An Adaptive Beamforming Algorithm for Smart Antenna Applied to an MC-CDMA System with co-channel Interference in Ricean fading channel

[1] Le Minh Tuan, [1] Pham Van Su, [2] Jewoo Kim and [1] Giwan Yoon
[1] School of Eng., Information & Communications University (ICU)
58-4, Hwaam-dong, Yusong-gu, Taejon 305-348, Korea
letuan@icu.ac.kr
Tel.: +82-42-866-6201 Fax.: +82-42-866-6227
[2] TeleCIS, Inc., 418 South Abbott Avenue, Milpitas, CA 95129, U.S.A.

Abstract

In this paper, an adaptive beamforming algorithm, based on the Minimum Mean Squared Error (MMSE) criterion, is devised for adaptive antenna applied to an MC-CDMA system. A new method for updating the weight vector is derived. Computer simulations show that proposed algorithm is capable of rejecting co-channel interference that affects the MC-CDMA system. Thus, the BER performance of the MC-CDMA system is improved compared with that of the MC-CDMA system without using adaptive antenna and that of the DS-CDMA system with adaptive antenna in multi-path Ricean fading channel

I. Introduction

Co-channel interference and multi-path fading effects are the main limitations facing wireless communication systems. Therefore, finding solutions to overcome these limitations is vitally important for these systems to be able to serve a huge number of users. Recently, an approach, called the multi-carrier CDMA (MC-CDMA), [1]-[2], has been proposed to overcome the limitation in the capacity of the CDMA systems due to inter-chip interference and multi-user interference in high data rate communications systems [1]. The MC-CDMA is a combination of the CDMA scheme and the orthogonal frequency division multiplexing (OFDM) technique. As a consequence of this combination, inter-chip interference could be eliminated and the complexity of the receiver could be reduced. Another key advantage of using OFDM is that the modulation and demodulation can be achieved in the discrete-domain by using a discrete Fourier transform (DFT) [3], which is efficiently implemented by using the fast Fourier transform (FFT). Thus, there would be almost no increase in the transmitter and receiver complexities of the MC-CDMA system.

It is also well known that adaptive antenna arrays, [4]-[6], have been introduced in the literature for TDMA and CDMA systems to mitigate rapid dispersive fading and to suppress co-channel interference so as to improve the performances of such systems. For the MC-CDMA with co-channel interference, adaptive antenna arrays are desirable. Unfortunately, there are up to now not many adaptive beamforming algorithms for antenna arrays applied to the MC-CDMA system. There have been several publications [7], [8] investigating the performance of MC-CDMA system using antenna arrays. Therefore, it is necessary to find as many good beamforming algorithms for this system as possible.

In this paper, we propose an adaptive beamforming algorithm based on the MMSE criterion for antenna array applied to the MC-CDMA system. In the proposed algorithm, the weight vector is first updated by short training process. Then a decision-directed technique is used for updating the weight vector so that the capacity could be more improved. Both of the processes are perform in the time domain. Simulation results show that the proposed algorithm is able to extract the desired signal while it compresses other undesirable co-channel interferers. As a result, the MC-CDMA system employing the proposed algorithm has a very high BER performance compared with the MC-CDMA system without using antenna arrays and the DS-CDMA using an adaptive antenna array in multi-path Ricean fading channel.

II. MC-CDMA System with an Adaptive Antenna Array

1. The transmitter of the MC-CDMA system:

In the transmitter the signal symbols of each user are first multiplied by the corresponding PNsequence assigned to each user. The spread signal of the m^{th} user can be written as:

$$y_m(t)=\sum_{i=-\infty}^{\infty}\sum_{j=0}^{N-1} b_m(i)c_{m,j}(i)p_c(t-jT_c-iT) \qquad (1)$$

where $b_m(i)=\pm 1$ is the i^{th} signal symbol of the m^{th} user. $c_{m,j}(i)=\pm 1$ is the j^{th} spreading chip of the m^{th} user corresponding to the i^{th} signal symbol. $p_c(t)$ is the unit-magnitude rectangular pulse given by:

$$p_c(t)=\begin{cases}1 & 0\le t<T_c\\ 0 & \text{otherwise}\end{cases} \qquad (2)$$

T_c is the chip duration. $T=NT_c$ is the signal symbol duration. And N is the processing gain.

Without loss of generality, let us consider the n^{th} signal symbol, the spread signal $y_m(t)$ may be expressed in the vector form as follows:

$$\underline{y}_m(n)=\left[y_{m,0}(n)\quad y_{m,1}(n)\quad \ldots \quad y_{m,N-1}(n)\right] \qquad (3)$$

where $y_{m,j}(n)=b_m(n)c_{m,j}(n)$, $j=0,1,\ldots N-1$.

This frequency-domain signal vector is then serial-to-parallel converted and is transformed in the time-domain signal by the IFFT as follows:

$$x_{m,l}(n)=\sum_{k=0}^{N-1} y_{m,k}(n)e^{j2\pi lk/N}$$
$$l=0,1,\ldots,N-1 \qquad (4)$$

where $y_{m,k}(n)$ is the symbol of the m^{th} user carried by the k^{th} sub-carrier of the n^{th} block or n^{th} signal symbol. $x_{m,l}(n)$ is the l^{th} time-domain sample of the n^{th} block. In this system the number of sub-carrier is equal to the processing gain N. Equation (4) can be rewritten in the vector form as follows:

$$\underline{x}_m(n)=\underline{y}_m(n)\mathbf{F}^H(n) \qquad (5)$$

where $\underline{x}_m(n)=\left[x_{m,0}(n)\quad x_{m,1}(n)\quad \cdots \quad x_{m,N-1}(n)\right]$, is the signal vector of the m^{th} user in the time-domain. And

$$\mathbf{F}(n)=\frac{1}{\sqrt{N}}\begin{bmatrix}1 & 1 & \cdots & 1\\ 1 & e^{-j2\pi(1)(1)/N} & \cdots & e^{-j2\pi(1)(N-1)/N}\\ \vdots & \vdots & \ddots & \vdots\\ 1 & e^{-j2\pi(N-1)(1)/N} & \cdots & e^{-j2\pi(N-1)(N-1)/N}\end{bmatrix}$$

represents the FFT operation matrix.
H denotes the Hermitian transpose.
After that the time-domain signal vector, $\underline{x}_m(n)$ is parallel-to-serial converted and is up converted to transmit to the base station.

2. The receiver of the MC-CDMA system:

In the receiver, the received signal is first down converted to get the base-band signal. Then the desired signal is obtained through the use of the smart antenna. Let us make the following assumptions:

-There are M signals impinging at an array of K elements, $K\ge M$.

-The channel is frequency selective fading.

-The number of sub-carrier N is chosen appropriately so that sub-carriers experience frequency nonselective fading.

-Perfect phase and timing synchronizations are achieved.

Under the above assumptions, the signal matrix, $V(n)$, received at the array antenna is represented by:

$$V(n)=A(\theta)Z(n)+G(n) \qquad (6)$$

where,

$$V(n)=\begin{bmatrix}v_{0,0}(n) & v_{0,1}(n) & \cdots & v_{0,N-1}(n)\\ v_{1,0}(n) & v_{1,1}(n) & \cdots & v_{1,N-1}(n)\\ \vdots & \vdots & \ddots & \vdots\\ v_{K-1,0}(n) & v_{K-1,1}(n) & \cdots & v_{K-1,N-1}(n)\end{bmatrix}$$

$$Z(n)=\begin{bmatrix}\beta_{0,0}x_{0,0}(n) & \ldots & \beta_{0,N-1}x_{0,N-1}(n)\\ \beta_{1,0}x_{1,0}(n) & \ldots & \beta_{1,N-1}x_{1,N-1}(n)\\ \vdots & \ddots & \vdots\\ \beta_{M-1,0}x_{M-1,0}(n) & \ldots & \beta_{M-1,N-1}x_{M-1,N-1}(n)\end{bmatrix}$$

$$A(\theta)=\begin{bmatrix}a_0(\theta_0) & a_0(\theta_1) & \cdots & a_0(\theta_{M-1})\\ a_1(\theta_0) & a_1(\theta_1) & \cdots & a_1(\theta_{M-1})\\ \vdots & \vdots & \ddots & \vdots\\ a_{K-1}(\theta_0) & a_{K-1}(\theta_1) & \cdots & a_{K-1}(\theta_{M-1})\end{bmatrix}$$

$A(\theta)$ is the array response matrix for M users.

$G(n)$ is the $K \times N$ matrix of additive white Gaussian noises with zero mean and power spectral density $N_0/2$.

$Z(n)$ is the matrix of the signals of M users at the antenna array.

$\beta_{m,k}$, $m = 0,1,\Lambda,M-1$, $k = 0,1,\Lambda\ N-1$, is a complex coefficient associated with the k^{th} snapshot of the m^{th} user, which is resulted from multi-path fading effects and is given by:

$$\beta_{m,k} = \alpha_{m,k} \exp(-j\phi_{m,k}) = \alpha^I_{m,k} + j\alpha^Q_{m,k} \tag{7}$$

Here we assume that $\alpha^I_{m,k}$ and $\alpha^Q_{m,k}$ are independent identically distributed (i.i.d) Gaussian random variables with nonzero mean $m^I_{m,k}$ and $m^Q_{m,k}$, respectively, and the same variance $b_{m,k}$. In other words, the magnitude $\alpha_{m,k} = |\beta_{m,k}|$ has a Ricean distribution with the probability density function (PDF) of the form [3]:

$$p_{\alpha_{m,k}}(x) = \frac{2x(K_{m,k}+1)}{\Omega_{m,k}} \exp\left[-K_{m,k} - \frac{(K_{m,k}+1)x^2}{\Omega_{m,k}}\right] \times I_0\left(2x\sqrt{\frac{K_{m,k}(K_{m,k}+1)}{\Omega_{m,k}}}\right) \tag{8}$$

where, $I_0(.)$ is the zero order modified Bessel function of the first kind.

$K_{m,k}$ is the Rice factor defined as the ratio of the specular power to scattered power, given by:

$$K_{m,k} = \frac{s^2_{m,k}}{2b_{m,k}} = \frac{(m^I_{m,k})^2 + (m^Q_{m,k})^2}{2b_{m,k}} \tag{9}$$

$\Omega_{m,k}$ is the average envelope power, given by:

$$\Omega_{m,k} = E\left[|\alpha_{m,k}|^2\right] = s^2_{m,k} + 2b_{m,k} \tag{10}$$

The desired signal vector of the m^{th} user, $\underline{s}_m(n)$, achieved by passing $V(n)$ through an adaptive beamformer with the weight vector $\underline{w}_m(n)$, is given by

$$\underline{s}_m(n) = \underline{w}^H_m(n)V(n) \tag{11}$$

where,

$$\underline{s}_m(n) = [s_{m,0}(n) \quad s_{m,1}(n) \quad \mathrm{K} \quad s_{m,N-1}(n)]$$

$$\underline{w}_m(n) = [w_{m,0}(n) \quad w_{m,1}(n) \quad \Lambda \quad w_{m,K-1}(n)]^T$$

and T denotes the transpose.

The weighted signal vector $\underline{s}_m(n)$ is then converted into the frequency-domain by the FFT operation, thus yielding:

$$\underline{\tilde{y}}_m(n) = [\tilde{y}_{m,0}(n) \quad \tilde{y}_{m,1}(n) \quad \mathrm{K} \quad \tilde{y}_{m,N-1}(n)] = \underline{s}_m(n)\mathbf{F}(n) = \underline{w}^H_m(n)V(n)\mathbf{F}(n) \tag{12}$$

This signal vector is converted to serial data and fed into a decision block. Based on the finite symbol property of the transmitted signal, the original spread signal from the transmitter could be recovered. Let us denote the recovered signal vector at the output of the decision block as $\underline{y}_{dm}(n)$. Note that this recovered signal vector corresponds to the transmitted spread signal vector $\underline{y}_m(n)$. The recovered signal vector, $\underline{y}_{dm}(n)$, is then multiplied by the spreading sequence assigned to the m^{th} user, $c_{m,j}(n)$, so that we can get the original signal symbol $b_m(n)$.

III. The proposed algorithm

1. Training period:

In this period only training signal is transmitted so as to train the weight vector of the array antenna. Note that, in the frequency-domain, both the received training signal and the received information signal are given by equation (12). In the time-domain, the training signal vector $\underline{x}_{tm}(n)$ and the received training signal vector $\underline{\tilde{x}}_{tm}(n)$ can be found from the corresponding frequency-domain training signal vector $\underline{y}_{tm}(n)$ and the received training signal vector $\underline{\tilde{y}}_{tm}(n)$ as follows:

$$\underline{x}_{tm}(n) = [x_{tm,0}(n) \quad x_{tm,1}(n) \quad \mathrm{K} \quad x_{tm,N-1}(n)] = \underline{y}_{tm}(n)\mathbf{F}^H(n) \tag{13}$$

and

$$\underline{\tilde{x}}_{tm}(n) = \underline{\tilde{y}}_{tm}(n)\mathbf{F}^H(n) = \underline{w}^H_m V(n)\mathbf{F}(n)\mathbf{F}^H(n) \tag{14}$$

or equivalently,

$$\underline{\tilde{x}}_{tm}(n) = \underline{w}^H_m V(n) = [\underline{w}^H_m \underline{v}_0(n) \quad \underline{w}^H_m \underline{v}_1(n) \quad \Lambda \quad \underline{w}^H_m \underline{v}_{N-1}(n)] \tag{15}$$

where $\underline{v}_i(n) = [v_{0,i}(n) \quad v_{1,i}(n) \quad \Lambda \quad v_{K-1,i}(n)]^T$, $i = 0,1,\mathrm{K},N-1$

Based on the MSE criterion, we propose a new cost function for the proposed algorithm applied to the MC-CDMA system as follows:

$$J(n)=\sum_{i=0}^{N-1}E\left[\left|\underline{w}_m^H(n)\underline{v}_i(n)-x_{tm,i}(n)\right|^2\right] \quad (16)$$

The gradient of equation (17) with respect to the weight vector $\underline{w}_m(n)$ is given by:

$$\nabla J(n)=\sum_{i=0}^{N-1}\left[2R_{tm,i}(n)\underline{w}_m(n)-2\underline{p}_{tm,i}(n)\right] \quad (17)$$

where,

$R_{tm,i}(n)=E\left[\underline{v}_i(n)\underline{v}_i^H(n)\right]$ is the correlation matrix of the i^{th} received training symbol of the n^{th} block.

$\underline{p}_{tm,i}(n)=E\left[\underline{v}_i(n)x_{tm,i}^*(n)\right]$ is the cross-correlation vector between the i^{th} received training symbol and the i^{th} training symbol at the receiver.

An adaptive solution that minimizes the cost function is [6]:

$$\underline{w}_m(n+1)=\underline{w}_m(n)-\frac{1}{2}\mu\nabla J(n)$$
$$=\underline{w}_m(n)-\mu\sum_{i=0}^{N-1}\left[R_{tm,i}(n)\underline{w}_m(n)-\underline{p}_{tm,i}(n)\right] \quad (18)$$

where μ is the step size parameter.

From equation (18) we see that in order to update the weight vector we must know the correlation matrix $R_{tm,i}(n)$ and the cross-correlation vector $\underline{p}_{pm,i}(n)$. In the proposed algorithm, the correlation matrix $R_{tm,i}(n)$ and the cross-correlation vector $\underline{p}_{pm,i}(n)$ are computed by using the moving-average (MA) procedure as follows:

$$R_{tm,i}(n)=f*R_{tm,i}(n-1)+\underline{v}_i(n)\underline{v}_i^H(n) \quad (19)$$

$$\underline{p}_{tm,i}(n)=f*\underline{p}_{tm,i}(n-1)+\underline{v}_i(n)x_{tm,i}^*(n) \quad (20)$$

where $0\le f\le 1$ is called the forgetting factor.

Thus in the training period the proposed algorithm is summarized as follows:

1. Initialize
$\hat{\underline{w}}_m(0)=0,\ n=0$.
2. Update the weight vector, $n=n+1$
- Receive a new training signal matrix $V(n)$.
- Calculate the correlation matrix and cross-correlation vector
$R_{tm,i}(n)=f*R_{tm,i}(n-1)+\underline{v}_i(n)\underline{v}_i^H(n)$
$\underline{p}_{tm,i}(n)=f*\underline{p}_{tm,i}(n-1)+\underline{v}_i(n)x_{tm,i}^*(n)$
$i=0,1,\Lambda,N-1$
- Calculate the gradient
$\nabla J(n)=\sum_{i=1}^{N-1}\left[R_{tm,i}(n)\underline{w}_m(n-1)-\underline{p}_{tm,i}(n)\right]$
- Update the weight vector
$\underline{w}_m(n)=\underline{w}_m(n-1)-\mu\nabla J(n)$.
3. Iterate step 2) until the weight vector converges

2. Communication period:

In this period, training signal is not used any more. A decision-directed approach is applied for updating the weight vector. The process for updating the weight vector is almost the same as that in the training period, except for the followings:

-The received information signal matrix now replaces the received training signal matrix and is still given by equation (6).

-The time-domain reference signal is now created from the output of the decision block $\underline{y}_{dm}(n)$ and is given by:

$$\underline{x}_{dm}(n)=\left[x_{dm,0}(n)\quad x_{dm,1}(n)\quad K\quad x_{dm,N-1}(n)\right]$$
$$=\underline{y}_{dm}(n)\mathbf{F}^H(n) \quad (22)$$

-The received information signal in the time domain is still given by:

$$\tilde{\underline{x}}_m(n)=\tilde{\underline{y}}_m(n)F^H(n)=\underline{w}_m^H V(n)\mathbf{F}(n)\mathbf{F}^H(n) \quad (23)$$

Or, equivalently

$$\tilde{\underline{x}}_{tm}(n)=\underline{w}_m^H V(n)$$
$$=\left[\underline{w}_m^H\underline{v}_0(n)\quad \underline{w}_m^H\underline{v}_1(n)\quad \Lambda\quad \underline{w}_m^H\underline{v}_{N-1}(n)\right] \quad (24)$$

During this period, the proposed algorithm work as follows:

4. Receive a new information signal matrix $V(n)$, $n=n+1$
- Calculate the output of the array
$\underline{s}_m(n)=\hat{\underline{w}}_m^H(n-1)V(n)$
- Convert into the frequency domain
$\tilde{\underline{y}}_m(n)=\underline{s}_m(n)F(n)=\underline{w}_m^H(n)V(n)\mathbf{F}(n)$
- Make decision to retrieve the original spread signal, denoted as $\underline{y}_{dm}(n)$.

- Despread $\underline{y}_{dm}(n)$ to get the original signal symbol $b_m(n)$.

5. Update the weight vector,

- Find the reference signal by converting $\underline{y}_{dm}(n)$ into the time domain as in equation (26)

$$\underline{x}_{dm}(n) = [x_{dm,0}(n) \quad \Lambda \quad x_{dm,N-1}(n)] = \underline{y}_{dm}(n)\mathbf{F}^H(n)$$

- Calculate the correlation matrix and cross-correlation vector

$$R_{tm,i}(n) = f * R_{tm,i}(n-1) + \underline{v}_i(n)\underline{v}_i^H(n)$$

$$\underline{p}_{tm,i}(n) = f * \underline{p}_{tm,i}(n-1) + \underline{v}_i(n)x^*_{dm,i}(n)$$

$$i = 0,1,\Lambda, N-1$$

- Calculate the gradient

$$\nabla J(n) = \sum_{i=1}^{N-1}\left[R_{tm,i}(n)\underline{w}_m(n-1) - \underline{p}_{tm,i}(n)\right]$$

- Update the weight vector

$$\underline{w}_m(n) = \underline{w}_m(n-1) - \mu\nabla J(n).$$

6. Repeat from step 4) until the end of the communication process.

IV. Simulation results and discussion

In the simulation, the channel is assumed to be multi-path Ricea fading with AWGN. The data symbols at the output of the spreader is binary; that is, $y_{m,k} = 1$ for bit 1 and $y_{m,k} = -1$ for bit 0. The number of sub-carriers for one block and the processing gain is the same and equal to $N = 64$. The spreading signal $c_m(t)$ is a Gold sequence. The antenna array is linear and the distance between adjacent elements is half of the wavelength, $\lambda/2$. The number of users is 6. The mobile is moving at a velocity that results in a maximum Doppler shift of 66.67 Hz. The number of multi-path is assumed to be 30.

Fig. 1 shows the BER performances for the MC-CDMA system in multi-path Ricean fading channel with AWGN when an adaptive antenna array is applied. The number of elements is changed. As can be seen from the figure, when the proposed algorithm is employed, BER performances of the system are greatly improved in comparison with the case in which no array is used. In addition, the improvement in BER performances of the system is proportional to the number of array elements exploited.

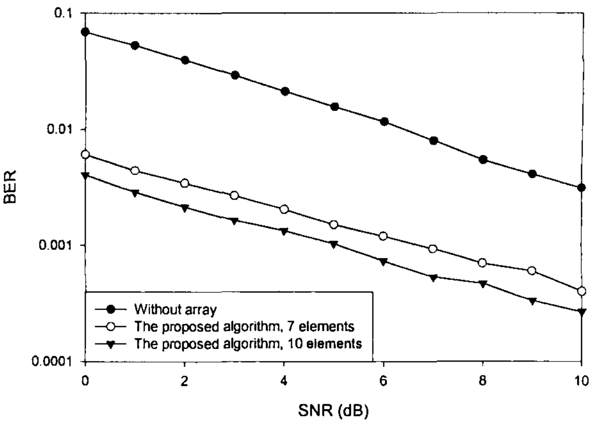

Fig.1 BER performance versus SNR for the MC-CDMA system in Ricean fading channel with the proposed algorithm when the number of elements is varied.

Fig. 2 illustrates the comparison of the BER performances for the MC-CDMA system with the proposed algorithm and the DS-CDMA system using the conventional MMSE algorithm presented in [6] in multi-path Ricean fading channel with AWGN. As shown in Fig. 9, with the aid of the proposed algorithm, BER performances of the MC-CDMA system are much higher than those of the DS-CDMA system exploiting smart antenna.

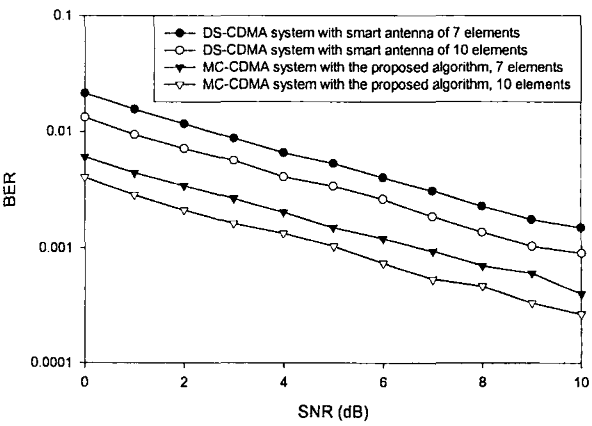

Fig. 2 Comparison of BER performances versus SNR for the MC-CDMA system with the proposed algorithm and the DS-CDMA system using smart antenna in Ricean fading channel when the number of elements is varied.

V. Conclusion

In this paper, an adaptive beamforming algorithm for the MC-CDMA system with array antenna is proposed. The proposed algorithm has a very good capability of suppressing co-channel interference, resulting in a MC-CDMA system with very high BER performances in multi-path Ricean fading channel with AWGN compared with the DS-CDMA system using smart antenna. The proposed algorithm initially requires a very short training period, saving capacity of the system. Furthermore, the weight vector is updated in a similar manner as the conventional beamforming algorithms for TDMA and CDMA systems. Consequently, the proposed algorithm is a good candidate for combating co-channel interference in future wireless communication networks.

References

[1] N. Yee, J. –P. Linnartz, and G. Fettweis, "Multi-carrier CDMA in indoor wireless radio networks" in Proc. PIMRC'93, Yokohama, Sept. 1993, Page(s): 109-113.

[2] Chouly, A.; Brajal, A.; Jourdan, S., "Orthogonal multicarrier techniques applied to direct sequence spread spectrum CDMA systems", Global Telecommunications Conference, 1993, including a Communications Theory Mini-Conference. Technical Program Conference Record, IEEE in Houston. GLOBECOM '93., IEEE , 1993, Page(s): 1723 -1728 vol.3.

[3] Gordon L. Stüber, "Principles of mobile comm.unication", Second edition, Kluwer Academic Publishers, Page(s): 175-181.

[4] Madhow, U., "Blind adaptive interference suppression for direct-sequence CDMA", Proceedings of the IEEE , Volume: 86 Issue: 10 , Oct. 1998, Page(s): 2049 –2069.

[5] Winters, J.H., "Signal acquisition and tracking with adaptive arrays in the digital mobile radio system IS-54 with flat fading", Vehicular Technology, IEEE Transactions on , Volume: 42 Issue: 4 , Nov. 1993, Page(s): 377 –384.

[6] Joseph C. Liberti, Jr., Theodore S. Rappaport, " Smart antennas for Wireless communications - IS-95 and 3rd Generation CDMA applications", Prentice Hall PTR 1999, Upper Saddle River, NJ 07458. Page(s): 96-96.

[7] Chan Kyu Kim; Yong Soo Cho, "Performance of a wireless MC-CDMA system with an antenna array in a fading channel: reverse link", Communications, IEEE Transactions on , Volume: 48 Issue: 8 , Aug. 2000, Page(s): 1257 –1261.

[8] Torlak, M.; Sang-Youb Kim; Joonhyuk Kang; Guanghan Xu; Hang Li, "Performance of MC-CDMA systems using antenna arrays", Signals, Systems, and Computers, 1999. Conference Record of the Thirty-Third Asilomar Conference on, Volume: 1 , 1999, Page(s): 179 -182 vol.1.