Simulation of the Performance of Smart Antennas in the Reverse Link of CDMA System

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***Abstract* — Spatial filtering, using adaptive or smart antennas, has emerged as a promising technique for improvement of spectral efficiency of future wireless communications systems, especially with regard to the reverse data transmission link. In this paper we present simulation results obtained for the reverse link of CDMA system with smart antenna technologies assuming perfect adaptation. Comparisons, in terms of BER performance, for different numbers of active users and a varying number of elements in an adaptive linear array are presented. The impact of different channel profiles on mean BER is also assessed.**

I. INTRODUCTION

An application of traditional array antennas in conjunction with suitable signal processing and tracking algorithms are currently receiving considerable attention as a means of increasing the spectral efficiency of cellular communication systems [1]. Particular interest in such adaptive or smart antenna systems has been shown with regard to Code Division Multiple Access (CDMA). The reason is that the third generation cellular networks, e.g. cdma2000 in North America and Wideband CDMA (W-CDMA in Europe and Japan, are based on CDMA. The inclusion of smart antennas in these CDMA systems can have a considerable impact on their evolution.

In CDMA systems, all users communicate simultaneously in the same frequency band and hence Multiple Access Interference (MAI) is a major cause of transmission impairment. Additionally, the ever present multipath fading significantly degrades the uplink (or reverse link) performance. Smart array antennas are able to reduce inter-cell interference by pointing the main beam in the direction of the desired user and by minimizing side lobes towards other users. This ability leads to increased system capacity [2].

An exact analysis of the performance of existing and future CDMA systems is difficult even when non-adaptive antennas are assumed. The objective of this paper is to develop a simulation model, which can serve as a benchmark for the analysis of different smart antenna algorithms.

In order to test the validity of the developed model, first we simulate the conventional (single) antenna system for which theoretical results are available. After confirming its validity, the model is then used to generate results for multi-antenna situations. In this case, the smart antenna combining strategy as proposed by Song et. al. [3] is applied.

The paper is organized as follows. In Section II, we present the system and channel models. Section III discusses the simulation methodology and assumptions involved in the presented work. Section IV shows the simulation results along with a discussion of the results. Finally, Section V presents the conclusions.

II. SYSTEM AND CHANNEL MODEL

The block diagram of the mobile transmitter of the CDMA system is shown in Fig. 1 and follows specifications of the IS-95 CDMA reverse link [4]. For simplicity, we ignore the convolutional encoder and interleaver. In practice, channel coding is an essential component of CDMA systems.

Let K denote the number of users in the system. The transmitted signal $s_k(t)$ of the kth user can be written as

$$s_k(t) = \Re\{[W^h(t)a^k(t)a_I(t) + jW^h(t-T_o)a^k(t-T_o)a_Q(t-T_o)]e^{-j\omega_c t}\} \quad (1)$$

where $W^h(t)$ is the hth Walsh function, $a_I(t)$ is the In-phase (I) channel spreading sequence, $a_Q(t)$ is the Quadrature (Q) channel spreading sequence, $a^k(t)$ is the kth user long code sequence, T_o is the half chip offset time, $\omega_c = 2\pi f_c$ and f_c is the carrier frequency. The transmitted power of each user is assumed to be of one unit.

We consider a Rayleigh fading channel. The complex baseband impulse response of the channel for the kth user is given by

$$h^k(t) = \sum_{l=1}^{L^k} \alpha_l^k e^{-j\phi_l^k} \delta(t-\tau_l^k) \quad (2)$$

where $\delta(\cdot)$ is the Dirac delta function, l is the multipath index, L^k is the number of resolvable multipaths of the kth user and $\{\alpha_l^k\}_{l=1}^{L^k}$, $\{\phi_l^k\}_{l=1}^{L^k}$ and $\{\tau_l^k\}_{l=1}^{L^k}$ are the random channel amplitude, phases and delays.

The base station employs a uniform linear array of N omni-directional antenna elements with a constant inter-element spacing d (N being much less than number of users K, excluding the possibility of purposely forming nulls towards interfering users). Such an antenna system is a realistic assumption for a CDMA base station. Other array geometries (such as a circular array) are not considered at the moment. The individual elements are assumed to be identical and independent of each other i.e. mutual coupling between the elements is ignored. As shown in our other work [5], ignoring mutual coupling effects does not significantly influence the interference rejection capabilities of such type of arrays, especially for the element spacing in the range of half wavelength ($\lambda/2$) spacing, which is typically used in these arrays.

Assuming half wavelength spacing and that the Direction Of Arrival (DOA) of users θ is measured from the broadside of the array, the $N \times 1$ antenna array response vector can be written as [6]

$$\mathbf{a}(\theta) = [1 \quad e^{-j\pi \sin\theta} \quad \cdots \quad e^{-j(N-1)\pi \sin\theta}]^T \tag{3}$$

where $(\cdot)^T$ denotes transpose operation.

The received signal at the nth antenna element can be written as

$$r_n(t) = \sum_{k=1}^{K} \sum_{l=1}^{L} s_k(t - \Gamma^k - \tau_l^k) \alpha_l^k(t) e^{-j\phi_l^k(t)} e^{-j(n-1)\pi \sin\theta_l^k(t)} + n_n(t) \tag{4}$$

where n is the antenna index, Γ^k is the random delay of the kth user due to the asynchronous nature of the CDMA system and $n_n(t)$ is Additive White Gaussian Noise at the nth antenna.

The block diagram of the receiver with the smart antenna processor is shown in Fig 2. Here, we assume that perfect Signal to Noise Ratio (SNR) beamforming is performed. Thus the weight vector is assumed to match perfectly with the array response vector i.e. we do not consider the effects of imperfect adaptation. Thus $\mathbf{w}$ is given by [7]

$$\mathbf{w} = \frac{1}{N}\mathbf{a}(\theta_1) \tag{5}$$

where $\mathbf{a}(\theta_1)$ is the array steering vector towards the desired user. Although the true array response vector would not be known in practice, the assumed beamforming provides an upper bound on the system performance.

Using (4) we can work out expressions for the decision statistic and the bit error rate. For the conventional case of a single antenna and a single user with L Rayleigh fading multipaths, the mean BER is given as [4]

$$\overline{P_b(e)} = \frac{M/2}{M-1} \sum_{m=1}^{M-1} \binom{M-1}{m} \frac{(-1)^{m+1}}{(1+m+m\rho)^L} \cdots \sum_{l=0}^{m(L-1)} \Psi_l(m) \binom{L+l-1}{l} \left(\frac{1+\rho}{1+m+m\rho}\right)^l \tag{6}$$

where $M = 64$, $K = \log_2(M)$, $\rho = (K/L)(E_b/N_o)$ and $\Psi_l(m)$ are recursive coefficients defined in [4, Ch. 9].

III. SIMULATION METHODOLOGY

Based on the above described model, a computer program in Matlab for simulating performances of the system with the smart antenna processor has been developed. In the model, the spreading sequences are generated using the generator polynomials as specified in the IS-95 standard [4]. The random number generators that are used are initialized to the same state for each E_b/N_o. The DOA angles from the users are assumed independent of each other. The initial DOA of the paths is chosen arbitrarily between -90° and 90° and then increased or decreased linearly with 0.01° per snapshot rate to simulate a movement of each mobile in an azimuth direction. The snapshot rate (smart antenna weight vector adaptation rate) is assumed equal to Walsh symbol rate.

The random asynchronous user delay is assumed to be uniformly distributed over the interval $[0, T_c]$, where T_c is the chip period. An over-sampling factor of four is used (i.e. there are 4 samples/chip). The random carrier phases are assumed to be uniformly distributed in the range $[0, 2\pi]$. To test the model and the associated computer algorithm, three different channel scenarios are considered: (i) Rayleigh faded single path in Additive White Gaussian Noise (AWGN) (ii) two equal strength Rayleigh fading multipaths in AWGN and (iii) two unequal strength Rayleigh fading multipaths (of relative strengths 0dB and -10 dB) in AWGN. The constant path delay is $\tau = 5T_c$ and the maximum Doppler frequency considered is $f_D = 100$ Hz in all cases. This corresponds to a fast vehicular channel. Zero angle spread is assumed for simplicity. In addition the total average multipath power is normalized to one for each user. Also all the signals from the K users arrive at the N antennas with the same power level i.e. an ideal power control scenario is assumed.

The figure of merit used here is the mean Bit Error Rate (BER). This is the mean that is taken over the ensemble of channel Rayleigh fading parameters and the Direction of Arrival angles. It is estimated using Monte Carlo simulation methodology [8]. A minimum of 10,000 frames are assumed to be received in all simulation runs. This allows for a reliable estimate of the true mean BER to be obtained.

IV. Results And Discussion

Fig. 3 shows the comparison of the simulated and theoretical plots (from (6)) of mean BER versus E_b/N_o for the conventional cases. There is good agreement between the simulated and theoretical values, which confirms the validity of the simulation model.

Fig. 4 shows the plot of mean BER versus E_b/N_o for the case of a single user for different number of antennas and multipaths. As seen in Fig.4, the performance of the CDMA system improves as the number of antennas and the number of multipaths increases.

Table I shows the E_b/N_o required to achieve a specific mean BER (10^{-2} and 10^{-3}) for the simulation scenario of Fig. 4. The Table illustrates the performance gain in E_b/N_o due to the use of smart antenna combining. We see that the gain in E_b/N_o follows the well known linear relationship in array signal processing of Signal to Noise Ratio (SNR) vs. N i.e. the reduction in E_b/N_o is equal to $10\log_{10}(N)$ [7]. This improvement in E_b/N_o translates to an increase in system capacity or coverage or both.

Fig. 5 shows the plot of average BER versus number of users for the case of $N = 4$ element linear array and $L = 2$ Rayleigh faded multipaths having equal and unequal amplitudes respectively with E_b/N_o=10dB. The performance improvement of the smart antenna scheme is again evident from the figure. The degradation in performance for the case of two unequal strength paths may be due to the fact that IS-95 CDMA reverse link uses non-coherent detection with equal gain combining. The Rake finger output corresponding to the strong multipath (relative strength 0 dB) dominates over that of the weak path (relative strength -10dB), which smears out as the interference level increases. Thus the performance in this case is between the cases of $L = 1$ and $L = 2$ (equal strength) multipaths and asymptotically tends towards the $L = 1$ curve, as interference becomes more dominant with increase in the number of users.

V. Conclusion

In this paper, we have reported on a model and the associated computer software for quantitative assessment of performance of a smart antenna system in CDMA multi-user situations. Using the developed model, the performance of smart antenna system has been evaluated in a multipath fading environment. Simulation results have been presented for the following two cases:- (i) conventional case of single antenna to check the validity of the developed model by comparing the theory with the simulated results, and (ii) smart antenna processing using linear array antennas in a Rayleigh fading multipath environment in AWGN. Performance improvement of multiple antennas in terms of E_b/N_o has been shown and found to agree with theoretical value of $10\log_{10}(N)$. It has been found that the channel profile has an effect on the system performance. The reported results assume perfect adaptation. They may be used as a benchmark for comparing the performance of various smart antenna algorithms.

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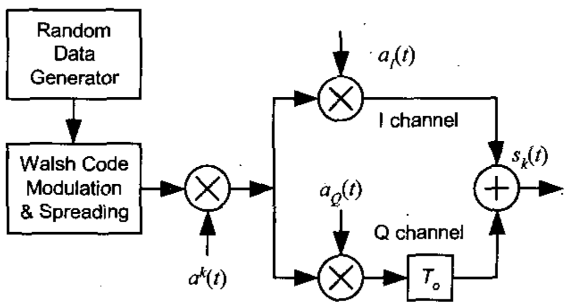

Fig. 1. The block diagram of the IS-95 CDMA transmitter.

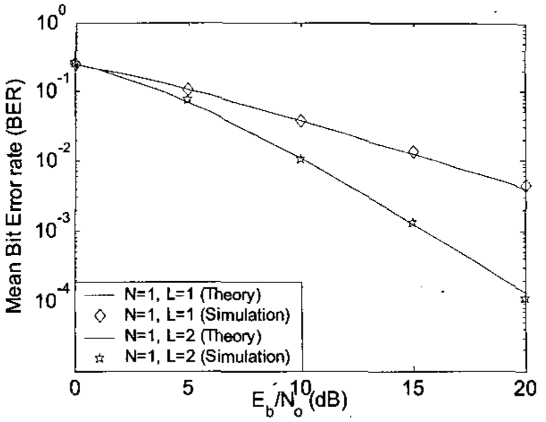

Fig. 3. The plots of BER versus E_b/N_o for the conventional case of a single user ($K = 1$) for a single antenna ($N = 1$) and $L = 1, 2$ Rayleigh faded multipaths respectively.

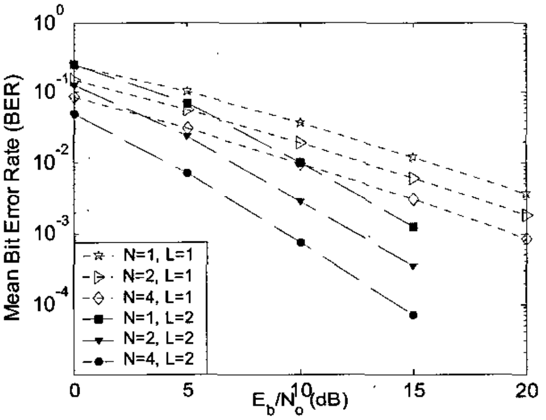

Fig. 4. The plots of mean BER versus E_b/N_o for the case of a single user ($K = 1$) for different number of antennas (N) and Rayleigh faded multipaths (L).

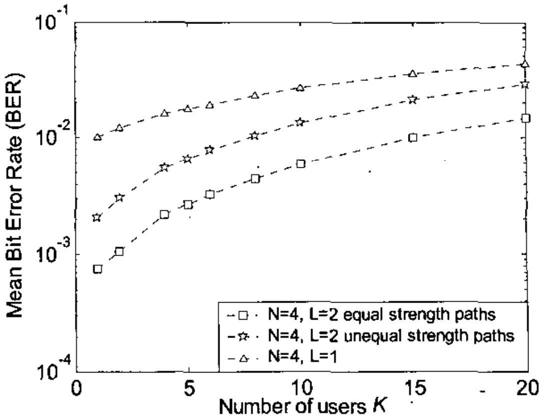

Fig. 5. The plot of mean BER versus number of users K for the case of $N = 4$ element linear array and $L = 2$ Rayleigh faded multipaths/user with $E_b/N_o = 10$ dB.

TABLE I

RATIO OF BIT ENERGY TO NOISE DENSITY (E_B/N_O) REQUIRED TO ACHIEVE SPECIFIED PERFORMANCE IN TERMS OF BIT ERROR RATE FOR A SINGLE USER.

E_b/N_o (dB) required to achieve	***BER 10^{-2}***	***BER 10^{-3}***
N=1, L=1 (Theory)	15.96	26.01
N=2, L=1	12.86	22.63
N=4, L=1	9.83	19.64
N=1, L=2 (Theory)	10.18	15.51
N=2, L=2	7.16	12.44
N=4, L=2	4.16	9.35

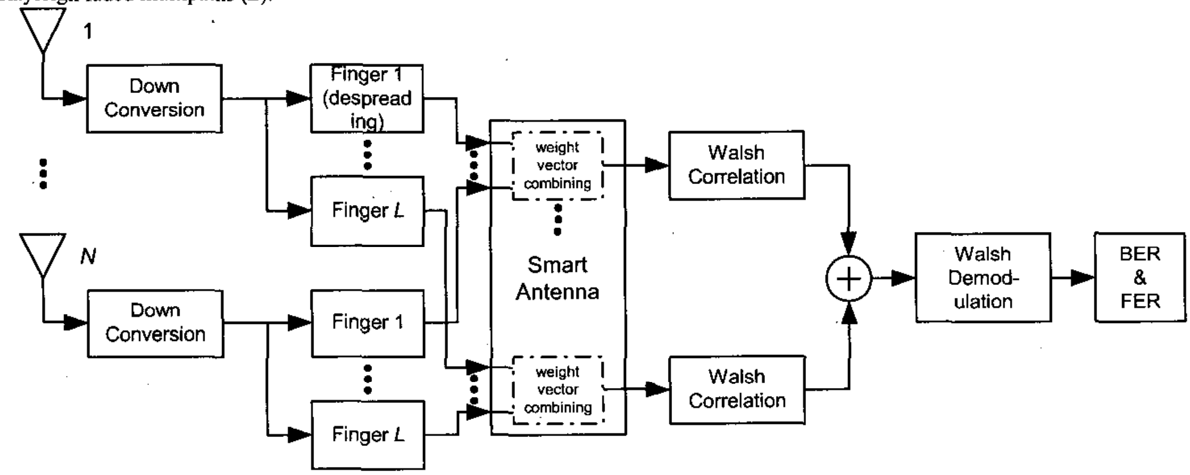

Fig. 2. The block diagram of the receiver incorporating the smart antenna for the CDMA reverse link.