Null-steering Beamforming for Cancellation of Co-channel Interference in CDMA Wireless Communication System

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Abstract—**Multipath fading effects and co-channel interference are the main limitations facing wireless communication systems. The problem to enhance the capacity of a code-division multiple-access (CDMA) in wireless communication system can be solved implementing an interference management. Many techniques controlling or suppressing an interference in CDMA wireless communication systems by transmitter and/or receiver, such as the transmit power control, multiuser detection, receiver beamforming, and transmit beamforming have been proposed to date. This paper deals with the possibilities to cancel unwanted signals by steering nulls of the pattern in the direction of arrival (DOA) of the signal while keeping the main beam to desired direction. Here we proposed a null steering beamforming algorithm to suppress co-channel interference in CDMA wireless communication systems that is based on the iterative method. Finally, simulation results confirm our theoretical study and efficacy of the proposed beamforming algorithm for CDMA wireless communication systems.**

Keywords-Code-division multiple-access (CDMA); null steering; co-channel interference; beamforming; iterative method;

I. INTRODUCTION

The demand for high-capacity flexible wireless services is ever-growing. Implementation of CDMA in wireless communication systems demonstrates great benefits to solve this problem and, consequently, wireless CDMA (WCDMA) has been a strong candidate to be the standard for third-generation (3G) wireless communication systems [1]–[4].

CDMA appears to be the most popular civilian applications that use spread spectrum wireless communications. In CDMA wireless communication system, users share time and frequency resources simultaneously. This occurs through assigning each user a distinct digital code [5]. This code is added to the information data and modulated onto the carrier, using spread spectrum techniques. Since each user has a uniquely addressable code, privacy is inherent.

Multipath fading effects and co-channel interference (CCI) are the main limitations facing wireless communication systems [6]. In cellular radio systems, sources of interference include mobile units in the same cell, a call in progress in a neighboring cell, other base stations operating in the same frequency band, or any non cellular system which inadvertently leaks energy into the cellular frequency band [7].

Frequency-division multiple-access (FDMA) and time-division multiple-access (TDMA) cellular systems rely on spatial attenuation to control intercell interference. As a result, neighboring cells need to be assigned different frequencies to protect against the co-channel interference. In contrast, CDMA cellular system can apply a universal one-cell frequency reuse pattern [8]. Frequency reuse implies that in a given coverage of area there are several cells that use the same set of frequencies. These cells are called co-channel cells and the co-channel interference refers to the interference caused between two cells transmitting on the same frequency within a network. Since co-channel interference is caused by another cell transmitting the same frequency, we cannot simply filter out the interference by increasing the carrier power of the transmitter. This is because an increase in carrier transmit power increases the interference to neighboring co-channel cells. To reduce CCI the co-channel cells need to be physically separated by a minimum distance to provide sufficient isolation due to propagation [5] and [7].

It is also well known that adaptive antenna arrays have been introduced in [9] – [11] for TDMA and CDMA system to mitigate rapid dispersive fading and to suppress CCI so as to improve the performances of such systems. The implementation of beamforming in a CDMA system is different from that in an FDMA system or in TDMA system. In an FDMA system, beamforming is carried out continuously in each individual channel, whereas in a TDMA system, beamforming is carried out on a frame-by-frame basis for the entire TDMA frequency band. In a CDMA system, beamforming is carried out continuously for the entire CDMA frequency band. Moreover, the choice of beamforming configuration depends on the type of CDMA system, namely, a synchronous or asynchronous CDMA system. In a synchronous CDMA system, the information bit duration of each user signal in the system is time-aligned at the base station [12].

978-1-4244-7907-8/10/$26.00

Most of the beamforming techniques which have been proposed for mobile communications perform spatial filtering by forming comparatively sharp nulls in the direction of the interfering mobile stations [13]. If the direction of radio frequency interference (RFI) is stable, we can design a corresponding pattern of the antenna array so that the great null of pattern can appear in the direction of RFI. However, the direction of RFI is different from time to time. So, the null of pattern can change according to the direction of RFI automatically [10].

In this paper, we propose a null steering beamforming algorithm to mitigate CCI in the CDMA wireless communication system. The beamforming algorithm is based on the iterative methods. The proposed beamformer can effectively suppress CCI and improve the system performance at high interference. The simulation results confirm our theoretical investigation.

The remainder of this paper is organized as follows. Section II describes the CDMA wireless communication system model. In Section III, we have discussed the proposed beamforming algorithm. To evaluate the proposed approach computer simulation results are presented in Section IV. Finally, some conclusions are discussed in Section V.

II. SYSTEM MODEL

A. Null Steering Beamforming

A null steering beamformer is used to cancel a plane wave arriving from a known or unknown direction and thus produces a null in the response pattern of the plane wave's DOA. One of the earliest schemes, referred to as Digital Interference Cancelling Adaptive Null Network Equipment (DICANNE) [14], achieves null steering by estimating the signal arriving from a known direction by steering a conventional beam in direction of the source and then subtracting the conventional beam output from each element. DICANNE is a real-time digital processor that is designed to reject a plane wave interference from an operator-controlled direction prior to normal beamforming. An estimate of the signal is made by delay-and-sum beamforming using shift registers to provide the required delay at each element, such that the signal arriving from the beam steering direction appears in phase after the delay, and then summarizes these wave forms with equal weighting. Then, this signal is subtracted from each element after the delay. The process is very effective for canceling strong interference and could be repeated for multiple interference cancellation.

Although the process of subtracting the estimated interference using the delay-and-sum beamformer in the DICANNE scheme is easy to implement for single interference, it becomes cumbersome as the number of interferences is increased. A beam with unity response in the desired direction and nulls in interference directions may be formed by estimating beamformer weights using suitable constraints [15].

Assume that $\mathbf{S}_0$ is the steering vector in the direction where unity response is required and that $\mathbf{S}_1, \ldots, \mathbf{S}_k$ are steering vectors associated with k directions where nulls are required. The desired weight vector is the solution of the following simultaneous equations:

$$\mathbf{w}^H\mathbf{S}_0 = 1$$

$$\mathbf{w}^H\mathbf{S}_i = 0, \; i = 1,2,...,k \tag{1}$$

Using matrix notation, (1) can be written in the following form

$$\mathbf{w}^H\mathbf{A} = \mathbf{e}_1^T \tag{2}$$

where $\mathbf{A}$ is a matrix with columns being the steering vectors associated with all directional sources including the look direction, that is,

$$\mathbf{A} = \left[\mathbf{S}_0, \mathbf{S}_1, \ldots, \mathbf{S}_k\right] \tag{3}$$

and $\mathbf{e}_1$ is a vector of all zeros except the first element which is one, i.e.

$$\mathbf{e}_1 = \left[1, 0, \ldots, 0\right]^T \tag{4}$$

For $k = L-1$, $\mathbf{A}$ is a square matrix and L is the number of elements array. When the numbers of required nulls are less than $L-1$, $\mathbf{A}$ is not a square matrix. A suitable estimate of weights may be produced using the following equation

$$\mathbf{w}^H = \mathbf{e}_1^T\mathbf{A}^H\left(\mathbf{A}\mathbf{A}^H\right)^{-1} \tag{5}$$

Although the beam pattern produced by this beamformer has nulls in the interference directions, it is not designed to minimize the uncorrelated noise at the array output. It is possible to achieve this by selecting weights that minimize the mean output power subject to above constraints.

B. Optimal beamforming

The null steering scheme that described in the null steering beamforming section requires knowledge of the interference directions and the beamformer using the weights estimated by this scheme does not maximize the output signal-to-noise ratio (SNR). The optimal beamforming method overcomes these limitations and maximizes the output SNR in the absence of errors. It should be noted that the optimal beamformer, also known as the minimum variance distortionless response (MVDR) beamformer, does not require knowledge of directions and power levels of interferences as well as the level of the background noise power to maximize the output SNR. It only requires the direction of the desired signal as a spatial reference signal.

Let us consider an L-dimensional complex vector $\mathbf{w}^H$ representing the weights of the beamformer that maximize the output SNR. For this array an expression for $\mathbf{w}^H$ is given by [15]:

$$\mathbf{w}^H = \frac{\mathbf{R}_N^{-1}\mathbf{S}_0}{\mathbf{S}_0^H\mathbf{R}_N^{-1}\mathbf{S}_0} \tag{6}$$

where $\mathbf{R}_N$ is the array correlation matrix of the noise alone, i.e. it does not contain any signal arriving from the look direction.

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The weights for the optimal beamformer have been discussed and computed using the noise alone matrix inverse (NAMI) processor. NAMI processor is also known as the maximum likelihood (ML) filter [15] since it defines the ML estimate of the signal source power assuming that all sources are interference. It should be noted that $\mathbf{R}_N$ may be not invertible when the background noise is very small. In this case, it becomes a rank deficient matrix.

In practice, when the estimate of the noise alone matrix inverse is not available, the total array correlation matrix (signal plus noise) $\mathbf{R}$ is used to estimate the weights and the processor is referred to as the signal-plus-noise matrix inverse (SPNMI) processor. An expression for weights of the constrained processor for this case is given by the following equation [15]:

$$\mathbf{w}^H = \frac{\mathbf{R}^{-1}\mathbf{S}_0}{\mathbf{S}_0^H\mathbf{R}^{-1}\mathbf{S}_0} \tag{7}$$

These weights are the solution of the following optimization problem, namely to minimize $\mathbf{w}^H\mathbf{R}\mathbf{w}$ at the condition

$$\mathbf{w}^H\mathbf{S}_0 = 1 \tag{8}$$

Thus, the processor weights are selected by minimizing the mean output power of the processor while maintaining unity response in the searching direction.

III. ITERATIVE NULL STEERING

According to Equation (7) we must solve the following linear equation

$$\mathbf{w}^H\mathbf{R} = \mathbf{S}_0 \tag{9}$$

In the case of unknown vector, a calculation of $\mathbf{w}^H$ requires in general $O(n3)$ operations (unless $\mathbf{R}$ has some special property that makes it easily invertible). In spite of this fact, it is possible to apply iteration design that converges to the solution.

Jacobi theorem says that the solution to the linear system $\boldsymbol{Ax} = \boldsymbol{b}$ can be obtained starting with $\mathbf{x}_0$, and using iteration scheme [16]

$$\mathbf{x}_{k+1} = \mathbf{M}\mathbf{x}_k + \mathbf{C} \tag{10}$$

where

$$\mathbf{M} = \mathbf{D}^{-1}\left(\mathbf{L} + \mathbf{U}\right)$$

and

$$\mathbf{C} = \mathbf{D}^{-1}\mathbf{b} \tag{11}$$

$\mathbf{D}$, $\mathbf{L}$ and $\mathbf{U}$ are the diagonal, strictly lower triangular and strictly upper triangular parts of $\mathbf{A}$ respectively.

If $\mathbf{x}_0$ is carefully chosen, a sequence $\{\mathbf{x}_k\}$ is generated which converges to the suitable solution. A sufficient condition for the method to be applicable is that $\mathbf{A}$ is strictly diagonally dominant or diagonally dominant and irreducible. The "true" sufficient condition for Jacobi iteration to converge is that the "spectral radius (ρ)" of $\mathbf{M} = \mathbf{D}^{-1}(\mathbf{L} + \mathbf{U})$ is less than unit. That is, the magnitude of the largest eigenvalue of $\mathbf{M}$ must be less than unit. Since the diagonal matrix is easily invertible, the Jacobi iteration has a particularly simple implementation.

For our problem the Jacobi iteration corresponds to parallel interference method used in CDMA [17] and [18] and iterative methods in [19–21] at $\lambda = 1$. Marvasti method [19] also removes the linearity assumption of the modeling. Therefore when we have nonlinear effects (a receiver imperfections and nonlinearity) the proposed method works correctly

$$\mathbf{w}_{k+1} = \mathbf{S}_0 - \left(\mathbf{R} - \mathrm{I}\right)\mathbf{w}_k \tag{12}$$

At first, let us consider $\mathbf{w}_0 = \mathbf{S}_0$ that corresponds to

$$\mathbf{w}_k = \sum_{i=0}^{k}(-1)^i(\mathbf{R}-\mathbf{I})^i\mathbf{S}_0 \tag{13}$$

In terms of the Taylor series expansion, the convergence of this iteration may be understood by considering the residual error, therefore

$$\mathbf{R}^{-1} = \sum_{i=0}^{\infty}(-1)^i(\mathbf{R}-\mathbf{I})^i \tag{14}$$

This convergence occurs if the spectral radius of $\mathbf{R}$ will be lower than 2. In other words, the main idea of this algorithm is to rebuild the inverse of the system by iteration. If we define $\mathbf{I}$ as the unity operator, we have:

$$\mathbf{R}^{-1} = \frac{\mathbf{I}}{\mathbf{R}} = \frac{\mathbf{I}}{\mathbf{I}-\mathbf{E}} \tag{15}$$

In this equation, we assume that $\mathbf{E}$ is the processing error. If the norm of the $\mathbf{E}$ was less than one (in linear case, this assumption is converted to the condition that spectral radius $\rho(\mathbf{R}) < 2$), then by using Taylor expansion for this function we have:

$$\mathbf{R}^{-1} = \frac{\mathbf{I}}{\mathbf{I}-\mathbf{E}} = \mathbf{I}+\mathbf{E}+\mathbf{E}^2+\mathbf{E}^3+\ldots \tag{16}$$

Now, the outputs in the ith and (i+1)th iterations are defined by the following form:

$$\mathbf{w}_i = \left(\mathbf{I}+\mathbf{E}+\mathbf{E}^2+\mathbf{E}^3+\ldots+\mathbf{E}^{i-1}\right)\mathbf{S}_0 \tag{17}$$

$$\mathbf{w}_{i+1} = \left(\mathbf{I}+\mathbf{E}+\mathbf{E}^2+\mathbf{E}^3+\ldots+\mathbf{E}^{i}\right)\mathbf{S}_0 \tag{18}$$

According to (17) and (18), it could be easily shown that,

$$\mathbf{w}_{i+1} = \left(\mathbf{I}-\mathbf{R}\right)\mathbf{w}_i + \mathbf{S}_0 \tag{19}$$

and this result is same as the result of Jacobi method. A simple generalization which improves the Jacobi style iteration is brought about introducing a parameter or a sequence of parameters. Under carefully selection of these parameters, the convergence speed of the Jacobi method re-defeated, and the convergence speed can be improved [19].

Now, a first order iteration can be determined in the following form:

$$\mathbf{w}_{i+1} = \mathbf{w}_i - \lambda_i \left(\mathbf{R}\mathbf{w}_i - \mathbf{S}_0 \right) \tag{20}$$

If **R** is symmetric positive definite, then the parameter that results in fastest convergence of the first order stationary iteration takes the form

$$\lambda_{\text{opt}} = \frac{2}{\lambda_{\min} + \lambda_{\max}} \tag{21}$$

where $\lambda_{\min}$ and $\lambda_{\max}$ are respectively the minimum and the maximum eigenvalues of **R**.

A second order iteration, which depends on the two most recent estimates, can be presented in the following form:

$$\mathbf{w}_{i+1} = \alpha_i \mathbf{w}_i + \left(1 - \alpha_i\right) \mathbf{w}_{i-1} - \beta_i \left(\mathbf{R}\mathbf{w}_i - \mathbf{S}_0 \right) \tag{22}$$

where the best choice of α and β are, [17]:

$$\alpha_{\text{opt}} = \frac{2}{1 + \sqrt{1 - \left(\frac{1 - \lambda_{\min}/\lambda_{\max}}{1 + \lambda_{\min}/\lambda_{\max}} \right)^2}} \tag{23}$$

and

$$\beta_{\text{opt}} = \frac{2\alpha_{\text{opt}}}{\lambda_{\min} + \lambda_{\max}} . \tag{24}$$

The Chebychev method is another iterative method in which the optimal λ_k is known for a given number of iteration steps. The optimum value for λ_k is given by [17]:

$$\lambda_{i_{\text{opt}}} = \frac{\lambda_{\max} - \lambda_{\min}}{2} \cos\left(\frac{i - 1/2}{i_{\max} + 1} \pi \right) + \frac{\lambda_{\max} + \lambda_{\min}}{2} \tag{25}$$

IV. COMPUTER SIMULATION

In this section, we present computer simulation examples to evaluate the performance of the proposed beamformer that based on four uniform linear array (ULA) antennas with $\lambda/4$ distance. The main beam have been detected to 20^0 and the two interference have been located in 60^0 and -20^0. The beam responses generated by the conventional optimum beamforming in comparison to the proposed null steering beamforming are presented in Fig. 1 and Fig. 2 for 10 and 50 iterations respectively. Simulations show that using 50 iterations in Chebychev method the results will be better in comparison with the conventional beamformer and there is no need for more iteration. As we see, in terms of the peak at 20^0 and null at -20^0 and 60^0, the conventional optimum beamformer method achieves the best nulls but the worst peak. Thus, the Chebychev method is the best, both in terms of null and peak and in terms of providing a fast convergence.

According to the fact that there are no more than two or three jammers or interferences in military or civil wireless communications [17], it is not reasonable to use more than 6 elements. According to the fact that the presented method is independent of the number of sources there is no need to simulate for a more complicated case. The simulation results for 25 element arrays and 50 iterations for the conventional beamformer and Chebychev acceleration method are shown in Fig. 3.

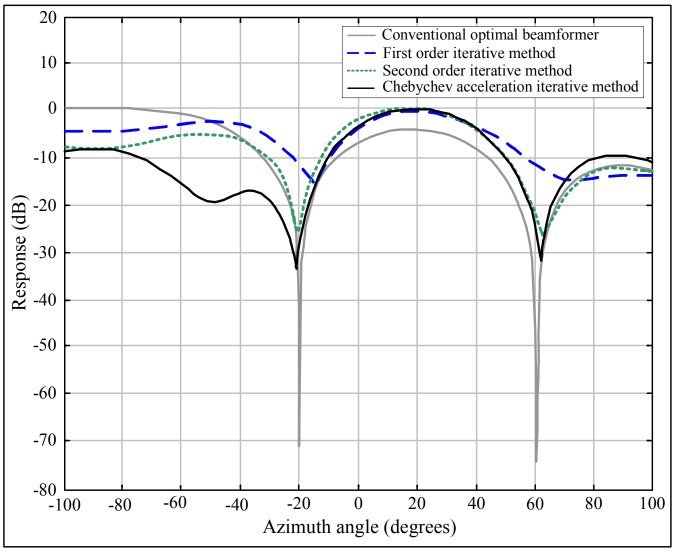

Figure 1. Comparison between the conventional beamformer and iterative method after 10 iterations.

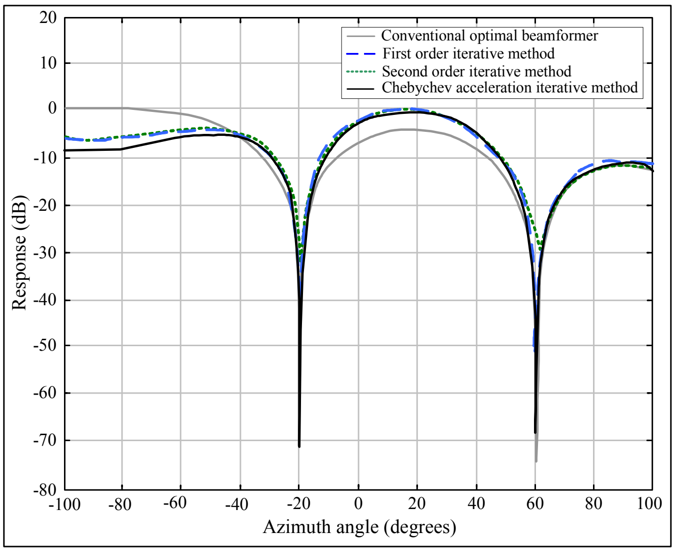

Figure 2. Comparison between the conventional beamformer and iterative method after 50 iterations.

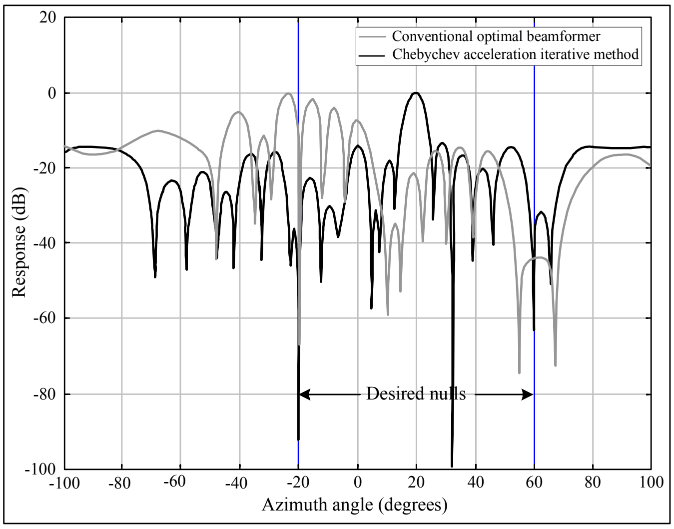

Figure 3. Comparison between the conventional beamformer and chebychev acceleration method after 50 iterations for 25 elements array.

V. CONCLUSION

In this paper, we presented a CCI canceller for CDMA wireless communication system under the use of the iterative method to define limits of the conventional inverse matrix calculation which can not be efficient when the matrix is ill-conditioned. To simplify the implementation we have only used 4 elements but the results can be propagated for any number of elements. The simulation results show us that this algorithm converges only after 20 iterations. Investigations of the proposed beamforming algorithm allow us to conclude that CCI in CDMA wireless communication systems can be suppressed effectively. Computer simulation results confirm our theoretical study.

ACKNOWLEDGMENT

This work was supported in part by the Kyungpook National University Research Fund 2009.

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