A Novel Beam Forming Technique for CDMA 2000 Wireless Communication: Performance Analysis

ABDUL WAHEED UMRANI*, FAHIM AZIZ UMRANI**, AND AHSAN AHMAD URSANI*

ABSTRACT

A novel beamforming algorithm based on conjugate gradient methods is described and its performance is computed in terms of bit error rate for practical CDMA 2000 communication systems. The proposed technique attempts to maximize signal-to-noise plus interference of the received signal, and is based on solving the eigenvalue problem where the optimization of the weight vector is done using the pilot channel. The performance is simulated for practical CDMA 2000 1X communications systems in wireless propagation environments with high angle spread. The performance of the proposed beamforming algorithm is also compared with existing beamforming algorithms. Simulation results show that the performance of the proposed algorithm is more robust to higher angle spread.

Key Words: **Beamforming, CDMA 2000 Systems, Conjugate Gradient Methods, Angle Spread.**

1. INTRODUCTION

The wireless systems based on CDMA 2000 standards are capable of using distinct carrier configurations, employing carriers with bandwidths of 1.25 MHz (backward compatibility to IS-95 system) and 3.75 MHz (to achieve data transmission rates compatible to 3G requirements) [1-2]. This standard also has a provision of using multiple antennas at the base station (smart antennas) to provide higher data rates, and increased system capacity. A great advantage of CDMA 2000 1X is the full compatibility with IS-95 systems, which allows the technologies to share all the transmission equipment and most of the infrastructure of existing networks, providing ease of technology migration. Both also share the same frequency band, thus CDMA 2000 1X does not require new licenses [3].

The beamforming algorithm for CDMA wireless communications are typically based on generalized eigenvector and eigenvalue solutions [4,8-9]. The algorithm in [4] is designed to maximize SNIR (Signal to Noise Interference Ratio). Although, it shows significant improvement in BER (Bit Error Rate) performance, it requires enormous amount of computation and has not been simple to apply in practice. Using the same approach of [4], Song [8] reported simple smart antennas, which are computationally cost efficient. In [9], the beamformer based

* Associate Professor, and **Lecturer,
Department of Telecommunication Engineering, Mehran University of Engineering and Technology, Jamshoro.

on finding the dominant mode of eigenvector and eigenvalues is proposed. Another class of beamformer for CDMA wireless communication system was proposed in [13-14], based on conjugate gradient method [7,10]. The two types of CDMA receiver structures were proposed depending on the channel conditions. The system performance is computed in terms of bit error rate for IS-95 standard. Gil, J.M., et. al. [17], Mohamed, N.A., et. al. [18] also used conjugate gradient algorithms to analyze the performance in fading channels. In [17], the authors used a WCDM (Wideband Directional Channel Model) to simulate the performance for UTRA-TDD based wireless communication system. Mohamed, N.A., et. al. [18] presented a simple conjugate gradient based beamforming algorithm for DS-CDMA systems in a two-cluster channel model However, not much detail is given about angle spread and angle-of-arrival distributions. The algorithm presented in [18] is similar to [13-14] with the exception of using different channel scenarios. However, [4,8-9,13-14,17-18] have assumed zero angle spread, which is not realistic in antenna arrays operating in mobile communication environment. We proposed a novel beamforming algorithm for CDMA mobile communications based on CGM that is robust to angular spread. For comparison, we consider the approach described in Fig. 8(a) of [14] and evaluate the performance for CDMA 2000 1X propagation environments. We consider the case of wideband spreading that occurs more frequently than the narrow spreading.

The next section describes the conjugate gradient methods in detail. Section 3 provides the details of the proposed algorithm and its application to CDMA 2000 1X systems with simulation results are given in Section 4. Finally, Section 5 summarizes the paper.

2.   CONJUGATE GRADIENT METHODS

The conjugate gradient methods [5,7] are found to be useful in many applications such as in optimization, electromagnetic theory, inverse scattering problems, adaptive filtering, and communication systems. An excellent introduction of several variations of CGM based algorithms is given in [5]. Sheng, P., et. al. [16] presents its analysis from the signal processing point of view. It also finds its application in wireless communications due to its faster convergence than any other iterative methods such as LMS and RLS [7]. This is due to the fact that RLS and LMS need to estimate R^{-1}. If the estimated R^{-1} loses the property of positive definiteness, that will cause the algorithm to diverge. This does not happen with the CGM since there is no need to compute the inverse of R. The CGM has two main characteristics. First, it produces a solution of the matrix equation very efficiently in a finite number of iterations (the number of unknown weights). This is very important if the antenna array is to operate in a mobile communications system in which fast convergence is required. Second, the convergence is guaranteed for any signal matrix.

The algorithm is used to solve the operator equation Rw=y, where R is a known matrix and w is the unknown weight vector to be computed for a known desired vector y. The solution converges with finite adaptation steps. In the CGM case, where the number of unknown is n, the number of adaptation steps is always less than n. The CGM is equivalent to minimizing the quadratic equation of the form:

$$f\left(w\right) = \frac{1}{2}\left\langle w, Rw \right\rangle - \left\langle w, y \right\rangle \tag{1}$$

where f(.) is the cost function, $\langle .,. \rangle$ denotes the dot product. The approximate solution $w^{(k+1)}$ at the $(k+1)^{th}$ step is obtained from $w^{(k)}$ at the kth step as follows:

$$w^{(k+1)} = w^{(k)} + \alpha^{(k)} p^{(k)} \tag{2}$$

where $\alpha^{(k)}$ is adaptation coefficient or step size and $p^{(k)}$ is the adaptation vector (also known as direction vector). The step size $\alpha^{(k)}$ should satisfy the following:

$$\frac{df}{d\alpha^{(k)}} = 0 \tag{3}$$

Then we have

$$\alpha^{(j)} = \frac{\left\langle p^{(j)}, r^{(j)} \right\rangle}{\left\langle p^{(j)}, Rp^{(j)} \right\rangle} \tag{4}$$

$$r^{(k)} = y \, Rw^{(k)} = \Delta f(w^{(k)}) \tag{5}$$

where $r^{(k)}$ is the residual vector and Δf denoting the gradient of the function f. The direction vector $p^{(k)}$ should satisfy the following:

$$\left\langle p^{(i)}, Ap^{(j)} \right\rangle = 0; \quad \text{for } i \neq j \tag{6}$$

where A is the projection matrix. Equation (6) means that the direction vector $p^{(i)}$ is mutually orthogonal to $p^{(j)}$. From this relation a new direction vector $p^{(k+1)}$ is to be found, which is conjugate to the vector $p^{(k)}$ and that will give us an optimal value.

Let us describe the calculation procedure, step by step as follows:

☐ The approximate solution at 0th step as initial value is $w^{(0)}$, $r^{(0)} = y - Rw^{(0)}$ and $p^{(0)} = r^{(0)}$.

☐ The kth adaptation coefficient or step size is:

$$\alpha^{(j)} = \frac{\left\langle r^{(j)}, p^{(j)} \right\rangle}{\left\langle p^{(j)}, Rp^{(j)} \right\rangle} \tag{7}$$

☐ The approximate solution at the $(k+1)^{th}$ step is:

$$w^{(k+1)} = w^{(k)} + \alpha^{(k)} \, p^{(k)} \tag{8}$$

☐ The residual at the $(k+1)^{th}$ adaptation is:

$$r^{(k+1)} = r^{(k)} - \alpha^{(k)} \, Rp^{(k)} \tag{9}$$

☐ The kth adaptation coefficient $\beta^{(k)}$ for p is:

$$\beta^{(j)} = \frac{\left\langle r^{(k+1j)}, r^{(k+1j)} \right\rangle}{\left\langle r^{(j)}, r^{(j)} \right\rangle} \tag{10}$$

☐ The direction vector p at the $(k+1)^{th}$ adaptation is:

$$p^{(k+1)} = r^{(k+1)} + \beta^{(k)} \, p^{(k)} \tag{11}$$

☐ Convergence criterion must be tested. If it is not met then, set k=k+1 and go to step 2.

Different versions of the CGM algorithm described above can be found in [7-8,16], where it is shown that one can terminate the algorithm in several ways.

3. PROPOSED ALGORITHM

In general a channel vector model for the uplink wireless communication assumes a narrow angle spread, which is normally the case for base stations with tall antenna heights. Therefore most beamforming algorithms have been developed for such a scenario. However, in practical environments, the signal transmitted by a subscriber inherently experiences multipath effect and each propagation path may consist of many scattered components of the signal, which results in wider angle spreads. In this section, we present an adaptive beamforming technique which is robust to such propagation environments.

The proposed CGM algorithm is a modified version of general CGM available in signal processing and described in Section 2. The general CGM uses only the undespread signal vectors $y=[Y_1, Y_2, ..., Y_M]$. Our proposed CGM algorithm [20] also uses the despread signal vector $x=[X_1, X_2, ... X_M]$ to estimate the weight vectors of the linear array. And where $x_m(t)$ and $y_M(t)$ are given by Equations (22-23), respectively. The proposed algorithm is based on maximizing the SNIR of the antenna array system, which is realized by maximizing following equation:

$$\max_{w \neq 0} SINR = \max_{w \neq 0} \frac{w^H R_{dd} w}{w^H R_{uu} w} \tag{14}$$

where d is the desired signal vector, u is the interference plus noise vector, and R_{dd}, R_{uu} are autocorrelation matrices

of desired signal and interference, respectively. Equation (14) is to maximize the signal-to-noise plus interference ratio and is equivalent to minimizing the Equation (1), therefore, it can also be written as a generalized eigen-value problem by:

$$R_{dd}w = \lambda_{max}R_{uu}w \qquad (15)$$

subject to the constraint $w^H R_{uu} w = 1$. Where $(.)^H$ denotes the Hermitian transpose, λ_{max} is the maximum eigenvalue. In general, it is almost impossible to separate perfectly into the desired and undesired signal in practical environment as given by Equation (14). In order to resolve this problem, the despread and un-despread signals are used instead. Therefore, in the generalized eigen-equation $R_{yy}w = R_{xx}\lambda_{max}w$, we represent the R_{xx} and R_{yy} as:

$$R_{xx} = E\{xx^H\} = R_{dd} + R_{uu} \qquad (16)$$

$$R_{yy} = E\{yy^H\} = R'_{dd} + R_{uu} \qquad (17)$$

where R_{dd} in Equation (17) is increased due to processing gain G after de-spreading, i.e. $R'_{dd} = N_p R_{dd}$ and $R'_{uu} \cong R_{uu}$ meaning the total interference approximately assumed same. The maximization problem can be written as:

$$\frac{E\left(w^H y y^H w\right)}{E\left(w^H x x^H w\right)} = \frac{w^H E\left(y y^H\right)w}{w^H E\left(x x^H\right)w} = \frac{w^H R_{yy}w}{w^H R_{xx}w} \qquad (18)$$

Putting Equations (16-17) in Equation (18), gives

$$\frac{w^H R_{yy}w}{w^H R_{xx}w} = \frac{R_{dd} + R'_{uu}}{R_{dd} + R_{uu}} \cong \frac{N_p R_{dd} + R_{uu}}{R_{dd} + R_{uu}} \qquad (19)$$

After some simplifications, we have

$$\frac{w^H R_{yy}w}{w^H R_{xx}w} = N_p - \frac{\left(N_p - 1\right)R_{uu}}{R_{dd} + R_{uu}} = N_p - \frac{\left(N_p - 1\right)}{\frac{R_{dd}}{R_{uu}} + 1} = N_p - \frac{\left(N_p - 1\right)}{SNIR + 1} \qquad (20)$$

It is clear from the last term of Equation (20) that to maximize eEquation (18) is to maximize SNIR. Therefore, the equation for finding the maximum eigenvector given by,

$$R_{yy}w = \lambda_{max}R_{xx}w \qquad (21)$$

The performance of beamforming algorithm is evaluated for CDMA wireless communication systems in [14] and has given two smart antenna receiver structures shown in Fig. 8 of [14], each one for narrow and wideband spreading, respectively. For comparison, we consider the approach of [14] and evaluate the performance for CDMA 2000 1X propagation environments. The major difference between the proposed algorithm and the beamforming technique of [14] is that the undespread signal vector is also considered in the proposed algorithm which attempts to maximize the SNIR. The weight vector optimization can be done using the data channel and the pilot channel. Since the CDMA 2000 1X system has the provision of the pilot channel, we use the pilot channel to optimize the weight vector.

4. APPLICATION TO CDMA 2000 1X WIRELESS COMMUNICATIONS

We consider a uniform linear array, which consists of M antenna elements with half-wavelength spacing between them. Suppose there are K (number of users) signals impinging on the array. After the down conversion the signal received at the mt^h antenna is given by:

$$X_m(t) = \sum_{i=1}^{K} \sum_{j=1}^{L} \sum_{s=1}^{L_s} G_i S_i\left(t - \tau_{i,j,s}\right) e^{j2\pi\left(f_d \cos\varphi_{i,j,s}t - f_c\tau_{i,j,s}\right)}$$
$$e^{-j2\pi\left(D_m/\lambda\right)\sin\theta_{i,j,s}} + n_i(t) \qquad (22)$$

where D_m is the distance of the mt^h antenna element measured from the reference antenna element, $\theta_{I,j,s}$ is the incident angle of scattered signal, $S_i(t)$ is the transmitted signal from ith user, i is the user index, j is the finger index for the number of multipath from the ith user, L_s is the number of scattered components, f_c is the carrier frequency, f_d is the Doppler frequency, and $n_m(t)$ is the White noise

All the scattered components in j^{th} cluster of the ith user are assumed to have same propagation delays (i.e. $\tau_{i,j,s} \cong \tau_{i,j}$). The signal after dispreading operation at the mt^h antenna can be obtained as:

$$Y_m(d) = \int_0^{T_b} G_m(t) \times PN_1(t) \, dt \qquad (23)$$

where T_b is the bit period and PN_1 is the Pseudo Noise sequence of the first user which is the desired user. The block diagram of the receiving structure for CDMA 2000 with adaptive antennas is shown in the Fig. 1. In CDMA 2000 system, the data channels consist of a fundamental channel and two supplementary channels with different data rates. The fundamental channel data rate is 76.8ksps (kilo symbols per second), and since the spreading is performed at the rate of 1.2288Mcps (mega chips per second), the processing gain for 9.6kbps is 128. Similarly, for supplementary channel 1 and 2, the data rates are 153.2 and 307.2ksps, with processing gain 64 and 32, respectively.

The de-spreading signal vector y is generated using the signal vector x. The de-spreading signal of the pilot channel, denoted by y_{pilot} is transmitted to as input signal to weight updating block, which is used to generate an optimal weight vector w. Note that for the case of using the pilot channel, the integration period can be set to an arbitrary value in contrast to the case where the weight vector is generated using data channel. Finally, the updated vector is transmitted into the receiver's modem and hence, the final array output is generated as $z=w^H y_{data}$.

We now show some simulation results to evaluate the performance of the proposed algorithm for CDMA 2000 1X environments. We only consider the fundamental data channel in this simulation setup. Similar results can be obtained for other two supplementary channels with different data rates. The simulation parameters assumed is listed in Table 1. Each data point is obtained from 50000 received samples. Note that the adaptive procedure shown above is based on solving the eigenvalue
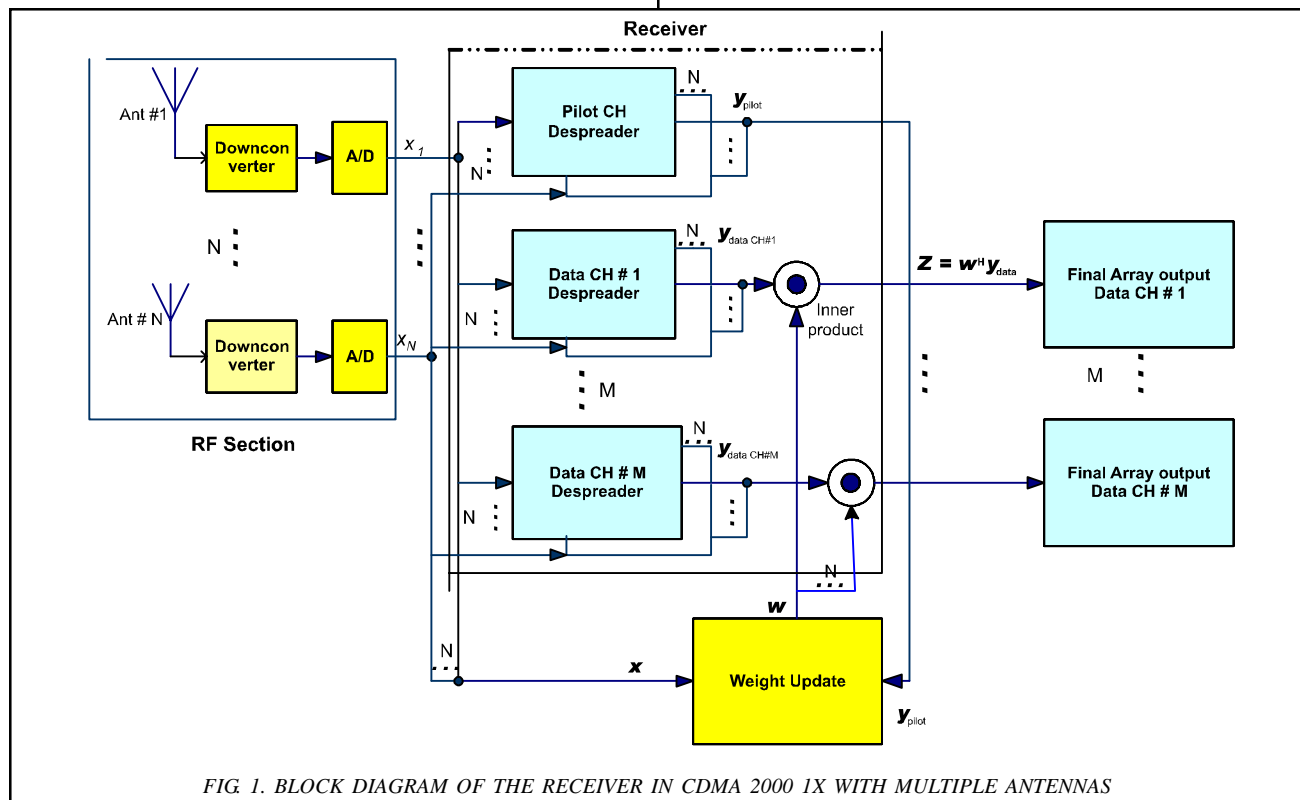

FIG. 1. BLOCK DIAGRAM OF THE RECEIVER IN CDMA 2000 1X WITH MULTIPLE ANTENNAS

problem, the optimization of the weight vector can be done in either using pilot or traffic channel. It particularly means that the data value is not required for weight optimization or computation. We know that in IS-95 system, we can only compute the weight vector from the traffic channel, similar to [14]. However, in CDMA 2000 1X system, we can utilize a pilot channel for the uplink as well as for the downlink. Each mobile terminal transmits a pilot signal and traffic channel at the same time, and since the pilot channel carries only un-modulated data, the processing gain for the pilot channel can be determined arbitrarily at the base station by properly setting the integral period during the de-spreading procedure of the pilot channel. We exploit this situation fully by performing the weight optimization on pilot channel instead of traffic channel for CDMA 2000 1X system.

In Fig. 2, we plot the bit error rate performance of proposed beamforming system as a function of given SNR (dB) at the input of each antenna for several values of number of antennas. The SNR is defined as the ratio of the power of the desired signal to noise measured at each antenna element. Angle spread is considered to be 0 and the

TABLE 1. SIMULATION PARAMETERS ASSUMED

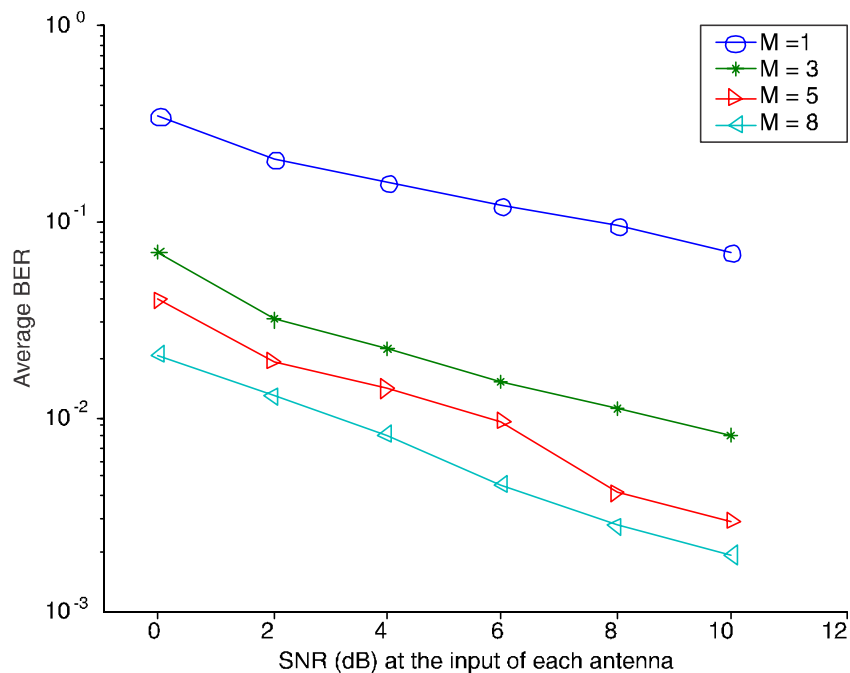|	
Integral Period	384 chips or 1.25ms
Doppler frequency	70Hz
Forgetting Factor	0.98
Change in AOA directions	0.01 degrees/snapshot
Snapshot	1ms
Number of RAKE fingers	2
Angle spread	0-20 degrees

FIG. 2. AVERAGE BER PERFORMANCE AS A FUNCTION OF SNR; K=20, $\sigma=0^o$

number of user (interferers) is set to 20. It can be noticed from the Fig. 2 that the proposed algorithm shows better performance as compared to a single antenna system. Fig. 3 illustrates the BER performance as a function of number of users for zero angle spread. In addition to that we also plot the performance of CGM algorithm proposed in [14] for comparison. Here M=6 and SNR=10 dB is assumed. It is quite obvious from the Fig. 3, that the performance of the proposed algorithm is slightly better than [14].

In Fig. 4 we plot a similar comparison for σ=10°. As one can see the proposed algorithm shows better performance than [14]. This is due to the fact that, as angle spread increases, the statistics of channel vary randomly at each snapshot and this increases the interference from other users which the algorithm of [14] is not able handle. And it is also due to that fact that the algorithm of [14] is based on maximizing the SNR, while the proposed algorithm attempts to maximize the SNIR, because it considers the undespread signal vector x. It

can be noticed from Figs. 2-4 that the BER performance of both the algorithms (i.e. CGM of [14], and the proposed algorithm) degrade as angle spread increases, however, the degradation in the proposed algorithm is not severe as compared to that of the CGM [14]. Again, this is due to the spatial filtering characteristics of the proposed algorithm, since it maximizes the SNIR unlike the algorithm of [14].

To see it more clearly, we plot the average BER performance as a function of angle spread as shown in Fig. 5. Here, K=10, SNR=10 dB. One can easily notice the difference in the gap of the two curves from Fig. 5 as the angle spread increases from 0-20 degrees. Therefore, it can be concluded that the proposed algorithm is more robust to the angle spread in the propagation environment. It can be seen from the results so far that the new technique proposed does not provide a spatial diversity gain, since the performance degrades as the angle spread increases. In [19] proposed a beamforming algorithm which seems to provide a diversity gain when

FIG. 3. AVERAGE BER PERFORMANCE AS A FUNCTION OF NUMBER OF USERS; SNR=10 dB, σ=0° AND M=6
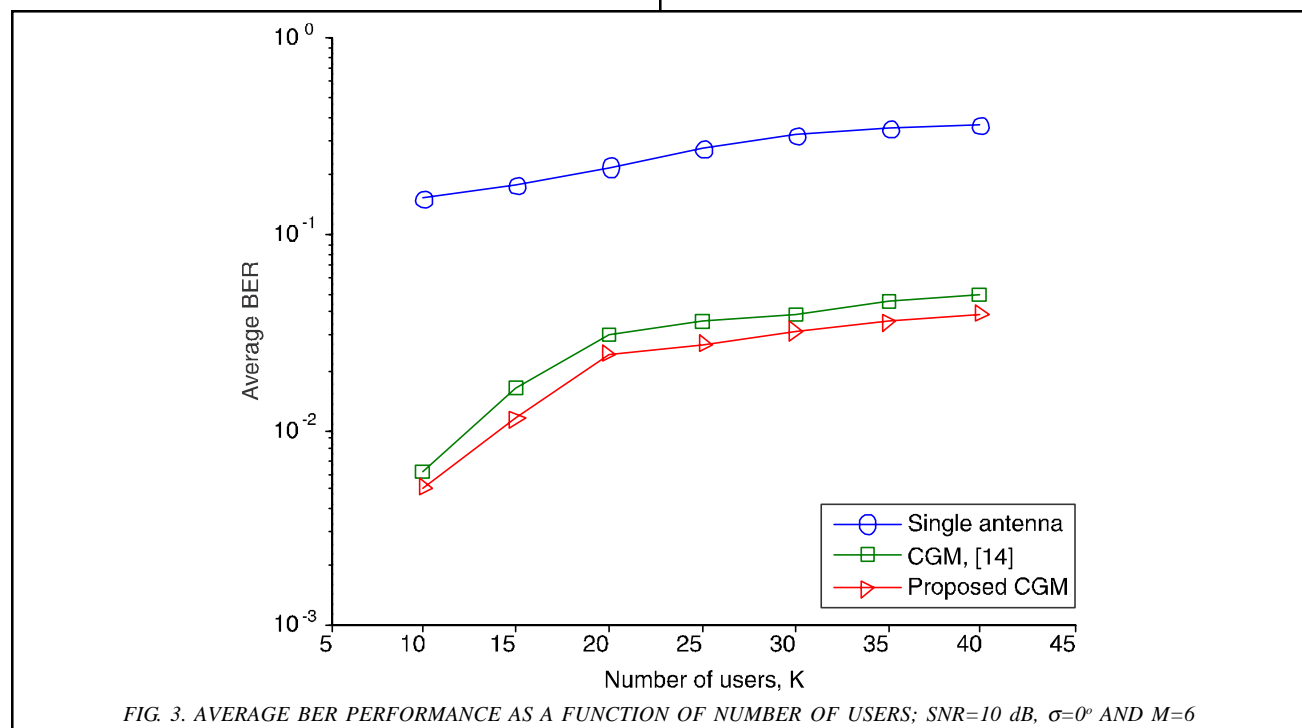
the angle spread is higher but at the expense of increased complexity. The algorithm in [19] computes the weight vector as the weighted sum of two eigenvectors (primary and secondary eigenvectors).
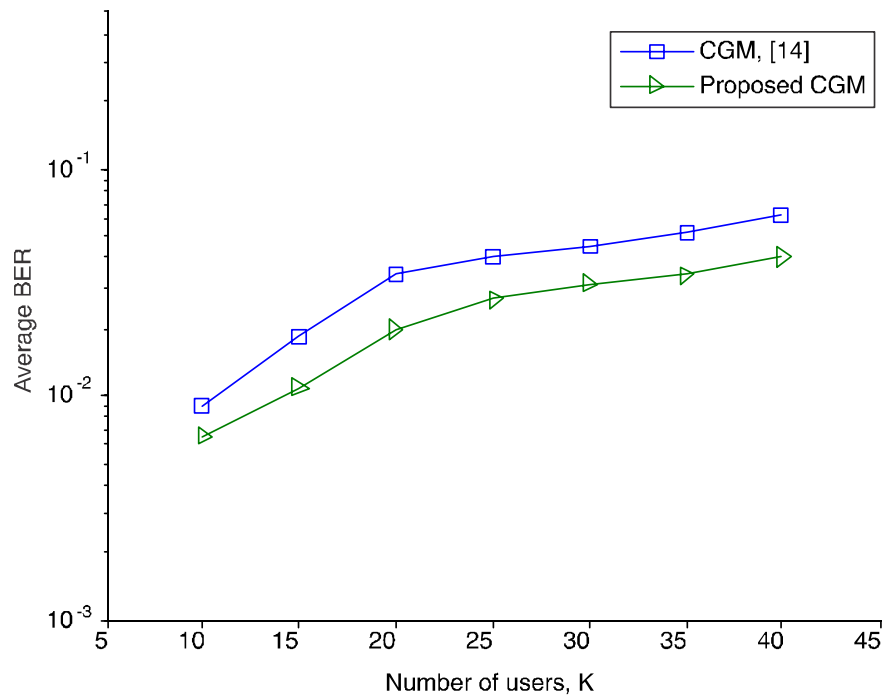
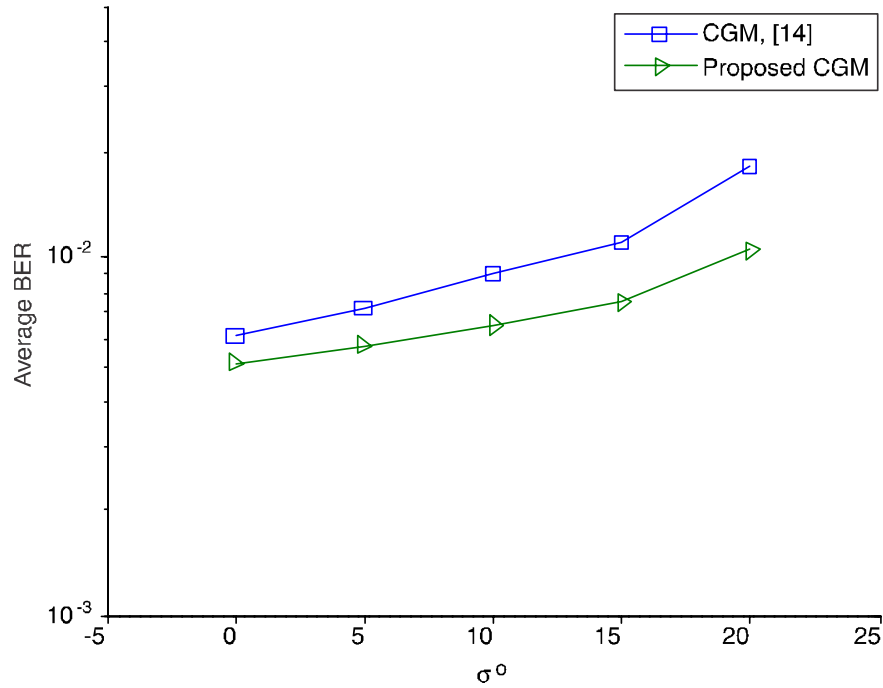FIG. 4. AVERAGE BER PERFORMANCE AS A FUNCTION OF NUMBER OF USERS; SNR=10 dB, $\sigma=0^o$ AND M=6.

FIG. 5. AVERAGE BER PERFORMANCE AS A FUNCTION OF ANGLE SPREAD; K=10, M=6

5.   CONCLUSION

The performance of beamforming algorithms developed for small or no angle spread degrades considerably as the angle spread increases. We described in detail a novel beamforming algorithm based on conjugate gradient methods. The proposed technique attempts to maximize SNIR of the received signal, and is based on solving the eigenvalue problem where the optimization of the weight vector is done using the pilot channel. The performance in terms of bit error rate is simulated for practical CDMA 2000 1X communications systems in wireless propagation environments with high angle spread. The performance of the proposed beamforming algorithm is also compared with the beamforming algorithm of [14]. Simulation results show that the performance of the proposed algorithm is more robust to increased angle spread.

ACKNOWLEDGMENTS

REFERENCES

[1]   3GPP2, "Physical Layer Standards for CDMA 2000 Spread Spectrum System," C.S0002-D v1.0 2003.

[2]   3GPP2, "Upper Layer (Layer 3) Signaling Standards for CDMA 2000 Spread Spectrum System," C.S0005-D v1.0 2004.

[3]   Korowajczuk L., et. al., "Designing CDMA 2000 Systems", Wiley, 2004.

[4]   Najuib A., "Smart Antenna for CDMA Wireless Communications", Ph.D. Thesis, Stanford University, 1996.

[5]   David, S.W., "Fundamentals of Matrix Computations", John Wiley & Sons, 2nd Edition, 2002

[6]   Golub, G.H., and Loan, C.F., "Matrix Computations", The John Hopkins University Press, 3rd Edition, 1996.

[7]   Haykin, S., "Adaptive Filter Theory", Prentice Hall Publishing Company, 4th Edition, 2002.

[8]   Song, Y.S., et. al., "Computationally Efficient Smart Antennas for CDMA Wireless Communication", IEEE Transactions on Vehicular Technology, Volume 50, No. 6, pp. 691-698, November, 2001.

[9]   Liu S. C., "New Space-Time Processing Techniques for Spread-Spectrum Wireless Network," PhD thesis, University of Maryland, USA, 1998.

[10]   Sarkar, T., "Application of Conjugate Gradient Method to Electromagnetic and Signal Analysis", Elsevier Science Publisher, 1991.

[11]   Choi, S., and Lee, S.S., "Comparison of the CGM to the Method of RLS in Terms of Convergence Rate", Proceedings of IEEE VTC, pp. 905-909, USA, 1993.

[12]   Choi, S., Son, H.M., and Sarkar, T., "Implementation of a Smart Antenna System on a General Purpose Digital Signal Processor Utilizing a Linearized CGM", Digital Signal Process, Volume 7, No. 2, pp. 105-119, 1997.

[13]   Choi, S., and Yun, D., "Design of Adaptive Antenna Array for Tracking the Source of Maximum Power and its Application to CDMA Mobile Communications", IEEE Transactions on Antenna and Propagations, Volume 45, No. 9, pp. 1393-1404, September, 1997.

[14]   Choi, S., and Shim, D., "A Novel Adaptive Beamforming Algorithm for a Smart Antenna System in a CDMA Mobile Communication Environment", IEEE Transactions Vehicular Techology, Volume 49, No. 5, pp. 1793-1806, September, 2000.

[15]   Li, H.J., and Liu, T.Y., "Comparison of Beamforming Techniques for WCDMA Communication Systems", IEEE Transactions on Vehicular Techology, Volume 54, No. 4, pp. 752-760, July, 2003.

[16]   Sheng, P., and Willson, A., "An Analysis of Conjugate Gradient Algorithms for Adaptive Filtering", IEEE Transactions on Signal Process, Volume 48, No. 2, February, 2000.

[17]   Gil, J.M., and Correla, L.M., "Combining Directional Channel Modeling with Beamforming Adaptive Antennas for UMTS", 12th IEEE International Symposium on PIMRC, Volume 2, pp. E132-E13630, USA, September 3-October 2000.

[18]   Mohamed, N.A., and Dunham, J.G., "A Simple Combined Conjugate Gradient Beamforming and Interference Cancellation Scheme for DS CDMA in a Multipath Fading Channel", IEEE Wireless Communication and Networking Conference, Volume 2, pp. 859-863, September 21-24, 1999.

[19]   Lee, W.C., and Choi, S., "Adaptive Beamforming Algorithm Based on Eigen-Space Method for Smart Antennas", IEEE Communication Letters, Volume 9, No. 10, pp. 888-890, October, 2005.

[20]   Umrani, A.W., "Performance Analysis of Spatial Diversity and Beamforming System for Wireless Communication Systems", Ph.D. Thesis, Nanyang Technological University, Singapore, 2008.