mathbf{x}_{\mathrm{h}e}(k)$ can be expressed as

$$\mathbf{w}_{\mathrm{h}e}(k) = [f_{\mathrm{h}0}(k)\ ,\ f_{\mathrm{h}1}(k)\ ,\ \cdots\ ,\ f_{\mathrm{h}d_1}(k)\ ,\ b_{\mathrm{h}1}(k)\ ,\ b_{\mathrm{h}2}(k)\ ,\ \cdots\ ,\ b_{\mathrm{h}d_2}(k)]^{\mathrm{T}} \tag{13}$$

$$\mathbf{x}_{\mathrm{h}e}(k) = [y_{\mathrm{h}}(k)\ ,\ y_{\mathrm{h}}(k-1)\ ,\ \cdots\ ,\ y_{\mathrm{h}}(k-d_1)\ ,\ \hat{a}_{\mathrm{h}e}(k-d_0-1)\ ,\ \cdots\ ,\ \hat{a}_{\mathrm{h}e}(k-d_0-d_2)]^{\mathrm{T}}, \tag{14}$$

where $\hat{a}_{\mathrm{h}e}(k-d_0)$ is the decision feedback signal of the equalizer.

In [15], the weight vectors $\mathbf{w}_{\mathrm{h}}(k)$ and $\mathbf{w}_{\mathrm{h}e}(k)$ can be determined by

$$\mathbf{w}_{\mathrm{h}e}(k+1) = \mathbf{w}_{\mathrm{h}e}(k) + \mu_2 \mathbf{x}_{\mathrm{h}e}(k) e^*_{\mathrm{h}e}(k), \tag{15}$$

where the μ_2 is the step size and error term $e_{\mathrm{h}e}(k)$ equals

$$e_{\mathrm{h}e}(k) = \left(\frac{y_{\mathrm{h}e}(k)}{|y_{\mathrm{h}e}(k)|} \right) - y_{\mathrm{h}e}(k) \tag{16}$$

$$\mathbf{w}_{\mathrm{h}}(k+1) = \mathbf{w}_{\mathrm{h}}(k) + \mu_3 \mathbf{x}'_{\mathrm{h}}(k) e^*_{\mathrm{h}e}(k), \tag{17}$$

where the μ_3 is the step size and $\mathbf{x}'_{\mathrm{h}}(k)$ equals

$$\mathbf{x}'_{\mathrm{h}}(k) = [\mathbf{x}(k)\ ,\ \mathbf{x}(k-1)\ ,\ \cdots\ ,\ \mathbf{x}(k-d_1)][f_{\mathrm{h}0}(k)\ ,\ f_{\mathrm{h}1}(k)\ ,\ \cdots\ ,\ f_{\mathrm{h}d_1}(k)]^{\mathrm{T}}\ . \tag{18}$$

The CMA-HAE can combat the CCI and ISI successfully, but the convergent rate of performance for CMA-HAE is slow. Besides, the coherent source will disturb the reception of desired signal also. In Section 3, we will propose the orthogonalized methods to improve these problems.

3. ORTHOGONALIZED ALGORITHMS FOR HYBRID OF ADAPTIVE ARRAY AND EQUALIZER

In this section, we use the OBHAE to improve the convergent rate of performance and the OSSB algorithm to suppress the coherent source. The OBHAE and the OSSB are described in the following.

3.1. The orthogonalized blind algorithm

The structure of the OBHAE is shown in Figure 3. The output signal of the equalizer is constrained to a constant that can be used to train the adaptive array and equalizer simultaneously. Therefore, the CCI and ISI can be suppressed by both the adaptive array and equalizer successfully. Besides, the orthogonal input vector of adaptive array for OBHAE is orthogonalized by multiplying the inverse of the covariance matrix for the modified input vector. The OBHAE will improve the convergent rate of the performance for the CMA-HAE. Thus, the OBHAE solves the problems of interference and improve the convergent rate of the system. The OBHAE is presented in the following. The output signal of adaptive array $y_{\mathrm{ob}}(k)$ equals

$$y_{ob}(k) = \mathbf{w}^H_{ob}(k)\mathbf{x}(k), \tag{19}$$

where the input vector $\mathbf{x}(k)$ of adaptive array is expressed as Equation (7) and the weight vector $\mathbf{w}_{ob}(k)$ of adaptive array for the OBHAE is

$$\mathbf{w}_{\mathrm{ob}}(k) = [w_{\mathrm{ob}1}(k)\ ,\ w_{\mathrm{ob}2}(k)\ ,\ \cdots\cdots\cdots\ ,\ w_{\mathrm{ob}N}(k)]^{\mathrm{T}}\ . \tag{20}$$

A DFE is used to cancel the ISI from the adaptive array output. The output signal of the DFE is expressed as

$$y_{\mathrm{obe}}(k) = \mathbf{w}^H_{\mathrm{obe}}(k)\mathbf{x}_{\mathrm{obe}}(k)\ , \tag{21}$$

where the weight vector $\mathbf{w}_{\mathrm{obe}}(k)$ and input vector $\mathbf{x}_{\mathrm{obe}}(k)$ can be expressed as

$$\mathbf{w}_{\mathrm{obe}}(k) = [f_{\mathrm{obo}}(k)\ ,\ f_{\mathrm{ob}1}(k)\ ,\ \cdots\ ,\ f_{\mathrm{ob}d_1}(k)\ ,\ b_{\mathrm{ob}1}(k)\ ,\ b_{\mathrm{ob}2}(k)\ ,\ \cdots\ ,\ b_{\mathrm{ob}d_2}(k)]^{\mathrm{T}} \tag{22}$$

$$\mathbf{x}_{\mathrm{obe}}(k) = [y_{\mathrm{ob}}(k)\ ,\ y_{\mathrm{ob}}(k-1)\ ,\ \cdots\ ,\ y_{\mathrm{ob}}(k-d_1)\ ,\ \hat{a}_{\mathrm{obe}}(k-d_0-1)\ ,\ \cdots\ ,\ \hat{a}_{\mathrm{obe}}(k-d_0-d_2)]^T\ , \tag{23}$$

with $\hat{a}_{\mathrm{obe}}(k-d_0)$ is the decision feedback signal of the equalizer. The amplitude of the output signal $|y_{\mathrm{obe}}(k)|$ for DFE can be constrained to a constant to adjust the vectors of the adaptive array and

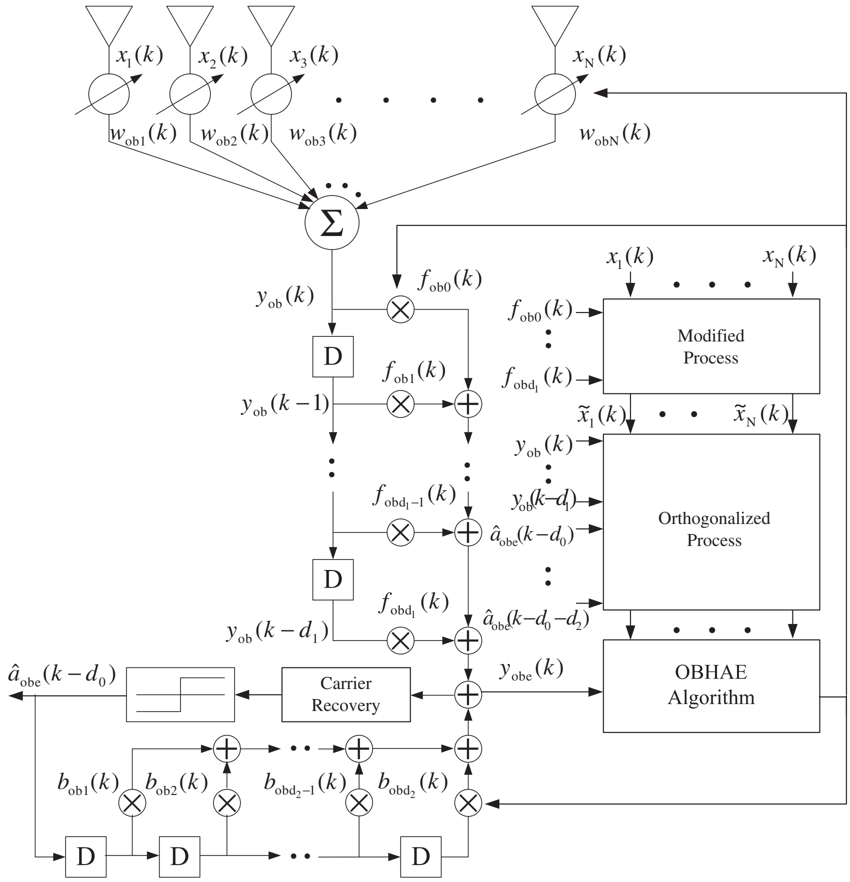

Figure 3. The structure of OBHAE system.

DFE for OBHAE, simultaneously. Thus, the weight vectors of the OBHAE can be determined by the cost function $J_{\text{ob}}(k)$ ($J_{\text{ob}}(k) = E[|y_{\text{obe}}(k)| - C]$). In steady state, we suppose that the vector $\mathbf{w}_{\text{ob}}(k)$ of adaptive array is stable.

$$\mathbf{w}_{\text{ob}}(k) = \mathbf{w}_{\text{ob}}(k-i), \quad \text{for} \quad i = 0, 1, \cdots, d_1 \quad . \tag{24}$$

The feed forward signal $y_{\text{ob}}(k-d)$ of the DFE can be expressed as

$$y_{\text{ob}}(k-d) = \mathbf{w}_{\text{ob}}^H(k)\mathbf{x}(k-d). \tag{25}$$

The output signal of the DFE is

$$\begin{aligned} y_{\text{obe}}(k) &= \mathbf{w}_{\text{ob}}^H(k)\mathbf{x}(k) f_{\text{ob0}}^*(k) + \mathbf{w}_{\text{ob}}^H(k)\mathbf{x}(k-1) f_{\text{ob1}}^*(k) + \cdots + \mathbf{w}_{\text{ob}}^H(k)\mathbf{x}(k-d_1) f_{\text{ob}d_1}^*(k) \\ &\quad + \hat{a}_{\text{obe}}(k-d_0-1)b_{\text{ob1}}^* + \cdots + \hat{a}_{\text{obe}}(k-d_0-d_2)b_{\text{ob}d_2}^* \\ &= \mathbf{w}_{\text{ob}}^H(k)\tilde{\mathbf{x}}(k) + \hat{a}_{\text{obe}}(k-d_0-1)b_{\text{ob1}}^* + \cdots + \hat{a}_{\text{obe}}(k-d_0-d_2)b_{\text{ob}d_2}^* , \end{aligned} \tag{26}$$

where the modified input vector $\tilde{\mathbf{x}}(k)$ equals

$$\tilde{\mathbf{x}}(k) = [\mathbf{x}(k), \mathbf{x}(k-1), \cdots, \mathbf{x}(k-d_1)]\, \mathbf{f}_{\text{ob}}^*(k), \tag{27}$$

and

$$\mathbf{f}_{\text{ob}}(k) = [f_{\text{ob0}}(k), f_{\text{ob1}}(k), \cdots, f_{\text{ob}d_1}(k)]^{\text{T}} \quad . \tag{28}$$

Therefore, the cost function $J_{ob}(k)$ can be expressed as,

$$J_{ob}(k) = E\left[\left|\mathbf{w}_{ob}^{\mathbf{H}}(k)\tilde{\mathbf{x}}(k) + C'\right| - C\right] \quad \text{, with } \mathbf{w}_{obe}(k) \text{ fixed,} \tag{29}$$

where C' is defined as

$$C' = \hat{a}_{obe}(k - d_0 - 1)b_{ob1}^{*} + \cdots + \hat{a}_{obe}(k - d_0 - d_2)b_{obd_2}^{*}\,. \tag{30}$$

The modified input vector $\tilde{\mathbf{x}}(k)$ can be orthogonalized by multiplied the inverse of the covariance matrix of the vector $\tilde{\mathbf{x}}(k)$[19]. Thus, the cost function $J_{ob}(k)$ can be expressed as

$$J_{ob}(k) = E\left[\left|\mathbf{w}_{ob}^{\mathbf{H}}(k)\mathbf{R}_{\tilde{\mathbf{x}}\tilde{\mathbf{x}}}^{-1}(k)\tilde{\mathbf{x}}(k) + C'\right| - C\right] \quad , \tag{31}$$

where $\mathbf{R}_{\tilde{\mathbf{x}}\tilde{\mathbf{x}}}^{-1}(k+1)$ can be determined by recursive method as

$$\mathbf{R}_{\tilde{\mathbf{x}}\tilde{\mathbf{x}}}^{-1}(k+1) = \frac{\mathbf{R}_{\tilde{\mathbf{x}}\tilde{\mathbf{x}}}^{-1}(k)}{1-\alpha} - \frac{1}{1-\alpha}\left[\frac{\alpha\mathbf{R}_{\tilde{\mathbf{x}}\tilde{\mathbf{x}}}^{-1}(k)\tilde{\mathbf{x}}(\mathbf{k})\tilde{\mathbf{x}}^{\mathbf{H}}(k)\mathbf{R}_{\tilde{\mathbf{x}}\tilde{\mathbf{x}}}^{-1}(k)}{(1-\alpha) + \alpha\tilde{\mathbf{x}}^{\mathbf{H}}(k)\mathbf{R}_{\tilde{\mathbf{x}}\tilde{\mathbf{x}}}^{-1}(k)\tilde{\mathbf{x}}(k)}\right]. \tag{32}$$

Therefore, the weight vector $\mathbf{w}_{ob}(k)$ of the adaptive array for orthogonalized algorithm can be found by

$$\mathbf{w}_{ob}(k+1) = \mathbf{w}_{ob}(k) + \mu_4\mathbf{R}_{\tilde{\mathbf{x}}\tilde{\mathbf{x}}}^{-1}(k+1)\tilde{\mathbf{x}}(k)e_{obe}^{*}(k) \quad , \tag{33}$$

where μ_4 is the step size and error term $e_{obe}(k)$ equals

$$e_{obe}(k) = \left(\frac{y_{obe}(k)}{|y_{obe}(k)|}\right) - y_{obe}(k). \tag{34}$$

The cost function $J_{ob}(k)$ can be expressed by other method with respect to the weight vector $\mathbf{w}_{obe}(k)$ as

$$J_{ob}(k) = E[|y_{obe}(k)| - C] = E\left[\left|\mathbf{w}_{obe}^{\mathbf{H}}(k)\mathbf{x}_{obe}(k)\right| - C\right] \quad . \tag{35}$$

The input vector $\mathbf{x}_{obe}(k)$ of the equalizer can be orthogonalized by multiplying the inverse of the covariance matrix of the input vector $\mathbf{x}_{obe}(k)$. The cost function $J_{ob}(k)$ equals

$$J_{ob}(k) = E\left[\left|\mathbf{w}_{obe}^{\mathbf{H}}(k)\mathbf{R}_{\mathbf{x}_{obe}\mathbf{x}_{obe}}^{-1}(k)\mathbf{x}_{obe}(k)\right| - C\right], \tag{36}$$

where $\mathbf{R}_{\mathbf{x}_{obe}\mathbf{x}_{obe}}^{-1}(k+1)$ can be determined by recursive method as

$$\mathbf{R}_{\mathbf{x}_{obe}\mathbf{x}_{obe}}^{-1}(k+1) = \frac{\mathbf{R}_{\mathbf{x}_{obe}\mathbf{x}_{obe}}^{-1}(k)}{1-\alpha} - \frac{1}{1-\alpha}\left[\frac{\alpha\mathbf{R}_{\mathbf{x}_{obe}\mathbf{x}_{obe}}^{-1}(k)\mathbf{x}_{obe}(\mathbf{k})\mathbf{x}_{obe}^{\mathbf{H}}(k)\mathbf{R}_{\mathbf{x}_{obe}\mathbf{x}_{obe}}^{-1}(k)}{(1-\alpha) + \alpha\mathbf{x}_{obe}^{\mathbf{H}}(k)\mathbf{R}_{\mathbf{x}_{obe}\mathbf{x}_{obe}}^{-1}(k)\mathbf{x}_{obe}(k)}\right]. \tag{37}$$

The weight vector $\mathbf{w}_{obe}(k)$of the equalizer for orthogonalized algorithm can be found by

$$\mathbf{w}_{obe}(k+1) = \mathbf{w}_{obe}(k) + \mu_5\mathbf{R}_{\mathbf{x}_{obe}\mathbf{x}_{obe}}^{-1}(k+1)\mathbf{x}_{obe}(k)e_{obe}^{*}(k), \tag{38}$$

where μ_5 is the step size.

Thus, the orthogonalized algorithm of OBHAE can be determined by the Equations (32), (33), (34), (37) and (38).

In the OBHAE, the CCI can be suppressed by the adaptive array and the ISI can be removed by the adaptive array or the equalizer following the array. Therefore, the problems of interference can be solved by OBHAE successfully. Besides, the input vector is orthogonalized by the inverse of the covariance matrix of the input vector that will improve the convergence rate of the system performance in case the training sequence is absent. Although the OBHAE can suppress the CCI and ISI, the convergence performance of the system will be degraded in case of coherent interference present. In the next section, we will propose an OSSB algorithm to solve the problem of the coherent interference.

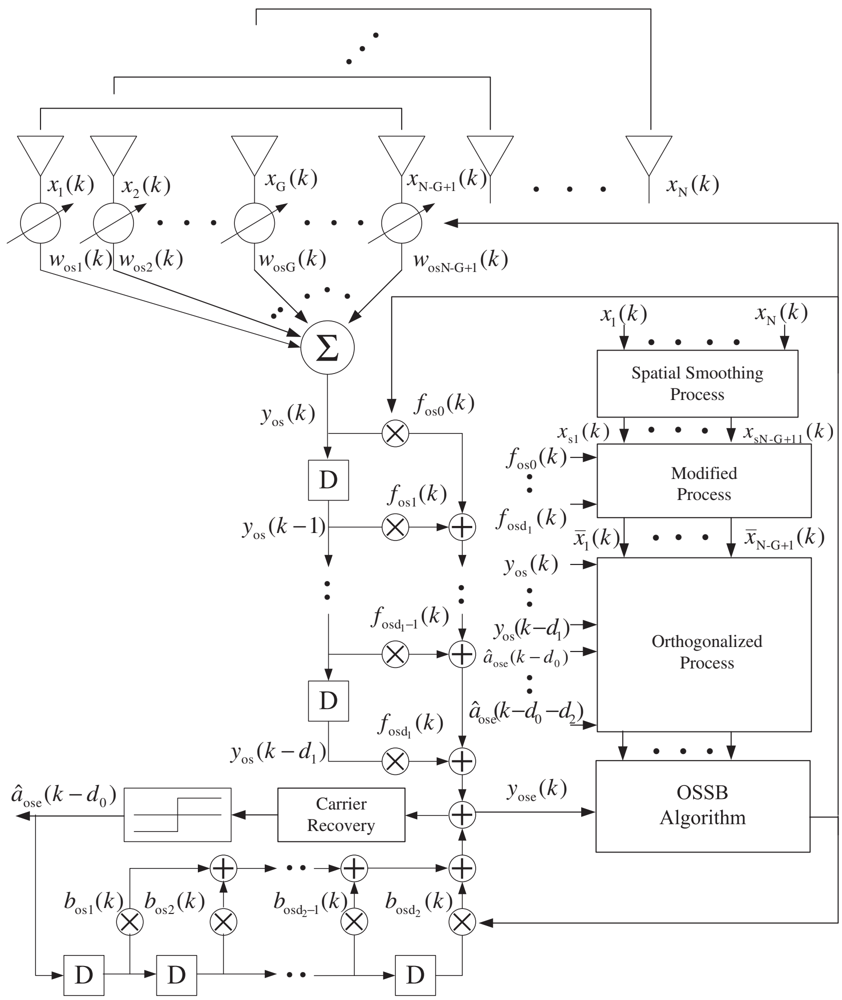

Figure 4. The structure of OSSB system.

3.2. *The orthogonalized spatial smoothing blind algorithm*

When the coherent interference presents, the performance of the OBHAE will be degraded. In Figure 4, we partition the adaptive array into G subarrays to generate the modified input vector of the spatial smoothing array. The input vectors of the subarrays are

$$\mathbf{x}_g(k) = [x_g(k)\ ,\ x_{g+1}(k)\ ,\ \cdots\cdots\ ,\ x_{N-G+g}(k)]^T \quad \text{for} \quad g = 1\ ,\ 2\ ,\ \cdots\ ,\ G. \tag{39}$$

The input vector of the spatial smoothing array $\mathbf{x}_s(k)$

$$\mathbf{x}_s(k) = \frac{1}{G}\sum_{g=1}^{G}\mathbf{x}_\mathbf{g}(k)\ . \tag{40}$$

The output signal of the spatial smoothing array is

$$y_{\text{os}}(k) = \mathbf{w}_{\text{os}}^H(k)\mathbf{x}_s(k) \tag{41}$$

$$\mathbf{w}_{\text{os}}(k) = [w_{\text{os}1}(k)\ ,\ w_{\text{os}2}(k)\ ,\ \cdots\cdots\cdots\ ,\ w_{\text{os}N-G+1}(k)]^{\text{T}}\quad . \tag{42}$$

Then, the output signal of the spatial smoothing array is fed into a DFE. The output signal of the DFE for OSSB is

$$y_{\rm ose}(k) = \mathbf{w}_{\rm ose}^{H}(k)\mathbf{x}_{\rm ose}(k), \tag{43}$$

where

$$\mathbf{w}_{\rm ose}(k) = [f_{\rm os0}(k)\,,\ f_{\rm os1}(k)\,,\ \cdots\,,\ f_{{\rm os}d_1}(k)\,,\ b_{\rm os1}(k)\,,\ b_{\rm os2}(k)\,,\ \cdots,\ b_{{\rm os}d_2}(k)]^{\rm T} \tag{44}$$

$$\mathbf{x}_{\rm ose}(k) = [y_{\rm os}(k)\,,\ y_{\rm os}(k-1)\,,\ \cdots\,,\ y_{\rm os}(k-d_1)\,,\ \hat{a}_{\rm ose}(k-d_0-1)\,,\ \cdots\,,\ \hat{a}_{\rm ose}(k-d_0-d_2)]^{\rm T}\,, \tag{45}$$

with $\hat{a}_{\rm ose}(k-d_0)$ is the decision feedback signal of the DFE for OSSB. Similar to the OBHAE, we can find the modified input vector of the spatial smoothing array as

$$\bar{\mathbf{x}}(k) = [\mathbf{x}_s(k)\,,\ \mathbf{x}_s(k-1)\,,\ \cdots\,,\ \mathbf{x}_s(k-d_1)]\ \mathbf{f}_{\rm os}^{*}(k), \tag{46}$$

and

$$\mathbf{f}_{\rm os}(k) = [f_{\rm os0}(k)\,,\ f_{\rm os1}(k)\,,\ \cdots\,,\ f_{{\rm os}d_1}(k)]^{\rm T}\quad . \tag{47}$$

The OSSB algorithm can be determined by

$$\mathbf{w}_{\rm os}(k+1) = \mathbf{w}_{\rm os}(k) + \mu_6\mathbf{R}_{\bar{\mathbf{x}}\bar{\mathbf{x}}}^{-1}(k+1)\bar{\mathbf{x}}(k)e_{\rm ose}^{*}(k) \tag{48}$$

$$\mathbf{R}_{\bar{\mathbf{x}}\bar{\mathbf{x}}}^{-1}(k+1) = \frac{\mathbf{R}_{\bar{\mathbf{x}}\bar{\mathbf{x}}}^{-1}(k)}{1-\alpha} - \frac{1}{1-\alpha}\left[\frac{\alpha\mathbf{R}_{\bar{\mathbf{x}}\bar{\mathbf{x}}}^{-1}(k)\bar{\mathbf{x}}(\mathbf{k})\bar{\mathbf{x}}^{\mathbf{H}}(k)\mathbf{R}_{\bar{\mathbf{x}}\bar{\mathbf{x}}}^{-1}(k)}{(1-\alpha)+\alpha\bar{\mathbf{x}}^{\mathbf{H}}(k)\mathbf{R}_{\bar{\mathbf{x}}\bar{\mathbf{x}}}^{-1}(k)\bar{\mathbf{x}}(k)}\right] \tag{49}$$

$$\mathbf{w}_{\rm ose}(k+1) = \mathbf{w}_{\rm ose}(k) + \mu_7\mathbf{R}_{\mathbf{x}_{\rm ose}\mathbf{x}_{\rm ose}}^{-1}(k+1)\mathbf{x}_{\rm ose}(k)e_{\rm ose}^{*}(k) \tag{50}$$

$$\mathbf{R}_{\mathbf{x}_{\rm ose}\mathbf{x}_{\rm ose}}^{-1}(k+1) = \frac{\mathbf{R}_{\mathbf{x}_{\rm ose}\mathbf{x}_{\rm ose}}^{-1}(k)}{1-\alpha} - \frac{1}{1-\alpha}\left[\frac{\alpha\mathbf{R}_{\mathbf{x}_{\rm ose}\mathbf{x}_{\rm ose}}^{-1}(k)\mathbf{x}_{\rm ose}(\mathbf{k})\mathbf{x}_{\rm ose}^{\mathbf{H}}(k)\mathbf{R}_{\mathbf{x}_{\rm ose}\mathbf{x}_{\rm ose}}^{-1}(k)}{(1-\alpha)+\alpha\mathbf{x}_{\rm ose}^{\mathbf{H}}(k)\mathbf{R}_{\mathbf{x}_{\rm ose}\mathbf{x}_{\rm ose}}^{-1}(k)\mathbf{x}_{\rm ose}(k)}\right], \tag{51}$$

where μ_6 and μ_7 are the step sizes and error term $e_{\rm ose}(k)$ equals

$$e_{\rm ose}(k) = \left(\frac{y_{\rm ose}(k)}{|y_{\rm ose}(k)|}\right) - y_{\rm ose}(k). \tag{52}$$

Thus, the OSSB can improve the convergence rate of the system and combat the problem of coherent interference in case of no training sequence transmitted.

4. SIMULATION RESULTS

Computer simulation results are presented here to demonstrate the performance of OBHAE and OSSB. In simulations, we compare the performances of the five systems, that is, CMA, CMA-AE, CMA-HAE, OBHAE, and OSSB. A five-element uniformly spaced array with half wavelength spacing is used for simulation with four scenarios of the incoming sources. The parameters of d_1 and d_2 are set to 2 in all scenarios. The initial value of weight vectors are set as $\mathbf{w}_{\rm c}(0) = [0\,,\ 0\,,\ 0\,,\ 0\,,\ 0]^{\rm T}$, $\mathbf{w}_{\rm e}(0) = [1\,,\ 0\,,\ 0\,,\ 0\,,\ 0]^{\rm T}$, $\mathbf{w}_{\rm h}(0) = [0\,,\ 0\,,\ 0\,,\ 0\,,\ 0]^{\rm T}$, $\mathbf{w}_{\rm he}(0) = [1\,,\ 0\,,\ 0\,,\ 0\,,\ 0]^{\rm T}$, $\mathbf{w}_{\rm ob}(0) = [0\,,\ 0\,,\ 0\,,\ 0\,,\ 0]^{\rm T}$, $\mathbf{w}_{\rm obe}(0) = [1\,,\ 0\,,\ 0\,,\ 0\,,\ 0]^{\rm T}$, $\mathbf{w}_{\rm os}(0) = [0\,,\ 0\,,\ 0\,,\ 0\,,\ 0]^{\rm T}$ and $\mathbf{w}_{\rm ose}(0) = [1\,,\ 0\,,\ 0\,,\ 0\,,\ 0]^{\rm T}$. The initial value of the covariance matrices are identical matrices. In scenario I, the base-band signal received by the n-th element is

$$\begin{aligned} x_n(k) = a(k-1)e^{jk_c(n-1)l\sin\theta_1} + 0.2a(k)e^{jk_c(n-1)l\sin\theta_2} + 0.2a(k-2)e^{jk_c(n-1)l\sin\theta_3} \\ + a_4(k)e^{jk_c(n-1)l\sin\theta_4} + n_n(k)\quad . \end{aligned} \tag{53}$$

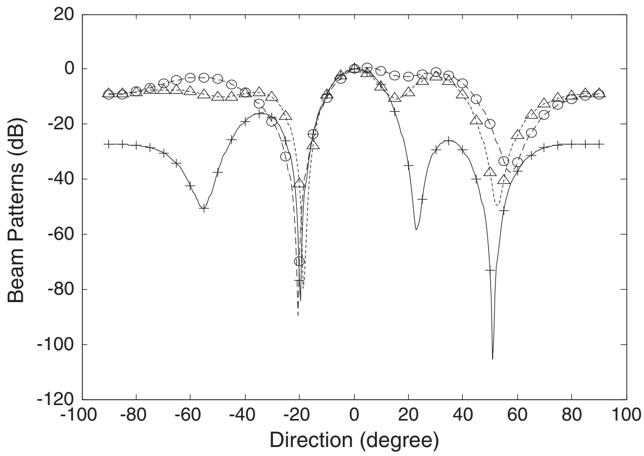

Figure 5. Beam patterns for scenario I.

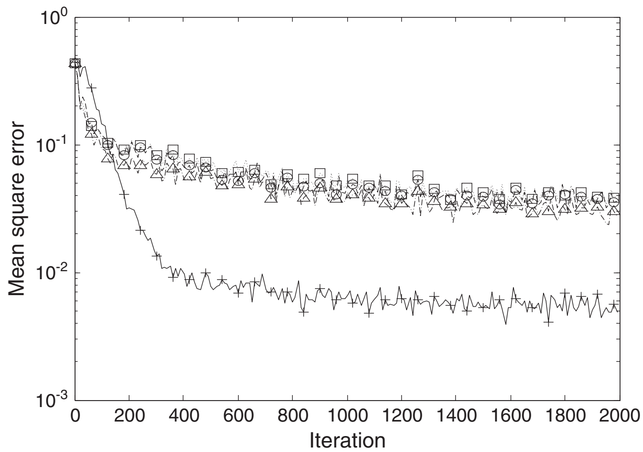

Figure 6. Transient behavior for scenario I.

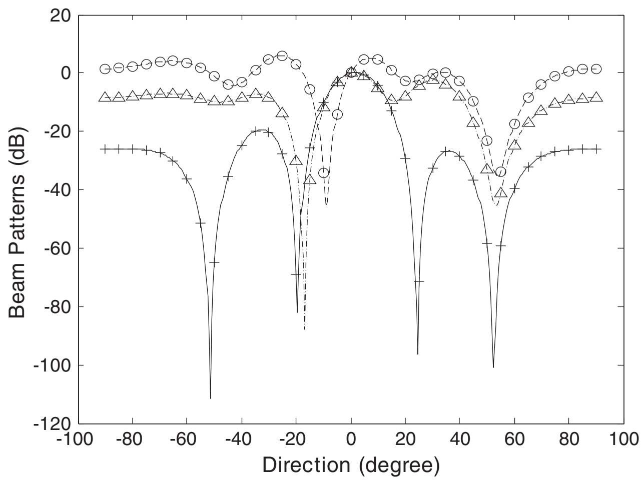

Figure 7. Beam patterns for scenario II.

In which there are three multipath signals and one CCI. The angles of the arrivals are $\theta_1 = 0°$, $\theta_2 = 50°$, $\theta_3 = -30°$, and $\theta_4 = -20°$. The power of the first signal is largest of the three multipath signals, so $a(k-1)$ can be considered as the desired signal and the other two as the multipath ISI in the adaptive array. The input SNR is 20 dB and the power of the CCI is -5 dB with respect to the signal power. The distribution of the noise signal is Gaussian distribution. We compare the performances of the CMA, the CMA-AE, the CMA-HAE, and OBHAE. In the scenario I, all multipath ISI are outside the main-beam and the adaptive array has enough elements to suppress the interferences. Figure 5 shows the beam patterns of the four systems in the scenario I. Under this circumstance, all the four systems will perform very well as shown in Figure 6. The OBHAE will have the best performance in those systems.

The scenario II uses for simulation is similar to the scenario I except that the angle θ_3 is changed to $-6°$. The second multipath signal is a main-beam multipath ISI because the separation between θ_1 and θ_3 is less than the beam-width of the array. Figure 7 shows the beam patterns of four systems in the scenario II. Both of the CMA and the CMA-AE will suffer the problem of main-beam multipath ISI. Therefore, the beam patterns of those two systems are disturbed by the main-beam multipath ISI. One can observe that the array in the OBHAE and the CMA-HAE can generate a main-beam in the direction of desired signal regardless the presence of the main-beam multipath ISI. Figure 8 shows the transient behaviors of the four systems. It can be found that the mean square errors of OBHAE and CMA-HAE are lower than the CMA-AE and the CMA array. Besides, Figure 8 also shows that the OBHAE has the best convergent performance in those four systems.

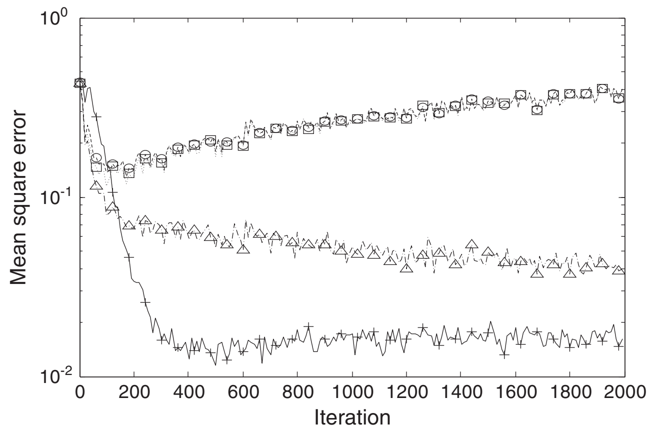

Figure 8. Transient behavior for scenario II.

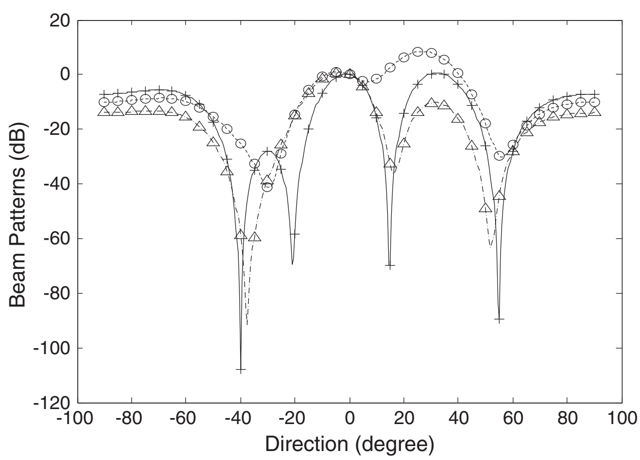

Figure 9. Beam patterns for scenario III.

In the scenario III, the array element is less than the number of sources. The base-band signal $x_n(k)$ is given by

$$x_n(k) = a(k-1)e^{jk_c(n-1)l\sin\theta_1} + 0.2a(k)e^{jk_c(n-1)l\sin\theta_2} + 0.2a(k-2)e^{jk_c(n-1)l\sin\theta_3} + a_4(k)e^{jk_c(n-1)l\sin\theta_4} + a_5(k)e^{jk_c(n-1)l\sin\theta_5} + a_6(k)e^{jk_c(n-1)l\sin\theta_6} + n_n(k) \quad . \tag{54}$$

In which the first three sources are multipath signals and the others are CCI. The angles of the arrivals are $\theta_1 = 0°$, $\theta_2 = 55°$, $\theta_3 = -50°$, $\theta_4 = -20°$, $\theta_5 = 15°$, and $\theta_6 = -40°$. The input SNR is 20 dB and the power of all the CCI are −5 dB with respect to the signal power. The signal $a(k-1)$ is considered as the desired signal. The beam patterns of the four systems in the scenario III are shown in Figure 9. Because there are six incoming sources the CMA array does not have enough degrees of freedom to suppress the five interferences, which degrade the performance of the adaptive array. Because the residual interference of the array output contain CCI, which fall in the directions of $\theta_5 = 15°$, the equalizer of CMA-AE cannot remove the residual CCI of the array output. Therefore, the equalizer of the CMA-AE cannot improve the performance of the CMA. However, for both the OBHAE and the CMA-HAE, the adaptive array can suppress three CCI successfully and the multipath ISI is canceled by the equalizer following the array. Thus, both the OBHAE and the CMA-HAE can perform better than the other two systems. The mean square errors of the four systems in scenario III are plotted in Figure 10. Moreover, the OBHAE has better performance than the CMA-HAE.

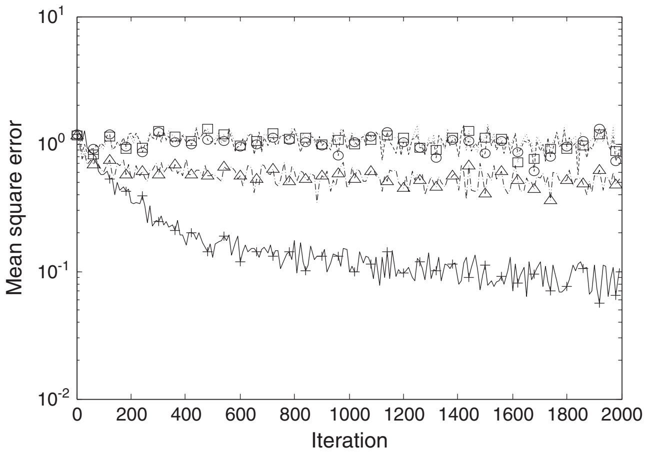

Figure 10. Transient behavior for scenario III.

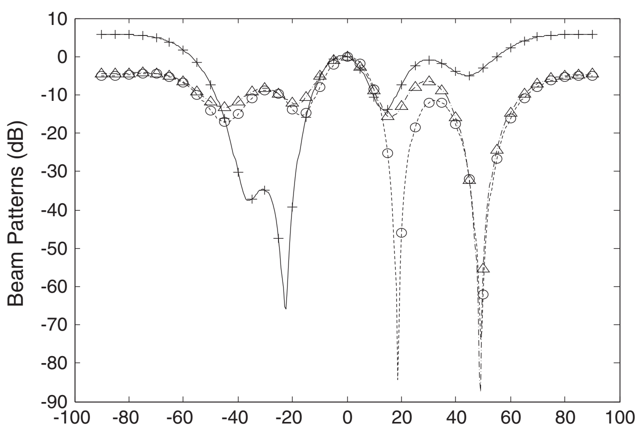

Figure 11. Beam patterns for scenario IV.

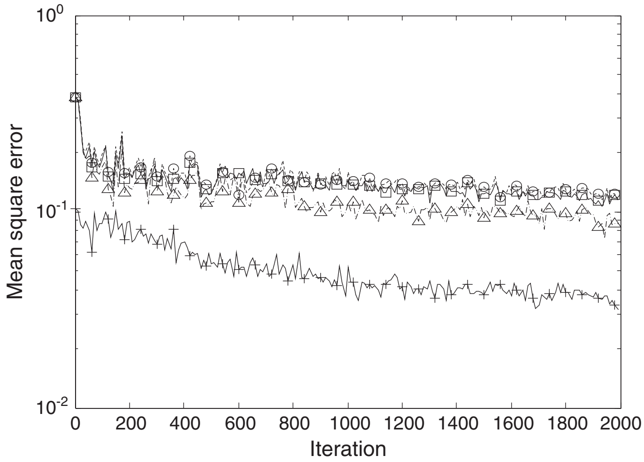

Figure 12. Transient behavior for scenario IV.

The signal model in the scenario IV is similar to scenario I except that a multipath signal is coherent with the desired signal $a(k-1)$. The base-band signal $x_n(k)$ is given by

$$x_n(k) = a(k-1)e^{jk_c(n-1)l\sin\theta_1} + 0.2a(k-1)e^{jk_c(n-1)l\sin\theta_2} + 0.2a(k-2)e^{jk_c(n-1)l\sin\theta_3} + a_4(k)e^{jk_c(n-1)l\sin\theta_4} + n_n(k) \quad . \tag{55}$$

Because the OBHAE cannot suppress the coherent interference, the performance of the OBHAE will be degraded by the coherent interference. We can combine the OBHAE with the spatial smoothing method to combat the coherent interference problem. Figure 11 shows that the OSSB algorithm can suppress the coherent interference in the direction of $-20°$ successfully. The mean square errors of CMA, CMA-AE, CMA-HAE, and OSSB in scenario IV are plotted in Figure 12. In Figure 12, it is shown that the proposed OSSB can improve the performance of the system in case of coherent interference present.

5. CONCLUSIONS

We have proposed a novel algorithm called OBHAE, which orthogonalizes the input vectors of the adaptive array and equalizer without using the training sequence. The weight vectors of the adaptive array and equalizer in the OBHAE are decided by the error function, which constrains the output of the OBHAE to a constant. In the OBHAE, the CCI can be canceled by the array and the ISI can be canceled by the array or the equalizer following the array. The OBHAE will perform better than the CMA and the CMA-AE in the cases of insufficient degrees of freedom and main-beam multipath ISI. Because the weights of the adaptive array and equalizer in the OBHAE are adjusted simultaneously, the OBHAE will have better convergent rate than both the CMA and the CMA-AE. Because the input vector is orthogonalized in advance, the OBHAE will have better performance than CMA-HAE. Besides, the OSSB algorithm has been proposed to improve the convergent performance of the OBHAE in the presence of coherent interference. Computer simulations have been presented to demonstrate the merits of OBHAE and OSSB.

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