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The Differential CMA Adaptive Array Antenna Using an Eigen-Beamspace System

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SUMMARY This paper addresses approaches to enhancement of performance of the CMA (Constant Modulus Algorithm) adaptive array antenna in multipath environments that characterize the mobile radio communications. The cost function of the CMA reveals that it has an AGC (Automatic Gain Control) procedure of holding the array output voltage at a constant value. Therefore, if the output voltage by the initial weights is different from the object value, then the CMA may suffer from slow convergence because suppression of the multipath waves is delayed by the AGC behavior. Our objective is to improve the convergence characteristics by adopting the differential CMA for the adaptive array algorithm. First, the basic performance of the differential CMA is clarified via computer simulation. Next, the differential CMA is incorporated into the eigen-beamspace system in which the eigenvectors of the correlation matrix of array inputs are used in the BFN (Beam Forming Network). This BFN creates the optimum orthogonal multibeams for radio environments and works helpfully as a preprocessor of the differential CMA. The computer simulation results have demonstrated that the differential CMA with the eigen-beamspace system has much better convergence characteristics than the conventional CMA with the element space system. Furthermore, a modified algorithm is introduced which gives the stable array output voltages after convergence, and it is confirmed that the algorithm can carry out more successful adaptation even if the radio environments are changed abruptly.

key words: *adaptive array, differential CMA, eigen-beamspace system, mobile communication, Marquardt method, steepest descent method*

1. Introduction

Recently, remarkable progress has been made in mobile communications, and the demand for those is increasing rapidly. However, since the utilization of frequency spectrum is restricted, quality of radio communication is degraded by interferences due to closely placed radio stations (e.g., co-channel interferences) and multipath propagation interferences. Therefore, the receiving systems which can suppress the unwanted signals while maintaining the desired signal are required eagerly.

It is known that adaptive arrays are one of the effective measures for suppressing the interferences in multipath environments [1]–[6]. Particularly, it is reported that CMA (Constant Modulus Algorithm) adaptive array has the superior performance [1]–[3], [5], [6].

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The CMA adaptive array was developed for the capture of constant envelope signals and works to eliminate the amplitude fluctuations of the array output signal due to the incidence of interferences. As a reference for the capture, the CMA has the desired constant amplitude of the array output in the cost function, and so it includes an AGC (Automatic Gain Control) procedure of holding the array output voltage at the constant value [1]. Therefore, if the output voltage by the initial weights is different from the object value, then the AGC procedure is prior to suppressing the multipath waves, which leads to slow convergence. Even though the array output amplitude is nearly equal to the expected value before adaptation (e.g., by the additional AGC circuit incorporated in the receiver), the optimization with the steepest descent method reveals slow convergence [6]. In this paper, accordingly, to make its convergence characteristics much better, we adopt the differential CMA [7] as the adaptive algorithm and discuss its performance in multipath environments.

Furthermore, we try to incorporate the differential CMA into the eigen-beamspace system [8], [9]. In this system, we compute the eigenvalues and eigenvectors of the correlation matrix of array inputs. Based on eigenstructure methods such as MUSIC [10], we can estimate the number of incident waves from the number of eigenvalues which are larger than the internal noise power. The eigenvectors are used for the beamforming weighting in the BFN (Beam Forming Network). This BFN creates the orthogonal multibeams and works as a preprocessor of the differential CMA. The eigenvalues are equal to the average powers of BFN outputs using the corresponding eigenvectors as the BFN weighting, and so we can choose the BFN outputs which are effectively used in the differential CMA. Also, the number of the chosen BFN outputs is equal to that of the incident waves, which enables the CMA to do the most efficient processing.

Through computer simulation, we show that the differential CMA with the eigen-beamspace system has better convergence characteristics than the conventional CMA system. In addition, we modify the optimization algorithm to get the more stable output voltages after convergence. Then, via computer simulation, we demonstrate that this algorithm provides not only higher stability but also more successful adaptability to the changing radio environments.

A brief outline of the paper now follows. In Sects. 2 and 3, we state the principles of the CMA and the differential CMA, respectively. Also, in Sect. 3, we present the basic performance of the differential CMA by computer simulation. In Sect. 4, after the concept of the eigen-beamspace system is explained, the performance of the differential CMA using the eigen-beamspace system is discussed. Finally, concluding remarks are given in Sect. 5.

2. Principle of the CMA Adaptive Array

The CMA was developed for the capture of constant envelope signals [1], [2]. The knowledge required in advance for the CMA is nothing except that the desired signal possesses the constant envelope. Therefore, the CMA is suitable for the mobile communications in which it is difficult to extract available information on the desired signal from the complex radio environments.

Now, we consider a K-element antenna array. Figure 1 shows a configuration of the array receiving system. Let x_i and w_i represent the input and weight at ith element respectively, and also $\mathbf{X}$ and $\mathbf{W}$ denote the input vector and weight vector, respectively, which are defined as

$$\mathbf{X} = [x_1, \cdots x_K]^T \tag{1}$$
$$\mathbf{W} = [w_1, \cdots w_K]^T \tag{2}$$

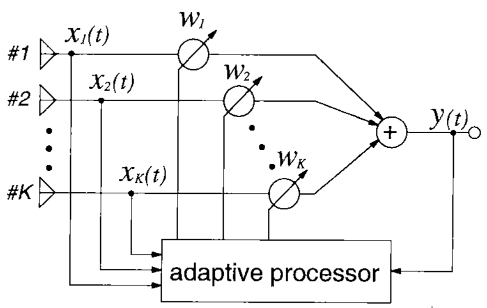
where T denotes the transpose. Then, the array output y is expressed as

$$y = \mathbf{X}^T\mathbf{W}^* \tag{3}$$

where $*$ denotes the complex conjugate.

The CMA adaptive array works to eliminate the amplitude fluctuations of the array output signal due to the incidence of interferences. Thus, the cost function to be minimized is normally represented as

$$Q(\mathbf{W}) = E\left[\left||y|^2 - \sigma^2\right|^2\right] \tag{4}$$



$x(t)$: input w: weight $y(t)$: output

Fig. 1 Configuration of a K-element adaptive array.

where $E[\cdot]$ stands for the ensemble mean and σ is an amplitude of the array output signal expected in the absence of signal degradation. Equation (4) is nonlinear with the array weights, and so the optimum weight vector cannot be described in a closed form. Therefore, the optimum weight vector of the CMA is obtained by using iterative methods. In this paper, we use the steepest descent method and Marquardt method [11], [12] as the iterative optimization algorithm.

3. Principle and Properties of the Differential CMA Adaptive Array

3.1 Principle

As presented in Eq. (4), the cost function of the conventional CMA includes an AGC procedure of holding the array output voltage at a constant value of σ. Therefore, if $|y|$ is different from σ at the initial state, the suppression of multipath waves is delayed because of the priority of the AGC precedence.

For improving this, we adopt the following cost function proposed in Ref. [7].

$$Q(\mathbf{W}) = E\left[\left||y(i)|^2 - |y(i-1)|^2\right|^2\right] \tag{5}$$

where $y(i)$ and $y(i-1)$ are the array output signals sampled at the ith data symbol and $(i-1)$th data symbol, respectively. By minimizing the cost function of Eq. (5), we obtain the optimum array weights. This algorithm is called the differential CMA. Since the algorithm does not specify the amplitude of the array output, it is expected that it can improve the convergence characteristics.

Also, it is noted that there may exist a trivial solution: $\mathbf{W} = 0$ in the differential CMA, but it can be removed by fixing one of the array weights at a constant.

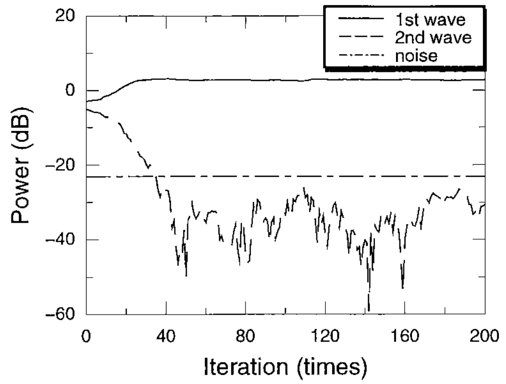
3.2 Properties of the Differential CMA

We discuss convergence characteristics of the differential CMA. To investigate the basic properties, we use a linear array of isotropic antenna elements. The element spacing of the array is a half wavelength of the carrier frequency and the number of elements is two or three. We generate a $\pi/4$-shifted QPSK signal which is transmitted over several multipath channels. Sampling rate is equal to $8/T$ for the symbol duration of T, and all the signals are not filtered and not disturbed by channel fading. A series of random binary PN (Pseudo Noise) codes is utilized as data transmitted and the differential detection system is used for code detection.

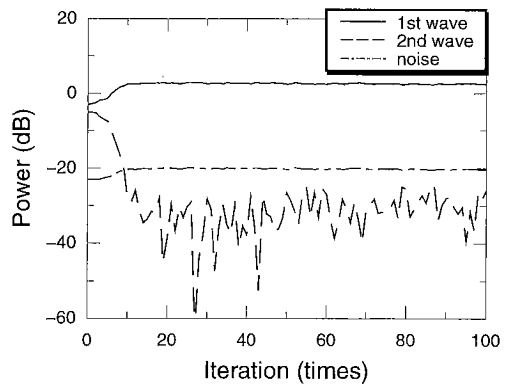
Table 1 gives the detail of radio environment used in simulation experiments for a 2-wave multipath model. Angles of arrival are measured from the broadside direction of array. The internal noises with an equal power exist at each antenna element, and the input SNR is

Table 1 Radio environment used in computer simulation of Sect. 3.2.

	power	angle of arrival	delay time
wave 1	0 dB	0°	0
wave 2	−2 dB	60°	T
Input SNR = 20 dB			



(a) steepest descent method



(b) Marquardt method

Fig. 2 Output powers vs. iteration (2-element linear array, differential CMA).

Table 2 Iteration numbers at which the average BERs become less than 10^{-6}.

	differential	conventional
steepest descent	17	33
Marquardt	6	7

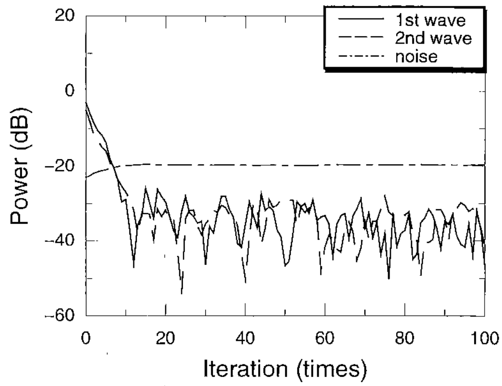


Fig. 3 Output powers vs. iteration (3-element linear array, differential CMA, Marquardt method).

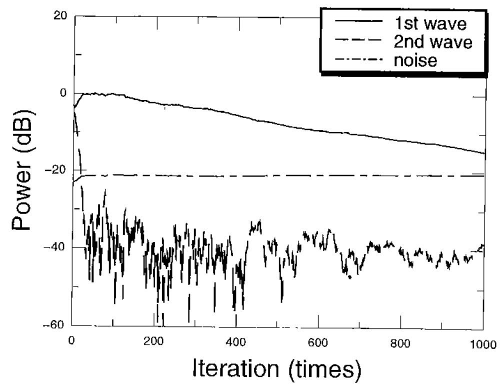


Fig. 4 Output powers vs. iteration up to 1000 (3-element linear array, differential CMA, steepest descent method).

defined as the power ratio of the first incident wave to the internal noise. In the CMA optimization, we use 15 snapshots for one update of weight vector. The initial weight vector is set to $\mathbf{W}_0 = [1, 0, \cdots, 0]^T$, which means the initial array pattern is isotropic, and w_1 is fixed at 1 in the differential CMA. Also, in the conventional CMA, we let $\sigma = 1$, which is equal to the amplitude of the first incident signal.

First, we show in Fig. 2 the output powers versus the iteration number for the 2-element system. From this figure, both the steepest descent method and the Marquardt method capture the first incident wave and suppress the second one. Also, iteration numbers at which the average BERs (Bit Error Rate) become less than 10^{-6} are shown in Table 2. For fair comparison, the stepsizes of the steepest descent method are chosen so as to make the output fluctuations at the stationary state almost the same in the differential CMA system and the conventional CMA system. It is found that the convergence rate is raised by the differential CMA particularly in the case of the steepest descent method.

Next, Figs. 3 and 4 show the output powers versus the iteration number for the 3-element system using the the Marquardt method and the steepest descent method, respectively. In the figure, it is noted that both two waves are suppressed. Since the Marquardt method provides much higher convergence rate than the steepest descent method [6], the suppression of both arriving waves arises so early. From these figures, we can conclude that suppression of all the incoming waves as shown in Figs. 3 and 4 is directly due to excess of the degrees of freedom of the array. In the background, there is also the reason that the differential CMA does not have any reference designating the amplitude of the array output.

4. Improvement by Use of an Eigen-Beamspace System

It has been clarified in the previous section that the differential CMA may suppress the desired signal as well as the undesired signals if the number of the degrees of freedom ($K-1$) is larger than that of the incident waves. Then, we must adjust the number of elements of the array according to the incident waves in using the differential CMA.

4.1 Eigen-Beamspace System

Now, in this section, we incorporate the differential CMA into an eigen-beamspace system [8], [9] in order to operate it successfully. Using the eigen-beamspace system, we can estimate the number of the incident waves almost exactly. That is why the eigen-beamspace system is much helpful to the differential CMA. As the similar beamspace system, the FFT-based beamfomer is often employed [13]. Indeed it creates a set of orthogonal beams, but they are not dependent on the powers and directions of the incoming waves. Therefore, using the FFT-based beamfomer cannot always offer the accurate number of the incident waves, which is required by the differential CMA. From that, it follows that the eigen-beamspace is preferable to the FFT-based beamspace for the differential CMA.

In the eigen-beamspace system, eigenvectors of the input correlation matrix are utilized as the beamforming weight vectors in the BFN. Then, the BFN outputs are led to the differential CMA. In the following, we explain the method of beamforming based on the eigen beamspace.

We obtain the correlation matrix from the input vector $\mathbf{X}$:

$$R_{xx} = E[\mathbf{X}\mathbf{X}^{\dagger}] \tag{6}$$

On assumption that the internal noises at the antenna elements are independent of each other, we get the following relations:

$$R_{xx}E = E\Lambda \tag{7}$$

$$\Lambda \triangleq \mathrm{diag}\,[\lambda_1, \lambda_2, \cdots, \lambda_K]$$
$$E \triangleq [\mathrm{e}_1, \mathrm{e}_2, \cdots, \mathrm{e}_K]$$

$\lambda_i \; (i = 1, \cdots, K)$: eigenvalues
$\mathrm{e}_i \; (i = 1, \cdots, K)$: eigenvectors

and

$$\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_L > \lambda_{L+1} = \cdots = \lambda_K = P_n \triangleq \lambda_{min} \tag{8}$$

where L is the number of the incident waves and P_n is the internal noise power. As shown in Eq. (8), we can estimate the number of the incident waves (L) from the number of eigenvalues larger than the internal noise power [10]. The eigenvectors $\mathrm{e}_i (i = 1, \cdots, K)$ are used for the beamforming in the BFN, and the beam outputs $b_i (i = 1, \cdots, K)$ are represented as follows:

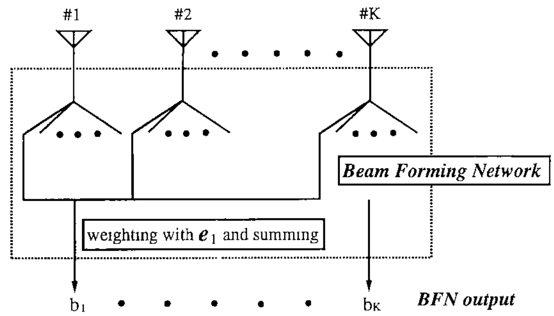


Fig. 5 Structure of the BFN with an eigen-beamspace system.

$$b_i = \mathrm{e}_i^{\dagger}\mathbf{X} \quad (i = 1, \cdots, K) \tag{9}$$

Since there is a relationship: $E[|b_i|^2] = \mathrm{e}_i^{\dagger} R_{xx} \mathrm{e}_i = \lambda_i$, we can see that the beams: $b_{L+1}, \cdots, b_K$ do not include the incident waves (including only the internal noises), and we can choose the beams: $b_1, \cdots, b_L$ as the BFN outputs available for the subsequent differential CMA. Figure 5 illustrates the method of beamforming in the BFN. As stated previously, the weight for the b_1 is fixed at a constant to avoid the trivial solution: $\mathbf{W} = \mathbf{0}$.

4.2 Properties of the Differential CMA Using an Eigen-Beamspace System

We carry out computer simulation to compare the differential CMA using the eigen-beamspace system with the conventional CMA using the element space system. For application in mobile communications, we use here a 4-element planar array shown in Fig. 6. Table 3 gives the detailed radio environment for a 2-wave multipath model. The signal transmitted and the detection system are the same as in Sect. 3. In this simulation, the signal is band-limited by the Nyquist filter with the bandwidth of $B = 1/T$ and roll-off factor of 0.5. Furthermore, we involve the Doppler effect so as to examine the dynamic characteristics. We suppose that the antenna system moves to the direction of 0° at a speed of 60 km/h for the carrier frequency of 1.5 GHz. In that case, the maximum Doppler frequency is equal to about 83 Hz. The eigenvalues and eigenvectors are obtained from the first 15 snapshots at the initial state. The other conditions are the same as in Sect. 3.

We show the beam patterns at the BFN outputs in Fig. 7 and the eigenvalues corresponding to their output powers in Table 4. From Fig. 7, it is found that both beam 1 and beam 2 capture the arriving waves and both beam 3 and beam 4 create nulls in their directions of arrival. Also, the eigenvalues of beam 3 and beam 4 are

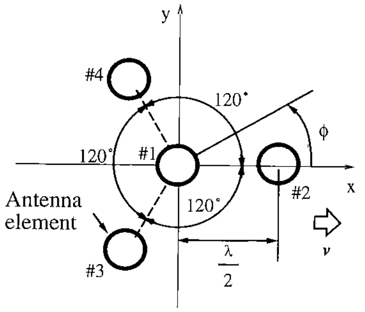


Fig. 6 Arrangement of a 4-element planar array.

Table 3 Radio environment used in computer simulation of Sects. 4.2 and 4.3.

	power	angle of arrival	delay time
wave 1	0 dB	0°	0
wave 2	−2 dB	20°	1.6T
Input SNR = 20 dB			

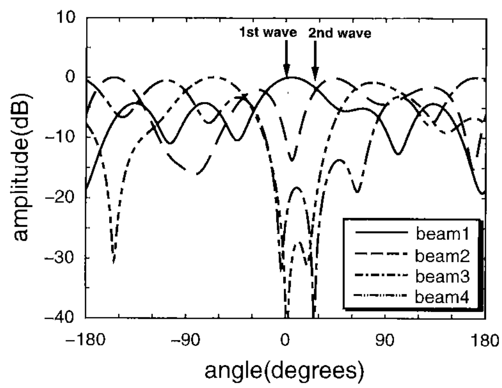


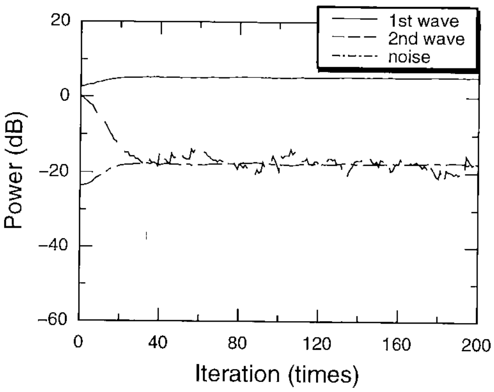
Fig. 7 Directional patterns of the eigen beams for Table 3.

Table 4 Eigenvalues corresponding to the eigen beams.

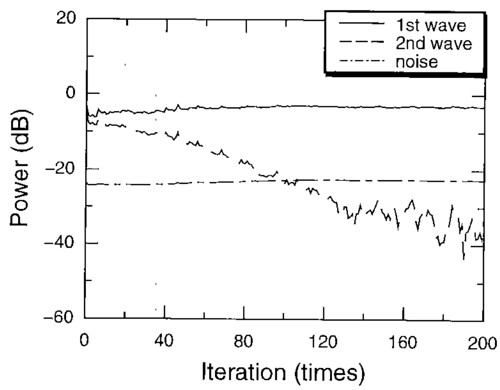
beam number	eigenvalue
beam 1	3.30
beam 2	0.777
beam 3	0.00522
beam 4	0.000341

quite smaller than those of beam 1 and beam 2. Therefore we operate the differential CMA using the outputs of beam 1 and beam 2.

Figures 8 and 9 show the array output powers versus the iteration number for the steepest descent method and the Marquardt method, respectively. The stepsizes of the steepest descent method in Fig. 8 are determined so as to make the output fluctuations at the stationary state almost the same in the differential CMA system and the conventional CMA system. You can see that the differential CMA system more quickly suppresses the second wave than the conventional CMA system particularly in the case of the steepest descent method. Such rapid convergence is obviously due to



(a) differential CMA using eigen-beamspace system



(b) conventional CMA using element space system

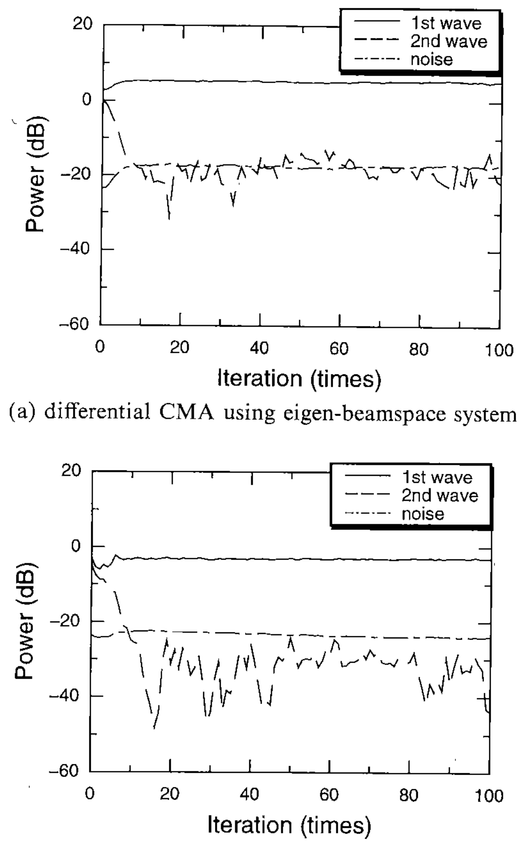
Fig. 8 Output powers vs. iteration (4-element planar array, steepest descent method).

the use of not only the differential CMA but also the eigen-beamspace system. In addition, the differential CMA system provides the higher SINR (Signal-to-Interference-plus-Noise Ratio) at the initial state. It is because the beam 1 has a higher gain in the arrival direction of the first wave. In contrast, the conventional CMA system suppresses more deeply the second wave and brings more stable outputs of the second wave after convergence, both in the steepest descent method and the Marquardt method. It is an advantage of the conventional CMA that has σ, the fixed object value of the output envelope, making the weight update finer and surer at the stationary state.

We next discuss techniques that enable the differential CMA system to have more stable stationary characteristics.

4.3 2-Mode Switching System

Now, we focus on the fluctuation of $||y(i)| - |y(i-1)||$, i.e., the difference of $|y|$ between the adjacent data time slots to understand the convergence behavior of the differential CMA. Figure 10 shows the the difference of $|y|$ (average among 15 snapshots) versus the iteration



(a) differential CMA using eigen-beamspace system

(b) conventional CMA using element space system

Fig. 9 Output powers vs. iteration (4-element planar array, Marquardt method).

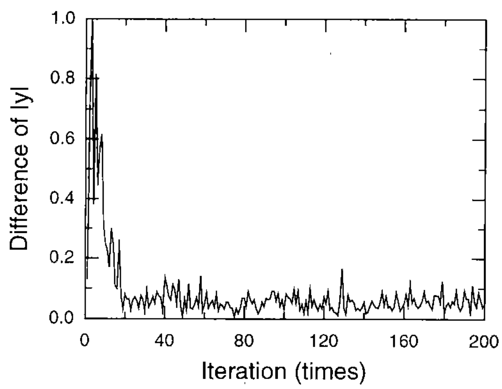
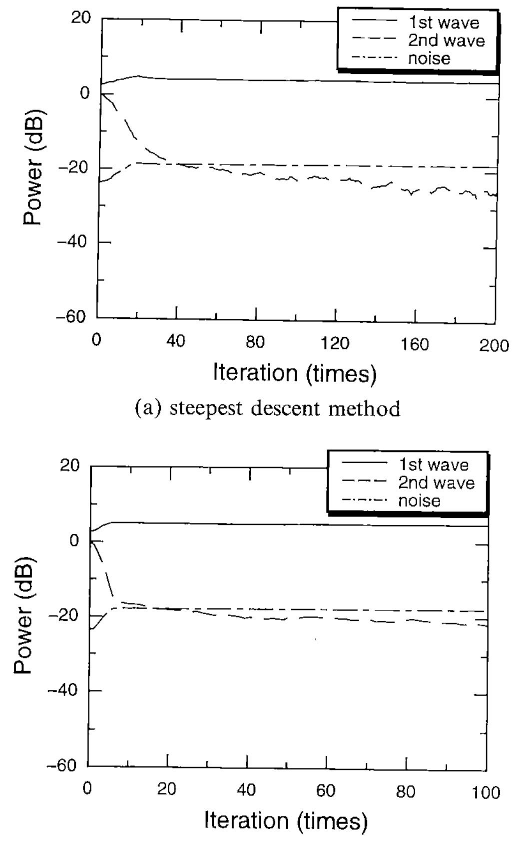


Fig. 10 Difference of $|y|$ vs. iteration (4-element planar array, steepest descent method).

number in the steepest descent method for the radio environment of Table 3.

From Figs. 10 and 8 (a), it is observed that after convergence, the difference of $|y|$ is settled at a small value almost less than 0.1 and the array output power of the second wave is suppressed down to the noise power level.

From the results, we introduce here an algorithm of



(a) steepest descent method

(b) Marquardt method

Fig. 11 Output powers vs. iteration using 2-mode switching system (4-element planar array, eigen-beamspace system).

switching the cost functions from the differential CMA to the conventional CMA when the difference of $|y|$ becomes smaller than a given threshold. Although the algorithm of this type was already proposed as the "2-mode switching system" in Ref. [7], it is different from *our* 2-mode system in terms of the way of switching. Since the 2-mode algorithm has two advantages of the high convergence rate of the differential CMA and the high stability of the conventional CMA, it is expected that it bears better convergence performance. Furthermore, we propose to get much more stable performance by reducing the stepsize in the steepest descent method and by increasing the Marquardt number in the Marquardt method when the cost functions are switched after convergence.

Figure 11 shows the output powers versus the iteration number using the 2-mode switching algorithm under the radio environment of Table 3. After switching of the cost functions, the stepsize of the steepest descent method is reduced by a factor of 1/5 and the Marquardt number of the Marquardt method is increased by a factor of 25. Also, the σ of the conventional CMA is let equal to the final $|y|$ in the differential CMA. It is found that the characteristics of high rate of convergence and

Table 5 Radio environment used in computer simulation of Sect. 4.4.

	power	angle of arrival	delay time
wave 1	0 dB	0°	0
wave 2	−2 dB	50°	$1.6T$
wave 3	−3 dB	100°	$2.2T$
Input SNR = 20 dB			

high stability are obtained, and also it is confirmed that it is effective to readjust the stepsize or Marquardt number after convergence.

4.4 Performance of 2-Mode Switching System under Changing Radio Environments

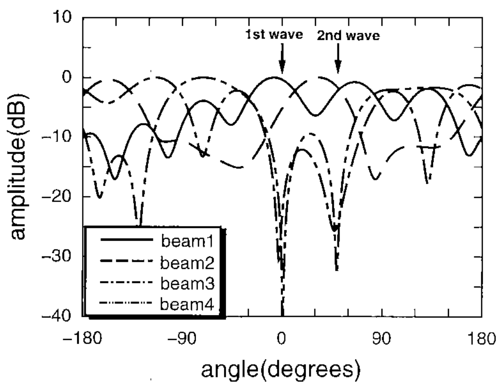
Next, we discuss whether the 2-mode system can adapt itself to changing radio environments. It is supposed that the third wave arrives suddenly after the 60th iteration. The radio environments are described in Table 5. The other conditions are the same as in the previous simulation.

In this simulation, the following iterative algorithm for computing the correlation matrix is used [14]:

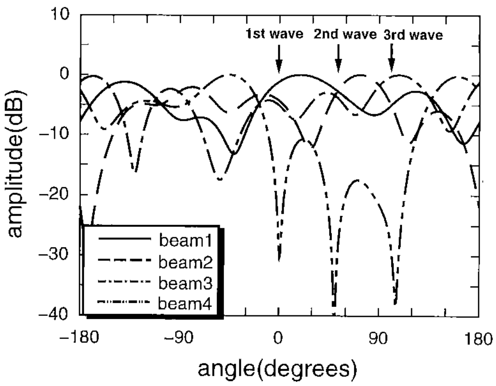
$$\begin{cases} R_{xx}(m) = \beta R_{xx}(m-1) \\ \qquad +(1-\beta)\overline{\mathbf{X}\mathbf{X}^{\dagger}}(m) \\ \qquad (m = 1, 2, ...) \\ R_{xx}(0) = \overline{\mathbf{X}\mathbf{X}^{\dagger}}(0) \end{cases} \tag{10}$$

where m is the iteration number, and $R_{xx}(0)$ and $R_{xx}(m)$ are the correlation matrices at the initial step and at the mth iteration, respectively. Also, β is the forgetting factor and is equal to 0.9 in this simulation. $\overline{\mathbf{X}\mathbf{X}^{\dagger}}(m)$ denotes the sample correlation matrix obtained from the 15 snapshots at the mth iteration. We are convinced that the radio environment is changed when the difference of $|y|$ becomes large again during the adaptive processing. Then, we compute the eigenvalues and eigenvectors of $R_{xx}(m)$ and make the eigen beams again. Figure 12 shows the patterns of eigen beams before and after change of the environment. From this figure, it follows that the beam 1 and beam 2 in (a) and the beam 1, beam 2, and beam 3 in (b) are used for the respective CMAs.

Figures 13 and 14 show the output powers versus the iteration and the difference of $|y|$ versus the iteration, respectively. The steepest descent method is used for optimization. In Fig. 14, the cost functions are switched from the differential CMA to the conventional CMA when the difference of $|y|$ becomes smaller than a threshold level of 0.1. Futher, when the difference of $|y|$ increases abruptly owing to change of the radio environment, the cost functions are switched again from the conventional CMA to the differential CMA. From Fig. 13, it is found that the 2-mode CMA with the eigen



(a) in the case of 2 waves arriving



(b) in the case of 3 waves arriving

Fig. 12 Directional patterns of eigen beams for Table 5.

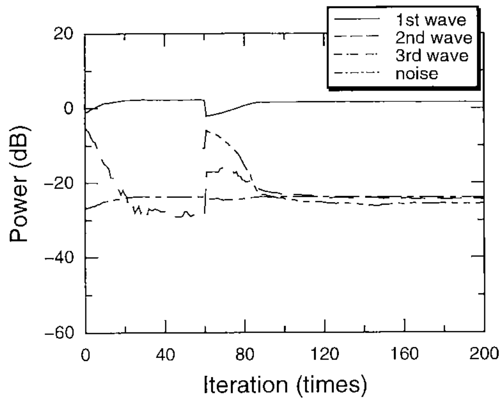
beamspace adapts so quickly itself to the abrupt arrival of the third wave, compared with the conventional CMA with the element space. Carrying out the further computer simulation with the different delay times of the third wave, we obtained the similar results. From these simulation results, it is confirmed that the 2-mode system provides the rapid convergence and the high stability even in case that the radio environment changes.

5. Conclusion

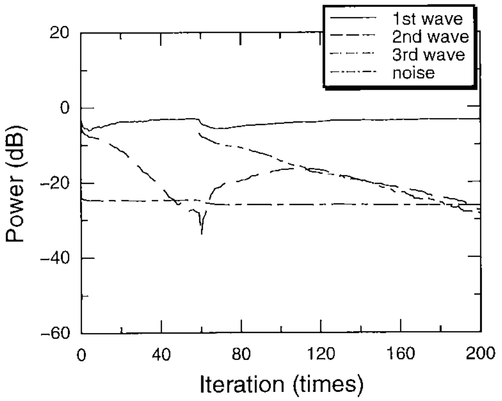
We have discussed the performance of the differential CMA adaptive array antenna using an eigen-beamspace system. Via computer simulation, it has been clarified that the differential CMA provides the rapid convergence relative to the conventional CMA. However, it has the shortcomings as follows:

- The differential CMA may suppress all incoming waves if the degrees of freedom of the array are too enough.
- The stability of the differential CMA after convergence is inferior to that of the conventional CMA.

Using the eigen-beamspace system, we can renovate the differential CMA to preserve the desired signal and fur-



(a) differential CMA using eigen-beamspace system



(b) conventional CMA using element space system

Fig. 13 Output powers vs. iteration in the case of changing radio environment (4-element planar array, steepest descent method).

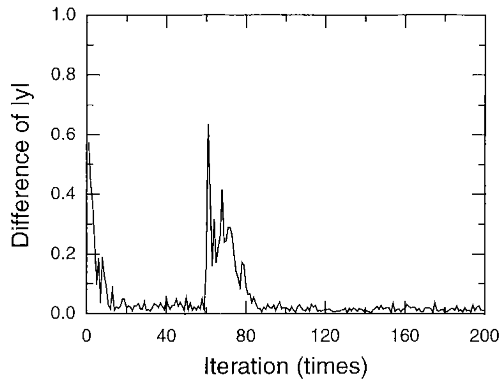


Fig. 14 Difference of $|y|$ vs. iteration in the case of changing radio environment (4-element planar array, eigen-beamspace system, steepest descent method).

ther to have better convergence characteristics than the conventional CMA with the element space system.

To get more stable performance, we proposed to use the 2-mode system that switches the cost functions from the differential CMA to the conventional CMA after convergence. Through computer simulation, we have demonstrated that the 2-mode system has more stable performance and also that it can adapt itself more rapidly to change of the radio environments.

In this paper, we have not discussed in detail the algorithm to get the eigenvalues and eigenvectors of the correlation matrix. After this, we must discuss and develop the best algorithm for computing them.

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