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A New Blind Beamforming Procedure Based on The Conjugate Gradient Method for CDMA Mobile Communications

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CONTENTS

ABSTRACT

The objective of this paper is to present an adaptive algorithm for computing the weight vector which provides a beam pattern having its maximum gain along the direction of the mobile target signal source in the presence of interfering signals within a cell. The conjugate gradient method (CGM) is modified in such a way that the suboptimal weight vector is produced with the computational load of O(16N), which has been found to be small enough for the real-time processing of signals in most land mobile communications with the digital signal processor (DSP) off the shelf, where N denotes the number of antenna elements of the array. The adaptive procedure proposed in this paper is applied to code division multiple access (CDMA) mobile communication system to show its excellent performance in terms of signal to interference plus noise ratio (SINR), bit error rate (BER), and capacity, which are enhanced by about 7 dB, $\frac{1}{100}$ times, and 7 times, respectively, when the number of antenna elements is 6 and the processing gain is 20 dB.

I. INTRODUCTION

In recent years, the adaptive antenna array in land mobile communication systems has received a keen interest from many researchers [1]-[7], due to its potential viability for enhancing the communication quality and capacity at the same time. One of the most serious problems, however, in realizing the adaptive antenna array in the actual land mobile communication system is that the computational load required for the adaptive beamforming is so heavy that the real-time processing of time-varying signals of mobile communications is not possible or the consequent hardware of the array system is not economically feasible.

This paper presents an alternative method of finding a suboptimal weight vector for an antenna array. The new technique utilizes the CGM [8], [9] for computing the weight vector in an iterative manner based on a blind procedure, in which the training symbols are not required to find the solution vector. The adaptive procedure presented in this paper is appropriate to CDMA signal environment because the technique is valid when the desired signal is much stronger than each interference, which should be satisfied in CDMA receiver by the chip correlator. More details about the application of the proposed technique in CDMA is given in Section III. The most attractive feature of the proposed method is in its simplicity without sacrificing the accuracy. The computational load for obtaining the target vector is in the order of only about O(16N). The required amount of computation at each snapshot is apparently much less than that of most conventional beamformers such as constant modulus algorithm [10] (CMA) or least mean square [4] (LMS). Another important feature of the proposed method is that its application is not restricted to certain specific modulation types or data rates. Recall that the blind beamformer utilizing the spectral self-coherent restoral [5] (SCORE) method cannot extract the target signal unless every signal source adopts a unique modulation type or data rate compared to all the other signal sources in a cell, which is unlikely realistic in actual mobile communications.

Let us consider the autocovariance matrix of the signals that are incident upon the array of N antenna elements. Since the maximum eigenvalue always represents the signals (not the noises), the corresponding eigenvector must be a linear combination of the input steering vectors. If the eigenvector corresponding to the largest eigenvalue is denoted by $\boldsymbol{e}_1$, this statement can be expressed with the following equation:

$$\boldsymbol{e}_1 = \sum_{k=1}^{M} \alpha_k \boldsymbol{a}(\theta_k), \tag{1}$$

where M is the number of signal components at the array input, α_k is a coefficient that is determined by the magnitude and angle distribution of every signal component, and $\boldsymbol{a}(\theta_k)$ denotes the steering vector of the kth signal component of incident angle θ_k. The matrices and vectors are denoted by upper- and lower-case bold letters, respectively.

If the antenna spacing is uniformly a half wavelength though it is not the necessary condition for the proposed algorithm to be valid, the steering vector, $\boldsymbol{a}(\theta_k)$, of the kth signal component is

$$\boldsymbol{a}(\theta_k) = [1 e^{j\pi \sin\theta_k} e^{j2\pi \sin\theta_k} \cdots e^{j(N-1)\pi \sin\theta_k}]. \quad (2)$$

Suppose the magnitude of the desired signal component is much larger than that of each interfering components which is quite realistic in many practical situations. In this particular signal environment, if the incident angle of the desired signal component is θ_1, the eigenvector corresponding to the maximum eigenvalue can approximately be represented by only the desired signal as follows:

$$\boldsymbol{e}_1 \approx \alpha_1 \boldsymbol{a}(\theta_1). \quad (3)$$

Consequently, when the desired signal is much larger than each interference, the eigenvector corresponding to the maximum eigenvalue is itself the direction vector multiplied by the coefficient, i.e., α_1. Note that the above-mentioned signal condition is always satisfied in CDMA systems after performing the cross-correlation between the received signal and the code sequence of target signal. Then, the desired signal would be, on average, larger than each interference signal by the amount of the processing gain.

From the above-mentioned statement, it can be observed that, once the eigenvector, $\boldsymbol{e}_1$, is found, a nice beam pattern having its main lobe along the direction of the desired signal can be obtained. The complex-valued coefficient α_1 can be removed by setting the first element of the eigenvector with a real-valued quantity, which means that the phase of the reference antenna element remains unchanged at every snapshot.

It is the conclusion of this section that a suboptimal beam pattern with its main lobe pointing to the direction of the desired signal can be obtained by setting the gain of each antenna element with the corresponding element of the eigenvector of the maximum eigenvalue. This is the very reason why we intend to solve the extreme-eigenvalue problem.

II. ADAPTIVE ALGORITHM: CGM

As discussed in the previous section, to obtain a suboptimal beam pattern is to set up the weight vector for the antenna elements with the eigenvector corresponding to the maximum eigenvalue. Then, the $\boldsymbol{y}$ array system would have a beam pattern with its main lobe along the direction of the target signal source [4], [6]. Once again, above-mentioned procedure is valid only when the target signal is much larger than each interference at the receiver such that the eigenvector of the maximum eigenvalue approximately consists of the direction vector of the target signal source only. There exists a few numerical methods for solving the extreme eigenvalue problem such as the CGM, Lagrange-procedure [11], and power series method [11]. In this paper, we consider the CGM [8], [9], [12]. The CGM has been known as being an efficient method for solving a matrix equation of the form $\boldsymbol{Aw} = \boldsymbol{y}$ where the matrix $\boldsymbol{A}$ and the excitation vector $\boldsymbol{y}$ are known. In the previous work [7], the CGM is modified in such a way that the iterations for searching for the eigenvector of the updated matrix are executed for each individual snapshot. The modification is based on the fact that the solution for the vector $\boldsymbol{w}(k)$ maximizes the Rayleigh quotient of the autocovariance matrix at each snapshot, where k denotes the snapshot index. In [7], this CGM is named modified CGM (MCGM).

Assuming each snapshot requires a single iteration, the adaptive procedure of the MCGM requires the computational load of O(3N^2+12N) including the matrix update at each snapshot. In most practical signal environments of land mobile communications, a single iteration at each snapshot results in a fairly good performance [7]. The reason for the repeated iterations not to be required is mainly due to the following facts: firstly, the initial guess for the gain vector, $\boldsymbol{w}(0) = \boldsymbol{x}(0)/\|\boldsymbol{x}(0)\|$, should be quite close to the exact eigenvector of the maximum eigenvalue because the initial autocovariance matrix is determined by the initial signal vector $\boldsymbol{x}(0)$ only, i.e., $\boldsymbol{R}_x(0) = \boldsymbol{x}(0)\boldsymbol{x}(0)^H$, secondly, the gain vector at each snapshot should be a pretty good solution even before the update procedure if it was a good solution for the previous snapshot of which the statistics should not be much different from that of the current one in a slowly-fluctuating time-variant signal environments, finally, the signal circumstance for the adaptive algorithm to converge is good because the power of desired signal is much larger than that of each interference.

With the computational load of O(3N^2+12N), it is possible to calculate the eigenvector with most DSPs off the shelf in a real-time processing. However, it can further be modified to result in even more simplified version. The key idea in developing the new version is that the matrix update can be eliminated by considering the instantaneous signal vector only, i.e., $\boldsymbol{R}_x(k) = \boldsymbol{x}(k)\boldsymbol{x}(k)^H$, at every snapshot. Then, all the matrix operations in the adaptive procedure of the MCGM disappear, e.g., the computation for the eigenvalue $\lambda(k) = \boldsymbol{w}^H(k)\boldsymbol{R}_x(k)\boldsymbol{w}(k)$ simply becomes $\lambda(k) = |y(k)|^2$ where $y(k)$ is the array output at kth snapshot, i.e., $y(k) = \boldsymbol{w}^H(k)\boldsymbol{x}(k)$. Since the new version utilizes the instantaneous signal vectors only, it is referred to as instantaneous CGM (ICGM). The primary motivation for developing the ICGM is to accelerate the tracking speed of the suggested beamformer by reducing the required number of operations. Although the ICGM produces the suboptimal vector very fast, requiring only about O(11N) operations at each iteration, there exists a performance degradation mainly due to the misalignment of the search direction vector $\boldsymbol{p}(k)$ in the adaptive procedure of the ICGM. A compromised version, namely linearized CGM (LCGM), is presented in this section. In developing the LCGM, some sophisticated approximations are used in dealing with the matrix equations, each of which would require the operations of O(N^2), in such a way that the total computational burden can be about O(16N). From the various computer simulations, it has been found that LCGM causes almost no degradation in performance compared to the MCGM. Though the computational load is a little heavier than that of the ICGM, the performance of the LCGM is almost as good as the original MCGM as will be shown in the next section.

Now let us consider the adaptive procedure of the ICGM taking a single instantaneous signal vector in forming the autocovariance matrix. The computation of the autocovariance matrix is not required in ICGM because it considers the instantaneous signal vector only, i.e., $\boldsymbol{R}_x(k) = \boldsymbol{x}(k)\boldsymbol{x}(k)^H$, at every snapshot. Therefore, the two terms of the matrix operations included in the adaptive procedure of the MCGM, i.e., $\boldsymbol{R}_x(k)\boldsymbol{w}(k)$ and $\boldsymbol{R}_x(k)\boldsymbol{p}(k)$, become $\boldsymbol{x}(k)\boldsymbol{x}^H(k)\boldsymbol{w}(k)$ and $\boldsymbol{x}(k)\boldsymbol{x}^H(k)\boldsymbol{p}(k)$ respectively. Then, the total procedure can be summarized as follows :

⟨Step 1⟩ Set up the initial gain vector with the signal vector itself, i.e., $\boldsymbol{w}(0) = \boldsymbol{x}(0)/\|\boldsymbol{x}(0)\|$, as in the MCGM.

⟨Step 2⟩ Compute the array output by $y(k) = \boldsymbol{w}^H(k)\boldsymbol{x}(k)$, and receive a new signal vector $\boldsymbol{x}(k+1)$.

⟨Step 3⟩ Update the adaptive gain $t(k)$ and the search direction vector, $\boldsymbol{p}(k)$, as follows:

$$t(k) = \frac{-B-\sqrt{B^2-4AC}}{2A}, \tag{4}$$

$$A = b(k)\mathrm{Re}[c(k)] - d(k)\mathrm{Re}[a(k)],$$

$$B = b(k) - \lambda(k)d(k),$$

$$C = \mathrm{Re}[a(k)] - \lambda(k)\mathrm{Re}[c(k)],$$

$$\lambda(k) = |y(k)|^2,$$

$$a(k) = y(k)\boldsymbol{x}^H(k)\boldsymbol{p}(k),$$

$$b(k) = |\boldsymbol{p}^H(k)\boldsymbol{x}(k)|^2,$$

$$c(k) = \boldsymbol{w}^H(k)\boldsymbol{p}(k),$$

$$d(k) = \boldsymbol{p}^H(k)\boldsymbol{p}(k),$$

$$\boldsymbol{p}(k) = \boldsymbol{r}(k) + \beta(k)\boldsymbol{p}(k-1), \tag{5}$$

$$\boldsymbol{r}(k) = \lambda(k)\boldsymbol{w}(k) - \boldsymbol{x}(k)\boldsymbol{x}^H(k)\boldsymbol{w}(k), \tag{6}$$

$$\beta(k) = -\frac{\boldsymbol{r}^H(k)\boldsymbol{x}(k)\boldsymbol{x}^H(k)\boldsymbol{p}(k)}{\boldsymbol{p}^H(k)\boldsymbol{x}(k)\boldsymbol{x}^H(k)\boldsymbol{p}(k)}. \tag{7}$$

⟨Step 4⟩ Update the gain vector as $\boldsymbol{w}(k+1) = \boldsymbol{w}(k) + t(k)\boldsymbol{p}(k)$, and normalize it by $\boldsymbol{w}(k+1) = \boldsymbol{w}(k+1)/\|\boldsymbol{w}(k+1)\|$.

⟨Step 5⟩ For more iteration in the current snapshot, go back to ⟨Step 3⟩ with $\boldsymbol{w}(k) <= \boldsymbol{w}(k+1)$, otherwise, go back to ⟨Step 2⟩ for the next snapshot.

Note that the matrix operations required in computing $\lambda(k)$, $a(k)$, $b(k)$ are respectively replaced with the corresponding vector operations. From (4) ∼ (7), it can be observed that the adaptive procedure of ICGM requires only about O(11N) operations at each iteration.

In order to present the adaptive procedure of the LCGM, let us investigate the two terms of the matrix operations included in the adaptive procedure of the MCGM, i.e., $\boldsymbol{R}_x(k)\boldsymbol{w}(k)$ and $\boldsymbol{R}_x(k)\boldsymbol{p}(k)$. Since the matrix operations that appear in the adaptive procedure of the MCGM are in only these two terms, it would significantly reduce the computational amount if these two matrix-oriented terms can be simplified into vector operations. Let $\boldsymbol{R}_x(k)\boldsymbol{w}(k)$ and $\boldsymbol{R}_x(k)\boldsymbol{p}(k)$ be denoted by vectors $\boldsymbol{v}(k)$ and $\boldsymbol{u}(k)$, respectively. Then, by fully exploiting the relations $\boldsymbol{R}_x(k+1) = f\boldsymbol{R}_x(k) + \boldsymbol{x}(k+1)\boldsymbol{x}(k+1)^H$ and $\boldsymbol{w}(k+1) = \boldsymbol{w}(k) + t(k)\boldsymbol{p}(k)$, where f is the forgetting factor lying in $0 \leq f \leq 1$, the iterative equations of these two terms can be written as follows:

$$
\begin{aligned}
\boldsymbol{R}_x(k+1)\boldsymbol{w}(k+1) &\triangleq \boldsymbol{v}(k+1)\\
&= f\boldsymbol{v}(k) + ft(k)\boldsymbol{u}(k)\\
&\quad + \boldsymbol{x}(k+1)\boldsymbol{x}^H(k+1)\boldsymbol{w}(k+1) \qquad (8)\\
\boldsymbol{R}_x(k+1)\boldsymbol{p}(k+1) &\triangleq \boldsymbol{u}(k+1)\\
&= f\boldsymbol{R}_x(k)\boldsymbol{r}(k+1) + fq(k)\boldsymbol{R}_x(k)\boldsymbol{p}(k)\\
&\quad + \boldsymbol{x}(k+1)\boldsymbol{x}^H(k+1)\boldsymbol{p}(k+1)\\
&\approx fq(k)\boldsymbol{u}(k) + \boldsymbol{x}(k+1)\boldsymbol{x}^H(k+1)\boldsymbol{p}(k+1) \qquad (9)
\end{aligned}
$$

where the residue vector $\boldsymbol{r}(k+1)$ is defined as $\boldsymbol{r}(k+1) = \lambda(k+1)\boldsymbol{w}(k+1) - \boldsymbol{R}_x(k+1)\boldsymbol{w}(k+1)$ with $\lambda(k+1) = \boldsymbol{w}^H(k+1)\boldsymbol{R}_x(k+1)\boldsymbol{w}(k+1)$. Since $\boldsymbol{R}_x(k+1)\boldsymbol{r}(k+1)$ should converge to zero as the entire procedure converges, $\boldsymbol{u}(k+1)$ can be expressed with a simple combination of vector operations as in (9). The constant $q(k)$ in (9) is determined by setting each search direction vector $\boldsymbol{p}(k)$ to be $\boldsymbol{R}_x(k+1)$-conjugate at each iteration.

Utilizing the above relations, the adaptive procedure of the LCGM can be summarized as follows:

⟨Step 1⟩ Set up the initial gain vector determined by the signal vector itself, i.e., $\boldsymbol{w}(0) = \boldsymbol{x}(0)/\|\boldsymbol{x}(0)\|$, as in the ordinary MCGM.

⟨Step 2⟩ Compute the array output by $y(k) = \boldsymbol{w}^H(k)\boldsymbol{x}(k)$, and receive a new signal vector $\boldsymbol{x}(k+1)$.

⟨Step 3⟩ Update the adaptive gain $t(k)$ and the search direction vector, $\boldsymbol{p}(k)$, as follows:

$$
\begin{aligned}
t(k) &= \frac{-B - \sqrt{B^2 - 4AC}}{2A}, \qquad (10)\\
A &= b(k)\mathrm{Re}[c(k)] - d(k)\mathrm{Re}[a(k)],\\
B &= b(k) - \lambda(k)d(k),\\
C &= \mathrm{Re}[a(k)] - \lambda(k)\mathrm{Re}[c(k)],\\
\lambda(k) &= \boldsymbol{w}^H(k)\boldsymbol{R}_x(k)\boldsymbol{w}(k) = \boldsymbol{w}^H(k)\boldsymbol{v}(k),\\
a(k) &= \boldsymbol{w}^H(k)\boldsymbol{R}_x(k)\boldsymbol{p}(k) = \boldsymbol{w}^H(k)\boldsymbol{u}(k),\\
b(k) &= \boldsymbol{p}^H(k)\boldsymbol{R}_x(k)\boldsymbol{p}(k) = \boldsymbol{p}^H(k)\boldsymbol{u}(k),\\
c(k) &= \boldsymbol{w}^H(k)\boldsymbol{p}(k),\\
d(k) &= \boldsymbol{p}^H(k)\boldsymbol{p}(k),\\
\boldsymbol{p}(k) &= \boldsymbol{r}(k) + \beta(k)\boldsymbol{p}(k-1), \qquad (11)\\
\boldsymbol{r}(k) &= \lambda(k)\boldsymbol{w}(k) - \boldsymbol{R}_x(k)\boldsymbol{w}(k)\\
&= \lambda(k)\boldsymbol{w}(k) - \boldsymbol{v}(k), \qquad (12)\\
\beta(k) &= -\frac{\|\boldsymbol{r}(k+1)\|^2}{\|\boldsymbol{r}(k)\|^2}. \qquad (13)
\end{aligned}
$$

⟨Step 4⟩ Update the gain vector as $\boldsymbol{w}(k+1) = \boldsymbol{w}(k) + t(k)\boldsymbol{p}(k)$ and normalize it by $\boldsymbol{w}(k+1) = \boldsymbol{w}(k+1)/\|\boldsymbol{w}(k+1)\|$.

⟨Step 5⟩ For more iteration in the current snapshot, go back to ⟨Step 3⟩ with $\boldsymbol{w}(k) <= \boldsymbol{w}(k+1)$, otherwise, go back to ⟨Step 2⟩ for the next snapshot.

Note that the matrix operations required in computing $\lambda(k)$, $a(k)$, $b(k)$ are respectively replaced with corresponding vector operations in the LCGM. The computational load of LCGM is tabulated in Fig. 1. Note that all the variables required to be updated at each snapshot is given in the order of actual computation in Fig. 1. The total amount of computation required to obtain the suboptimal gain vector at each iteration is in the order of about O(16N), i.e., 15.5N multiplications, 16N-9 additions, and 1 square root operation.

III. PERFORMANCE ANALYSIS

This section presents numerical results of various computer simulations that have been obtained by applying the three different versions of the CGMs, i.e., MCGM [7], [13], LCGM and ICGM, to the base station of a CDMA mobile communication system adopting the quadrature phase shift keying (QPSK) modulation scheme. The most attractive feature of the proposed technique is that no training sequences or reference signals are required in the beamforming procedures. The reason is that, since the maximum eigenvalue always represents the signals, the corresponding eigenvector must be a linear combination of the input steering vectors.

The output of the i^{th} chip correlator for the signal received in the m^{th} antenna element can be written as

$$x_m(t) = \sum_{n=1}^{M} \beta_{n,i} I_n(t) e^{j(m-1)\pi \sin\theta_n} + z_m(t), \quad (14)$$

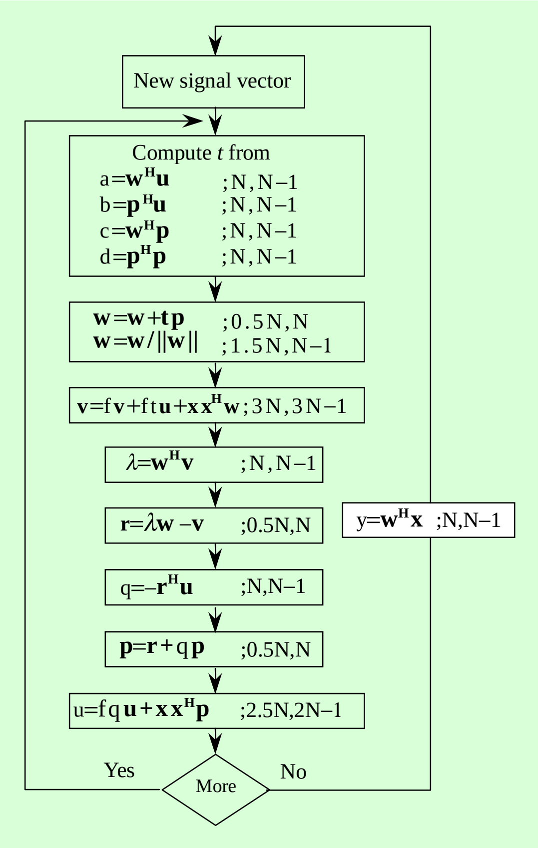

Fig. 1. Required amount of computation in each step of LCGM (Note that each variable is given in the order of computation for obtaining the target eigenvector in the adaptive procedure of LCGM, and required amount of multiplications and additions in each step of LCGM is given).

where $\beta_{n,i}$ is the average magnitude of each signal component determined by the processing gain at the i^{th} chip correlator, $I_n(t)$ denotes the QPSK modulated signal, and $z_m(t)$ denotes the additive white gaussian noise at m^{th} antenna element. The output of i^{th} chip correlator in (14) is obtained by

$$x_m(t) = \int_0^{T_b} \hat{x}_m(t+\tau) c_i(\tau) d\tau$$

$$= \int_0^{T_b} \left[\sum_{n=1}^{M} \hat{s}_n(t+\tau) e^{j(m-1)\pi \sin\theta_n} + \hat{z}_m(t+\tau) \right] \times c_i(\tau) d\tau$$

$$= \sum_{n=1}^{M} s_{n,i}(t) e^{j(m-1)\pi \sin\theta_n} + z_m(t), \qquad (15)$$

where T_b is the period of the chip sequence, and $\hat{s}_n(t)$ is the transmitted signal from n^{th} subscriber as received at the input port of the i^{th} correlator whereas $s_{n,i}(t)$ is as seen at the output port of the correlator, i.e.,

$$s_{n,i}(t) = I_n(t) \int_0^{T_b} c_n(\tau) c_i(\tau) d\tau. \qquad (16)$$

Note that a good power control and synchronization is assumed in this paper. Since the power of each symbol is constant as in QPSK modulated signals, i.e., the average magnitude of each signal component is determined by $s_{n,i}(t)$ as

$$\beta_{n,i} = \sqrt{E[|s_{n,i}|^2]} \text{ for every } n = 1,\ 2,\ \cdots,\ M (17)$$

Normalizing the power of the chip sequence, i.e., $\int_0^{T_b} c_n^2(\tau) d\tau = 1$, for $n \neq i$, $\beta_{n,i}$ must be much less than unity, for the CDMA system to be valid.

With above-mentioned signal modelling, if the incident angle of the desired signal component is θ_1, the eigenvector corresponding to the maximum eigenvalue can be represented as

$$\boldsymbol{e}_1 = \eta_{1,1} \boldsymbol{a}(\theta_1) + \sum_{n=2}^{M} \eta_{n,1} \boldsymbol{a}(\theta_n), \qquad (18)$$

where $\eta_{n,1}$ is complex constant determined by $\beta_{n,1}$ and θ_n for $n = 1,\ 2,\ \cdots,\ M$. In general, because $\beta_{1,1}$ is much larger than $\beta_{n,1}$ for $n \neq 1$, $\eta_{n,1} << 1$ is satisfied for $n \neq 1$. Therefore, the eigenvector corresponding to the maximum eigenvalue can approximately be represented by the desired signal as

$$\boldsymbol{e}_1 \approx \eta_{1,1} \boldsymbol{a}(\theta_1). \qquad (19)$$

Consequently, the suboptimal weight vector is

$$\boldsymbol{w} = \frac{1}{\sqrt{N}} \boldsymbol{e}_1. \qquad (20)$$

Adopting the suboptimal weight vector as given in (20), the array output at the k^{th} sampling time can be written as

$$y(k) = \sum_{n=1}^{M} I_n(k) \boldsymbol{w}^H \boldsymbol{a}(\theta_n) + \boldsymbol{w}^H \boldsymbol{z}(k)$$

$$\approx I_1(k) + \frac{1}{N} \sum_{n=2}^{M} I_n(k) \boldsymbol{a}^H(\theta_1) \boldsymbol{a}(\theta_n) + \frac{1}{N} \boldsymbol{a}^H(\theta_1) \boldsymbol{z}(k). \qquad (21)$$

Note that the first, the second, and the third term in (21) denotes the desired signal, the interfering signals, and the noise at the array output, respectively.

In order to present the actual performance of the proposed array, the following signal environment has been taken into consideration: (1) the number of antenna elements is 6, (2) the average desired signal power is 1, (3) the number of interferences $(M-1)$ is 20, and each interferer is determined by a random process distributed uniformly in the range of $-90^\circ \sim 90^\circ$ at each snapshot, (4) the average of each interference power is 0.01, and (5) the desired signal source is changing its incident angle by 0.01° at every snapshot starting from 0° at the initial snapshot for obtaining each value shown in Figs. 2∼7. It has been found from the various computer simulations that the array performance seems to be best when the forgetting factor is about 0.8 ∼ 0.9. The amount of change in arrival angles between adjacent snapshots is determined by the snapshot period and relative speed between transmitter and receiver, which is assumed not to exceed 150 km/h in land mobile communications [7].

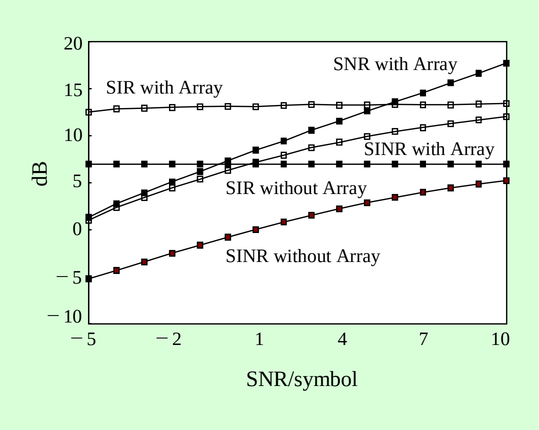

Fig. 2. SINR performance of MCGM.

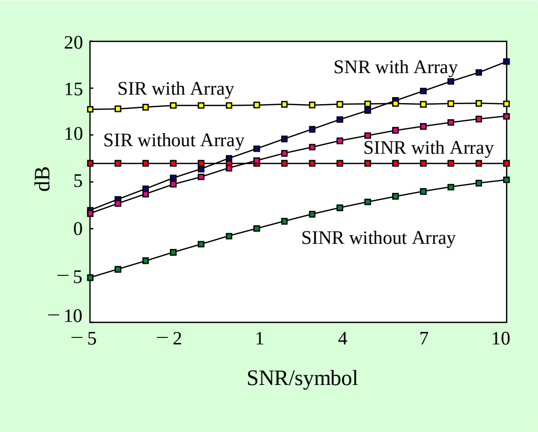

Fig. 3. SINR performance of LCGM.

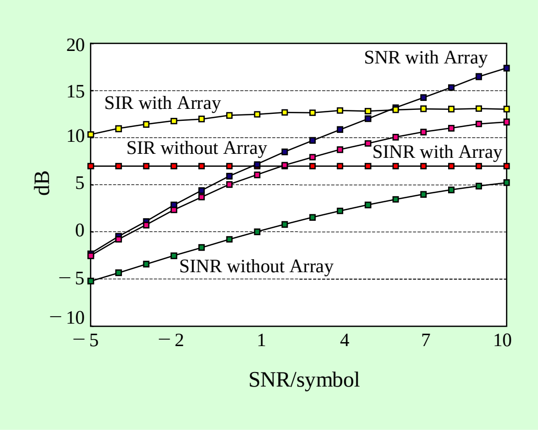

Fig. 4. SINR performance of ICGM.

The SINR performance of the proposed array consisting of 6 antenna elements is illustrated in Figs. 2, 3, and 4. For obtaining each value shown in Figs. 2, 3 and 4, at least 10,000 snapshots are taken. Figs. 2 and 3 show the performance of the presented antenna array system in terms of SINR when the system adopts MCGM and LCGM, respectively. From Figs. 2 and 3, it can be observed that the SINR performance of the LCGM is almost as good as that of MCGM. Recall that the required amount of computation at each snapshot of LCGM is much less than that of MCGM. Since it is assumed that each interfering signal is mutually uncorrelated, the total power of interferences is determined by the number of interferences and the average level of each interference. Figure 4 exhibits SINR performance of the ICGM. It can be observed that the SINR performance of the ICGM is inferior to MCGM or LCGM, when the given signal to noise ratio (SNR) is rela-

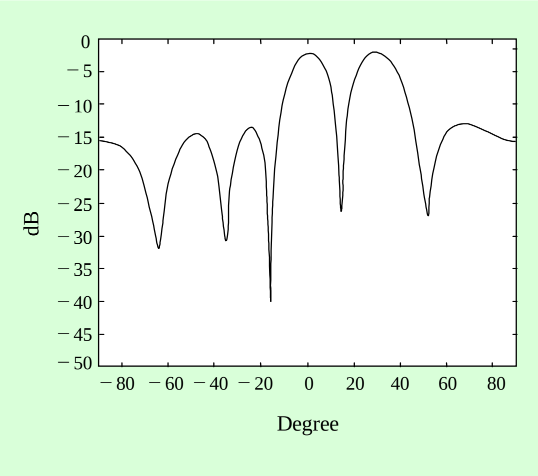

Fig. 5. Beampattern of LCGM with plural arrival angles, due to multipath (Angle of arrival = 0° and 30°).

tively low, i.e., SNR < 5 dB. However, as the given SNR increases, i.e., SNR > 5 dB, the SINR performance of the ICGM is almost the same as that of the MCGM and LCGM.

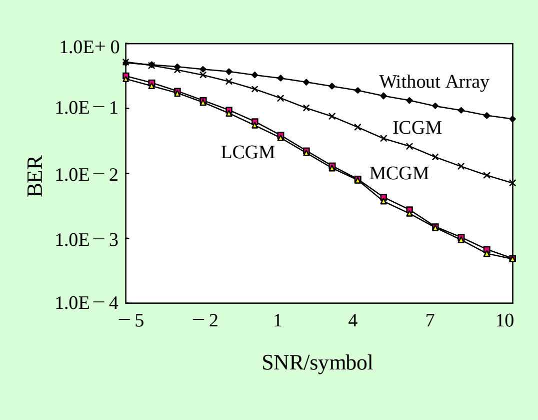

Fig. 6. BER performance of three CGMs as a function of SNR.

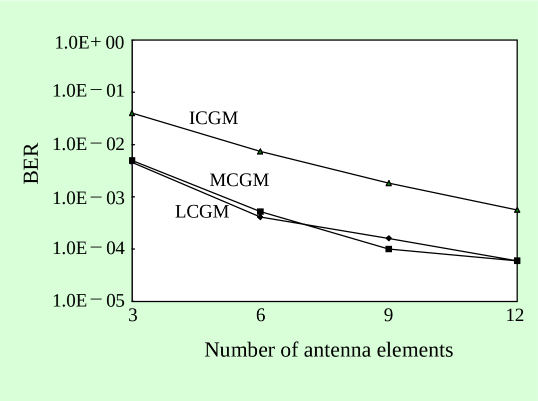

Fig. 7. BER performance of three CGMs as a function of the number of antenna elements.

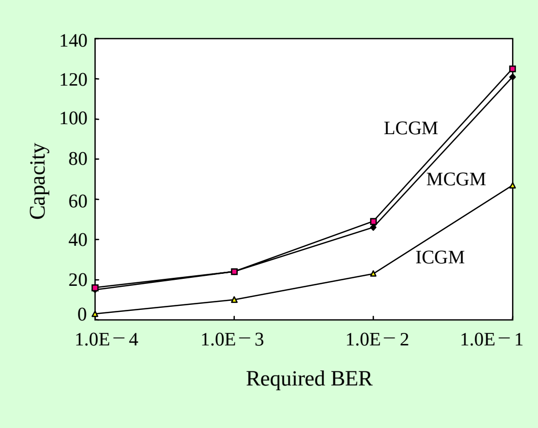

Fig. 8. The capacity improvement by the proposed methods (three CGMs).

The improvement in signal to interference ratio (SIR) by the proposed technique shown in Figs. 2, 3, 4 is based on the beampattern illustrated in Fig. 5. In Fig. 5, it is shown that the maximum gain is provided exactly toward the target signal sources, which is located in the direction of 0° and 30° from the broadside of the antenna array. Observe that the weight vector computed by the proposed algorithm generates the multibeam pattern when the desired signal is incident with plural arrival angles, i.e., 0° and 30°, due to multipath with each component being equally much stronger than each interferer. Compared to the conventional single antenna system, the proposed array provides excellent improvements in both SIR and SNR, which results in the remarkable reduction in BER as shown in Fig. 6. The BER performance [8] in this paper has been evaluated by the procedure of Monte-Carlo method, i.e., BER is calculated by dividing the number of error bits by the number of snapshot. Each data point in Fig. 6 has been obtained by repeating the evaluations until the number of error bits exceeds at least a few hundreds. In fact, for obtaining each value shown in Fig. 6 at least 100,000 snapshots are taken. Fig. 6 shows that LCGM causes almost no degradation in BER performance compared to the MCGM. However, there is a considerable degradation in BER performance when ICGM is utilized. In order to compare the BER performance as a function of the number of antenna elements, the same signal environment (the given SNR is 10 dB, the given number of interferences is 20, and the desired signal source is changing its incident angle by 0.01° at every snapshot) is taken into consideration in Fig. 7 for N = 3, 6, 9, 12. It can be observed from Fig. 7 that the BER performance of LCGM is almost as good as that of MCGM. The BER performance of ICGM is degraded as can be expected from Fig. 6.

The improvement in communication capacity achieved by the presented three CGMs is illustrated in Fig. 8. The maximum number of subscribers for the array to maintain a given BER performance, i.e., 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, respectively, is shown in Fig. 8. The capacity of the receiving system of a single antenna is not shown in Fig. 8 because the allowable number of subscribers is less than 1 when the given BER less than 0.0024. It can be observed that the proposed LCGM increases the capacity up to almost the same level as MCGM does while the ICGM exhibits relatively less improvement. For example, when the BER is to be $3*10^{-3}$, the antenna array implemented by the proposed LCGM can allow up to $32 \sim 33$ subscribers in the cell while the other CGMs, i.e., MCGM, and ICGM, and the base station of a single antenna can accomodate about $31 \sim 32$, $14 \sim 15$ and $1 \sim 2$ subscribers, respectively. The number of subscribers can be increased by more than fifteen times, when the base station adopts the antenna array of LCGM algorithm compared to a single antenna system. When the BER is 10^{-2}, the antenna array of LCGM can accomodate about $49 \sim 51$ subscribers while MCGM and ICGM and a single antenna system can allow up to $48 \sim 50$, $24 \sim 26$, and $6 \sim 7$ subscribers, respectively. In this case, the number of subscribers can be increased by more than seven times.

Table 1 shows the BER performances of the antenna array adopted the proposed

Table 1. The BER performance of base station implemented with antenna array adopted three CGMs and with single antenna.

Mode Number of interferences	Single Antenna	Antenna Array (MCGM)	Antenna Array (LCGM)	Antenna Array (ICGM)
1	0.00240	0.00000	0.00000	0.00005
5	0.00859	0.00000	0.00000	0.00027
10	0.02482	0.00000	0.00001	0.00107
15	0.04369	0.00001	0.00004	0.00362
20	0.06703	0.00043	0.00039	0.00692
25	0.09362	0.00127	0.00130	0.01321
30	0.11008	0.00269	0.00193	0.01965
35	0.13651	0.00465	0.00456	0.02975
40	0.15295	0.00766	0.00586	0.03796
45	0.17457	0.01025	0.01076	0.04912
50	0.18748	0.01384	0.01307	0.06051

When the BER is 10^{-2}, the antenna array of LCGM can accomodate about 49 $\sim$ 51 subscribers while MCGM and ICGM and a single antenna system can allow up to 48 $\sim$ 50, 24 $\sim$ 26, and 6 $\sim$ 7 subscribers, respectively. In this case, the number of subscribers can be increased by more than seven times.

Table 1 shows the BER performances of the antenna array adopted the proposed three CGMs with a comparison to the single antenna system at the given number of interferers. Table 1 describes the remarkable reduction in BER when the base station of CDMA mobile communication system adopts the antenna array with the proposed three CGMs.

IV. CONCLUDING REMARKS

The adaptive procedure of three different versions of CGM has been presented in this paper. Under an assumption that the desired signal received from the target source is much stronger than each of interferers, the gain vector for the antenna elements can be obtained by solving the extreme eigenvalue problem. In fact, the eigenvector corresponding to the maximum eigenvalue must correspond to the direction vector of the target source when the dominance condition is satisfied. Since the assumption that the desired signal is dominant compared to each component of interferences at the receiver can be accomplished in CDMA mobile communications by the chip sequence cross-correlator, the proposed algorithms can provide for a suboptimal beam pattern that increases the SINR and decreases BER, and eventually increases the capacity beamforming module can easily be realized by the proposed methods utilizing a general purpose DSP off the shelf.

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