Performance of Multicarrier-CDMA Uplink with Antenna Arrays and Multiuser Detection

Shreeram Sigdel, Kazi M. Ahmed, and Anil Fernando

Abstract: **In this paper, an uplink MC-CDMA system incorporating multiuser detection and smart antennas has been considered. The performance of asynchronous as well as synchronous system is studied over a correlated Rayleigh multipath slow fading channel. A simplified array-processing algorithm suitable for slow fading situation is investigated to overcome the heavy computational complexity associated with Eigen solutions. The effect of variable data rate in the system performance is considered and effectiveness of antenna array to handle high data rate is discussed. A brief investigation on the system performance degradation due to correlated channel is also carried out. Based on the extensive simulation carried out, the performance of the asynchronous uplink system is found dramatically improved with antenna array and multiuser detection. Asynchronicity and channel correlation are found to affect the system performance significantly. The investigated simplified algorithm produces similar results as Eigen solutions in slow fading situation with much reduced complexity.**

Index Terms: **MC-CDMA, MAI, adaptive antenna arrays, interference cancellation.**

I. INTRODUCTION

There has been quite an extensive research in downlink MC-CDMA [1]–[3] because of coherent nature, whereas very little research has been done in MC-CDMA uplink system. Multiples Access Interference (MAI) and near far problems are the major impediments of MC-CDMA uplink communication systems that heavily degrade BER performance in the asynchronous case [2]. Using MC-CDMA in the uplink of a practical cellular communications system results in asynchronous reception of different user signals and it suffers from MAI due to the loss of orthogonality between the codes caused by channel distortion. In addition to that more BER degradation is observed from subcarrier correlation, frequency offsets and power control errors. Channel correlation due to non-constant mobile velocities is also a factor, which has to be taken into account for the analysis of the real systems.

Many advanced signal-processing techniques have been proposed to combat interference and multipath distortion. These techniques are largely categorized into space-time processing with antenna array and multi-user detection [4]. The use of antenna array to reduce the amount of co-channel interference from the other users and therefore increase in the system capacity is the issue that has been extensively researched and it is also considered to be inevitable part of 3G and future generation systems. On the other hand, multi-user detection (MUD) techniques have been proposed to combat MAI, which is inherent in the practical CDMA systems, to enhance their capacity and performance [5]. Studies [6]–[8] have shown that performance of MC-CDMA uplink can be increased using antenna arrays. In [9], a code filtering approach in adaptive beamforming in CDMA has been derived and in [6], this technique is extended for MC-CDMA case. Asynchronicity has not been considered in [6], which is not the real uplink scenario. In [7], a pilot signal based beamforming in synchronous case has been considered, whereas in [7], synchronous MC-CDMA with antenna array in presence of carrier and synchronization-offset has been presented through simulation. Several authors have also proposed different MAI cancellation techniques in MC-CDMA systems [10]–[12].

In this paper, we evaluate the MC-CDMA asynchronous uplink performance with antenna arrays and interference cancellation in the context of correlated slow Rayleigh fading channel. A comparison of the system performance with single user detection with antenna array multi-user detection is presented. A simplified array-processing algorithm is discussed to overcome the problems associated with Eigen analysis methods for slow fading situations. The effect of spatial correlation among the antenna elements in the array is also studied. The antenna array assisted MC-CDMA system for handling variable data rates is briefly discussed. Effect of channel correlation is simulated with different mobile velocities. A necessity for the joint analysis of the system for the optimization of the use of antenna array processing, interference cancellation algorithms, and channel correlation has been highlighted.

This paper is organized as follows. In Section II, the basic MC-CDMA system configuration with antenna array and MUD is discussed. In Section III, a brief introduction to the simplified array-processing algorithm used is presented. Simulation results are presented in Section IV. Finally, in Section V the paper is concluded.

II. SYSTEM MODEL

Consider a MC-CDMA system with K users employing Walsh-Hadarmad spreading codes and transmitting the Binary Phase Shift Keying (BPSK) symbols through frequency selective slow Rayleigh fading channel. Assuming the receiver employing an antenna array of M elements and each user transmits with a single antenna, the vector channel response of the system can be written as [7],

$$\boldsymbol{h}_k(t) = \sum_{l=1}^{L} \beta_{k,l}\boldsymbol{a}(\theta_{k,l})\delta_k(t-\tau_{k,l}), \qquad (1)$$

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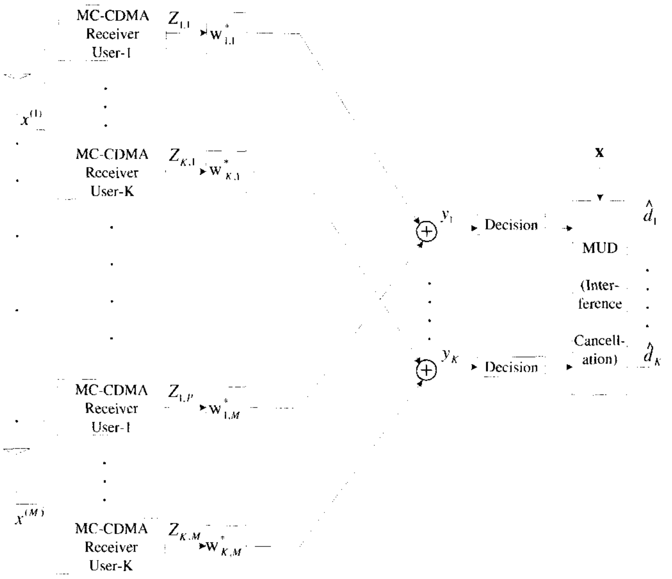

Fig. 1. MC-CDMA with antenna array and multi-user detection.

where L is the number of discrete multi paths incurred in the channel; $\beta_{k,l}$ is the complex path gain of user k for path l described by complex Gaussian random variables and $\tau_{k,l}$ are the lth path delay of the user k. $\boldsymbol{a}(\theta)$ is called *steering vector or array response vector* with direction of arrival of θ and for inter element distance of d and uniform linear array, it is given by,

$$\boldsymbol{a}(\theta) = [1, e^{-j2\pi d \sin\theta/\lambda}, e^{-j4\pi d \sin\theta/\lambda}, \ldots, e^{-j2\pi(M-1)d\sin\theta/\lambda}]. \tag{2}$$

For MC-CDMA system, the received signal vector can be expressed in discrete form as,

$$\boldsymbol{x}(n) = \sum_{k=0}^{K-1} s_k(n) \otimes \boldsymbol{h}_k(n) + \boldsymbol{\eta}(n), \tag{3}$$

where $\boldsymbol{x}(n)$ is the M dimensional vector given by $\boldsymbol{x}(n) = [x^{(1)}, x^{(2)}, \ldots, x^{(M)}]^T$. Assuming serial to parallel conversion factor to be unity for simplicity, the transmitted signal $s_k(n)$ of kth user is given by $s_k(n) = \sum_{\kappa=0}^{N-1} d_k C_k(\kappa) e^{j2\pi\kappa n/N}$; where d_k denotes the data symbol of kth user; $C_k(\kappa)$ is the κth chip of the spreading code of user k and N is the number of IFFT points or number of subcarriers. $\boldsymbol{\eta}(n)$ is additive Gaussian Noise vector. Note here that the circular convolution is a justified method with the use of guard bit insertion in between the two OFDM frames. In multicarrier systems, the received signal is first subjected to DFT to demodulate the information contained in the subcarriers. Let the DFT of $x^{(1)}(n)$ be denoted by $X^{(1)}(\kappa)$ for $\kappa = 0, 1, \ldots, N-1$, where N denotes the total number of subcarriers. The MC-CDMA receiver operation with antenna arrays and MUD is depicted in Fig. 1.

In each of the antenna elements basic MC-CDMA receiver operation is carried out. The combined output at each of the antenna elements can be written as

$$Z_m = \sum_{\kappa=0}^{N-1} X^m(\kappa) w(\kappa), \tag{4}$$

where $w(\kappa)$ is the subcarrier weighting factor and sometimes called the equalization factor. Maximal Ratio Combing (MRC) and Minimum Mean Square Error Combining (MMSEC) are known to be two major combining schemes [1] and they are sometimes called frequency diversity combining techniques. The output of the array is then expressed as,

$$y = \sum_{m=0}^{M-1} Z_m w_m^*. \tag{5}$$

This can be expressed in vector notation as $y = \boldsymbol{W}^H \boldsymbol{Z}$, where $\boldsymbol{W} = [w_1, w_2, \ldots, w_M]^T$ and $\boldsymbol{Z} = [Z_1, Z_2, \ldots, Z_M]^T$. The major objective is to find out the optimum weight vector $\boldsymbol{W}$ to get the array output with suitable criterion.

III. SIMPLIFIED ALGORITHM

In this section, we begin with the code filtering approach proposed in [12]. In this approach, the antenna output is correlated with kth user code to yield one sample per bit, thus obtaining post correlation matrix. From the preprocessing correlation matrix (correlation matrix of the input data vector $\boldsymbol{x}$) and the post correlation matrix (correlation matrix of the despreaded signal at the output $\boldsymbol{Z}$) the desired array response vector is estimated as the generalized principal Eigen vector of the matrix pencil of the two matrices discussed above. This procedure was adopted by [10] to derive the similar Eigen value solution to obtain the array response vector in MC-CDMA systems. There are, however, some fundamental problems for the implementation of this algorithm. In time variant channels, the recursive implementation of this algorithm would be necessary such that adaptive beamformer must continuously update the weight vector to match the changing environment, which in turn will involve the tracking of principal Eigen vector of pre- and post-processing covariance matrices and tracking of the undesired signal vector covariance matrix. Also the estimation of array response vector, interference and noise vector, matrix inverses and manipulations would lead to heavy computational complexity. Therefore, it is necessary to devise simplified algorithm to recursively track the weight vector. One of such algorithms was proposed for DS-CDMA in [13], which with some modifications can be used for MC-CDMA systems for the slow Rayleigh fading situation. The details could be found in the cited reference. Here some key assumptions are briefly discussed. The key assumption for this algorithm is that the signal of the targeted user is much stronger than the interfering signals. The assumption is valid for output signals of MC-CDMA receivers in each antenna element because the despreaded signal of the desired user is always stronger than the other user signals in power-controlled situation and it also depends on the processing gain which in turn refers to the subcarrier diversity in MC-CDMA system. In this context the Eigen vector corresponding to the maximum Eigen value of the autocovariance matrix of the received signal after despreading is equal to steering vector of the target signal source [14]. This method computes the sub-optimal weight vector that does not null the interferers but provides a maximum gain towards the desired user by minimizing the gain towards interferers. This algorithm uses an adaptive procedure to find the weight vec-

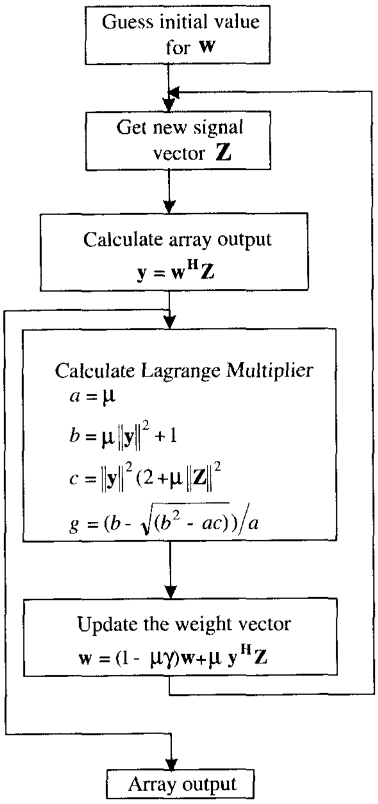

Fig. 2. Simplified algorithm.

tor based on Lagrange multiplier method. The following Figure summarizes the simplified algorithm, where the autocorrelation matrix of the post-processing vector is estimated by the instantaneous samples [13].

In Fig. 4, $0 < \mu < 1$ is the adaptive step size that is small enough to guarantee the convergence of the adaptive algorithm. In this algorithm, the weight vector and Eigen vector is updated iteratively once a new signal snap shot is received. However, for the convergence of the algorithm the principal Eigen vector should not change significantly at each snap shot. This condition is approximated by assumption of far field where by angle of the target signal doesn't change significantly at each snap shot. For the uplink situation discussed here and high-rise basestation antennas this assumption is valid.

For the multi-user detection, decision variables for each user, y_k, in (5) are evaluated and the hard decision data are fed into the interference cancellation module. This first stage of decision is referred to as the zeroth stage of interference cancellation (PIC0). A brute force PIC has been used here to evaluate the performance. In the interference cancellation module, the hard decision data are subjected to the spreading and channel fading with known channel parameters in asynchronous environment to generate the interference to each other appropriately. The interferences are then subtracted from the corresponding received signal of antenna elements for each user to generate interference-subtracted signal. This signal is then subjected to the process similar to the process in zeroth stage as explained above to have more reliable data outputs. Maximum three stages of interference cancellation have been used in the simulation here.

IV. SIMULATION RESULTS

Bit-error-rate (BER) performance of MC-CDMA uplink with antenna array and MUD is evaluated using Monte Carlo simulation method. Uplink mobile channel with BPSK modulation scheme and Walsh Hadarmad orthogonal codes of processing gain of 32 is used. The binary source data rate of 512 kbit/s and 1024 kbit/s are considered. The data bits are serial to parallel converted with s/p conversion factor of 4, spread in frequency domain, interleaved to minimize the subcarrier correlation and multicarrier modulated using IDFT technique so that the resulting signal is at chip rate of 4.096 Mchips/s, as in UMTS specification. Maximum twelve users are taken for simulation because of overwhelming time taken by the simulation process. The transmitted signals of each user are subjected to independent multipath relatively slow fading channel. The exponential power delay profile with delay spread of $1\mu s$ is assumed. The system is simulated for high mobile velocity of 100 km/h as well as 5 km/h to study the effect of the channel correlation. The asynchronicity is generated by uniformly randomly generated user delays that cause the users OFDM frames to overlap by random number of chips. Each users multipath are modelled to have different direction of arrival (DOA) such that the delay spread in the system doesn't exceed 20 degrees (from the broadside of the array) and mean DOA is zero degrees. Linear antenna array with maximum of six elements is considered in the receive array configuration. The DOA is randomly generated (Gaussian distributed [15], as the incoming field is expected to concentrate more on the azimuth because of the elevated antenna height) and (2) approximates the array response vector for each path and each user. The spatially correlated and spatially independent situations are taken care by inter element distance of antenna array. Interelement separation is assumed to be $\lambda/2$ for spatially correlated case, and for spatially independent case according to [12], at least 5λ is maintained. The spatially independent case is considered as the optimum diversity combining rather than beamforming.

Further it is assumed that there is perfect subcarrier synchronization, no frequency offset, no nonlinear distortion and perfect subcarrier amplitude estimation. The receiver at each antenna elements is assumed to be code locked on to the corresponding user. It should be noted here that the requirement of multicarrier system to have the frequency flat channel for each subcarriers has been maintained with the parameters discussed above. For the system considered here error control coding schemes have not been considered.

A. Performance with Antenna Array

Fig. 3 shows the BER performance of the asynchronous and synchronous MC-CDMA system with antenna array. Here MMSEC is taken to be the frequency diversity combining technique and simple equal gain combining is taken to show the performance of array combining. Since, mean DOA is taken as zero degree, the array response vector would most of the time be unity, which justifies the use of simple equal gain combining to study the performance in simplest case. The effect of asyn-

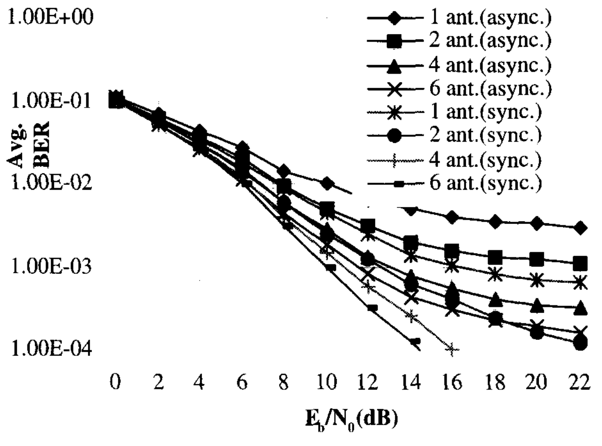

Fig. 3. Avg. BER performance of MC-CDMA uplink (8 users; spatially correlated case).

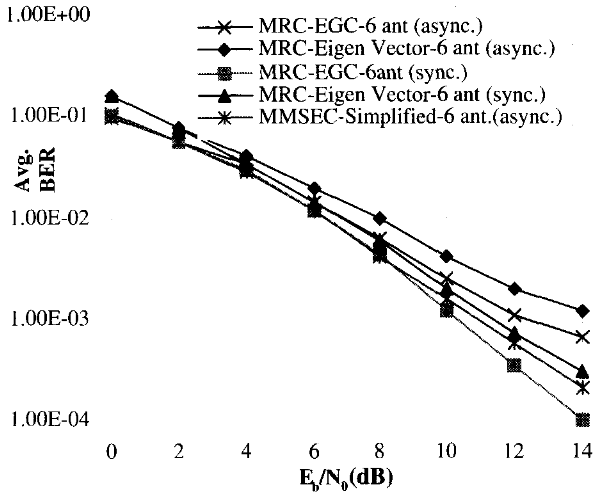

Fig. 4. Comparison of array processing algorithms (MRC-EGC, MRC-Eigen solution, MMSEC-simplified algorithm).

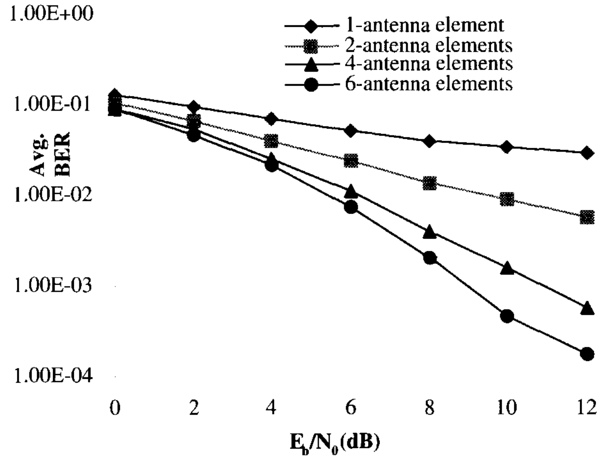

Fig. 5. Avg. BER performance of MC-CDMA uplink (8 users; 1024 kbit/s).

chronicity can be readily seen from this result. For BER of 10^{-3}, about 2 dB penalties in SNR could be observed. Obviously, the use of higher number of antenna elements enhances the performance and the interference could be suppressed effectively. Fig. 4 shows the performance with the different array processing algorithms studied. Here, MRC/MMSEC-EGC means MRC/MMSEC is used for frequency diversity combining in MC-CDMA receiver module and EGC is used to combine the outputs from each element. The effect of estimation of correlation matrices could be seen with comparison to simplified algorithm. This is one of the problems in using Eigen solutions for array response vector estimation. Simple EGC has produced a good result because of the simulation configuration adopted. It can be seen that the performance with simplified algorithm is better for the slow fading situation. It verifies that the simplified algorithm used is able to estimate the steering vector with comparable accuracy to that produced by Eigen analysis. However, the simplified algorithm used here may not be suitable for the use in fast fading and fast DOA changing environment. The convergence behavior of this algorithm is similar to normal LMS type algorithm and it depends on the step size parameter μ.

For spatially independent case, antenna array is simulated for the configuration where the elements are separated large enough to ensure independent spatial fading among antenna elements. The spatial fading correlation between two antenna elements depends on the angle spread and mean angle of arrival. Since the mean DOA is assumed to be zero, independent fading can be achieved with antenna element spacing of more than 5λ and relatively low correlation can be achieved with even 2λ [12]. For this particular simulation scenario, DOA factors could be excluded so that one to one independent channels could be formed.

B. Handling Variable Data Rates

Multicarrier assignment techniques can be used to handle variable bit rates and to handle the different traffic categories in the system. To study the effect on the performance of the system, we simulated the system with bit rate of 1024 kbits/s. For example, to handle this data rate we assign 16 subcarriers to transmit a data symbol to maintain the same bandwidth. This is analogous to the assignment of variable spreading factor in W-CDMA systems. Assigning 16-subcarrier diversity to carry a data symbol means the spreading factor of 16, where by frequency diversity is reduced to half compared to the previous case. However, for the lower data rate the small bandwidth compared to the high data rate could be used. For this case, the spreading factor could be kept same and the total number of subcarriers in the system could be reduced to half.

Fig. 5 shows the performance with 8 asynchronous users with 1024 kbits/s data rate and MRC frequency diversity combining. It can be observed that the system performance is degraded with higher data rate. However, with the higher number of antenna elements the difference in the performance is reduced. This result once again justifies the use of antenna array assisted MC-CDMA in handling variable rate data traffic.

C. Performance in Correlated Channel

Transmission of high data rate over multipath fading channel is prone to have correlated fading over the span of large number of symbols, especially in slowly fading channel for normal

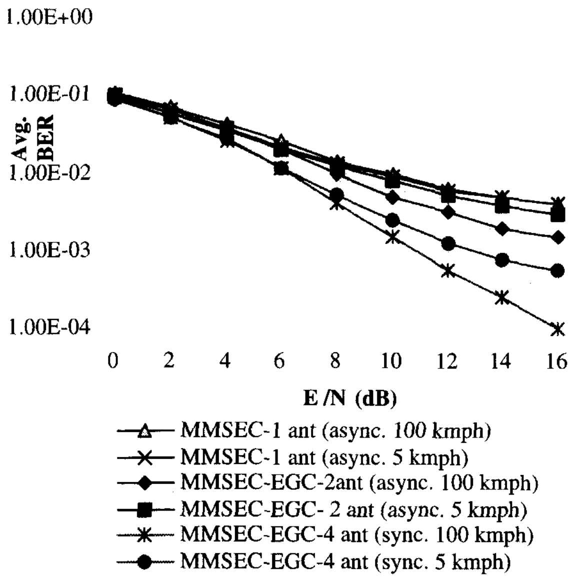

Fig. 6. Avg. BER performance of MC-CDMA uplink with antenna array in correlated channel.

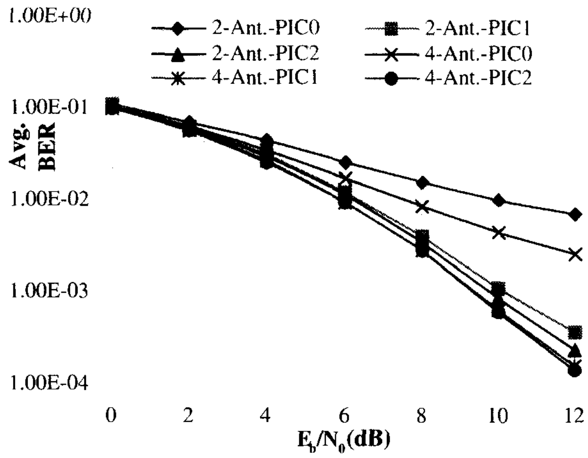

Fig. 7. BER performance of asynchronous MC-CDMA uplink with antenna array and MUD (12 users; spatially correlated case).

range of mobile speeds. Only the spatially correlated case is considered. Fig. 9 shows that the performance is similar in case of single antenna use. However, with the use of two antenna elements, there is virtually no improvement in the performance in case of 5 km/h as the channel is correlated more. The effect of the use of antenna array seems insignificant for highly correlated channel and the asynchronous MC-CDMA system. The performance is better for synchronous case but still worse than that for 100 kmph case. This infers to taking the channel correlation in to consideration in the system design. Theoretically, use of channel interleaving of sufficient depth at the transmitter and deinterleaver of the corresponding size at the receiver in conjunction with the use of error correction codes is a way to solve this problem. However, for uncoded system the performance is worse. The detailed analysis of this case in conjunction with error correcting codes is out of the scope of this paper.

D. Performance with Antenna Array and MUD

In this section the use of subtractive interference cancellation techniques along with antenna arrays are discussed based on the simulation results. The principles of these detectors are the regeneration of interference seen by each user and subtract them out from the received signal. These detectors are often implemented in multiple stages. Here, use of so called brute force parallel interference cancellation detectors is discussed. For large number of users in the system creating a large MAI and with the constraint of using large number of antenna elements as discussed in the previous section, multiuser detection is inevitable to achieve the required BER.

Fig. 7–9 assess the performance in spatially correlated as well as spatially independent cases. Maximum of 12 simultaneous users are simulated with two stages of PIC. First stage is denoted by PIC0 and later is by PIC1 and PIC2. Here PIC0 means there is no interference cancellation. Fig. 7 shows that the performance of the system with two and four antenna elements along with PIC are very close to each other for SNR less than 8 dB and differences could be observed for higher SNR values. BER of 10-3can be achieved at SNR of 10 dB in case of 2 antenna elements and two stage of PIC, where as same BER can be achieved at SNR of 9.2 dB and 4 antenna elements and one stage of PIC. The difference becomes higher for higher number of users. For higher number of users there would be improvements with successive stages of PIC, which is not prevalent in this result. This example shows the power of interference cancellation and infers to the necessity of joint system analysis with antenna array and MUD as an answer to how many antenna elements to use and when the MUD is necessary. Similarly, Fig. 8 shows the performance of the system with 8 asynchronous users and different number of antenna elements in spatially independent fading situation. It shows that use of PIC one stage along with 6 antenna elements in the array has performance very close to single user with six antenna elements. To realize the performance improvements more, simulation results for 12 users are also presented in Fig. 9. A dramatic improvement in BER by the use of just two antenna elements and one stage of PIC can be seen in this figure. It shows that this is very close to the performance with four antenna elements. Similarly the performance with four antenna elements and one stage of PIC is already close to the single user performance. It can be said that the performance difference in asynchronous and synchronous cases would also be minimized with the use of interference cancellation detectors.

The results show that there should be a joint analysis of the system using antenna array and MUD such that some kind of tradeoff between the use of number of antenna elements and use of MUD techniques could be made. The system design should take care of the system implementation complexity, algorithms computational complexity, hardware requirements and other resource constraints.

V. CONCLUSIONS

In this paper, performance of the MC-CDMA uplink system with antenna array and multiuser detection in frequency selective relatively slow fading Rayleigh fading channel is presented.

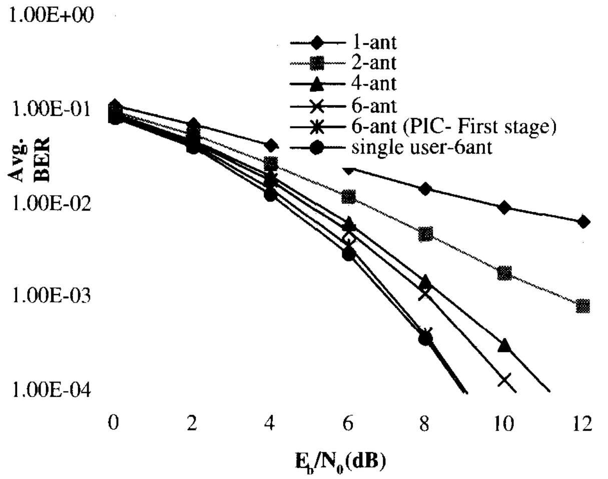

Fig. 8. Avg. BER performance of the async. MC-CDMA system with antenna array and MUD (8 users; spatially independent case).

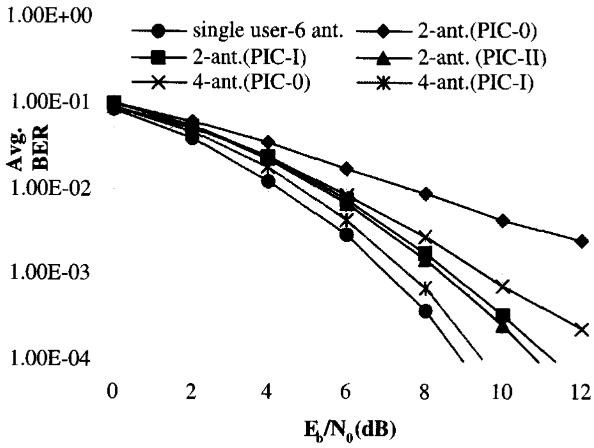

Fig. 9. Avg. BER performance of the async. MC-CDMA system with antenna array and MUD (12 users; spatially independent case).

The performance enhancement with the use of antenna array and MUD techniques is shown to be significant. A simplified algorithm to overcome the difficulty in implementing Eigen analysis methods is used and the performance is shown to be comparable. The effect of interelement separation of antenna elements is important one to be considered. The performance degradation due to variable data rates is effectively handled with the use of antenna arrays. The effect of channel correlation to the system performance with antenna array is shown to be significant. The necessity of joint analysis of channel correlation, antenna array processing and multiuser detection is highlighted.

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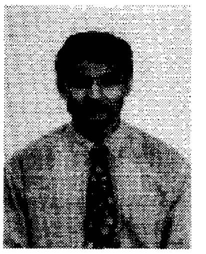

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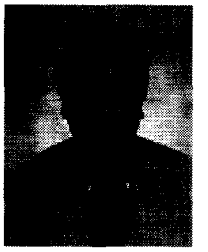

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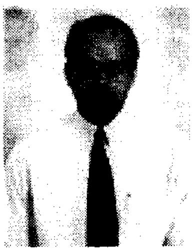

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