Directional Antenna Arrays in CDMA ST-Rake Receiving

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Introduction

Wireless communication has gained tremendous attention in recent years. The multi-user Rake receiver [1] was developed to reject multiple access interference (MAI) while exploiting the multipath diversity. In [2], the benefits of antenna arrays and the space-time (ST) receiver were presented. Reduced-dimension techniques were developed in [3] to ease computation and to estimate time-varying channels more rapidly. The above papers yielded great results in multiuser wireless communication but gave little attention to the effect of antenna directivity and the structure of the antenna arrays. In this paper, the effects of directive antennas and the array structure on ST-Rake receivers in direct-sequence CDMA (DS-CDMA) communication are studied. Conformal arrays with individual directional antennas are proposed. Using these arrays, the full-dimension ST adaptive receiver can be divided into multiple reduced-dimension receivers; therefore, computational requirements can be significantly reduced and fewer training data are needed to estimate the environment. In this paper, we demonstrate optimum system performance of directive antennas assuming known interference and noise statistics.

Data Model

Let $\mathbf{r}(t)$ be an M-dimensional baseband vector received by the M antennas of the receiving array. Using the notations of [2], $\mathbf{r}(t)$ can be represented as

$$\mathbf{r}(t) = \sum_{k=1}^{K}\sum_{l=1}^{L_k}\sqrt{P_k}\beta_k^l\mathbf{g}(\theta_k^l)\sum_{n=-\infty}^{\infty}\{b_k(n)c_k(t-nT_b-\tau_k^l)\}+\mathbf{n}(t) \qquad (1)$$

where K is the number of users, L_k, $b_k(n)$, $c_k(t)$ are the number of multipath components, the n^{th} symbol value, and the spreading waveform respectively for the k^{th} user. In this paper $\mathbf{g}(\theta)$ is the Hadamard product of antenna pattern $\mathbf{f}(\theta)$ and the array response vector $\mathbf{a}(\theta)$. P_k is the power of user k and β_k^l, θ_k^l, τ_k^l are the complex path gain, angle of arrival (AOA), and delay, respectively, for the l^{th} path of the k^{th} user. It is assumed that each user is assigned a code of N_c chips of duration T_c such that $T_b = N_cT_c$. Also in (1), $\mathbf{n}(t)$ is the M-dimensional vector of circularly complex Gaussian white noise.

ST Rake Receiver and Optimum Beamforming

In this paper, we study the optimum signal to interference and noise ratio (SINR) performance of the ST receiver under known interference and noise statistics. This allows us to characterize potential performance independently of the receiver implementation. We employ a post-despread Rake receiver to collect the multipath

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signals. We assume the signal of interest (SOI) is the first user. The sampled output with interval T_s is

$$\mathbf{y}(q) = \sum_{k=1}^{K}\sum_{l=1}^{L_k} \sqrt{P_k}\beta_k^l[\mathbf{g}(\theta_k^l)] \sum_{n=-\infty}^{\infty} \{b_k(n)R_{k,1}(qT_s - nT_b - \tau_k^l)\} + \mathbf{n}_y(t) \quad (2)$$

where $R_{k,1}(t)$ is the cross-correlation between the spreading codes of the desired and k^{th} user at a lag of t and q represents the q^{th} *finger*. Let Q be the number of *fingers* collected by the receiver. For the purpose of further processing, these data are formed into an MQ-dimensional space-time snapshot data vector

$$\mathbf{y}_{st} = [y_1(0), \cdots, y_1(Q-1), \cdots, y_M(Q-1)]^T \quad (3)$$

where $(\cdot)^T$ denotes the transpose operation and $y_m(q)$ is the q^{th} time sample of the m^{th} spatial channel. In this paper, we use output SINR as our performance metric. The optimum output (in terms of average SINR) is obtained by

$$y_o = \mathbf{w}^H \mathbf{y}_{st} \quad ; \quad \mathbf{w} = \mathbf{R}_{I+N}^{-1} \mathbf{y}_{st} \quad (4)$$

where $(\cdot)^H$ denotes the conjugate transpose operation and $\mathbf{w}$ is the optimum space-time filter. In (4), $\mathbf{R}_{I+N}$ is the interference covariance matrix due to both white noise and undesired users. For uncorrelated user signals and noise, $\mathbf{R}_{I+N} = \mathbf{R}_I + \mathbf{R}_N$.

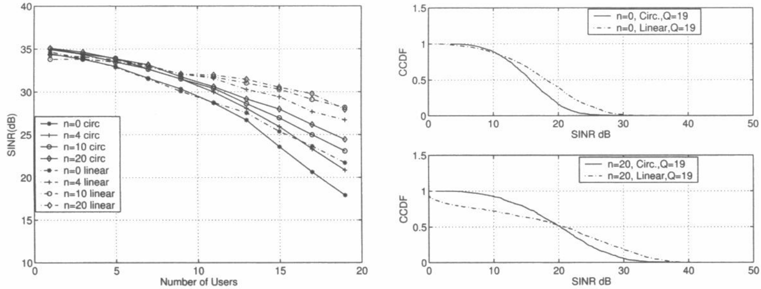
Numerical Simulation Results

In our simulations, we use two array configurations: linear and circular. We employ omni-directional antennas and antennas with power pattern $\cos^n(\theta)$ where n is an integer that controls directivity. For the linear array, the power pattern is two sided. We set n to 0, 4, 10, and 20, and for each n, the power pattern is normalized to ensure the same effective isotropic radiated power. The length of the linear array and the diameter of the circular array are both equal to 3.5 wavelengths. Each array has eight antennas. For the linear array, the eight antennas are uniformly spaced and their maximum gain is in the directions normal to the array. The eight antennas of the circular array are uniformly placed on a circle, and their maximum radiation is focused outward from the array center.

The modified Saleh-Valenzuela (SV) multipath propagation model [4] is selected as our channel model. The parameters used in the simulation are set to $\Gamma = 10ns$, $\gamma = 2ns$, $1/\Lambda = 25ns$, $1/\lambda = 2ns$, and $\sigma = 26°$.

All signals are BPSK modulated and spread with Gold codes of length 127. The power of the SOI is set to one and the powers of interfering users are Rayleigh distributed with a mean of one; therefore; the near-far condition can sometimes be severe. The input signal-to-noise-ratio (SNR) is 15 dB. It is also assumed that the Rake receiver captures 20 fingers. The number of users, K, changes from 1 to 19. The output SINR is obtained by averaging 1000 Monte-Carlo runs.

Fig. 1 shows the performances of the linear array and the circular array. It can be seen that when the antenna elements are isotropic, both the averaged output SINR



(a) SINR vs Number of Users

(b) SINR CCDF for 19 users

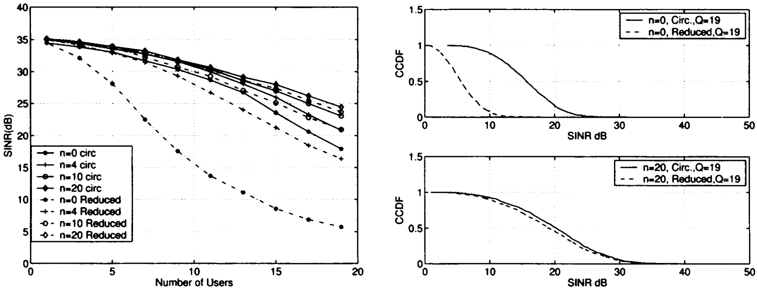
Figure 1: Performance of Circular Array VS Linear Array

and the complementary cumulative distribution function (CCDF) of the output SINR of the linear array are similar to (thought a bit better than) those of the circular array. For the linear array, antenna directivity results in higher average SINR but worse CCDF. This is somewhat expected. In the circular array, the SOI can be picked up by several antennas for any AOA. Therefore, the performance differs little to the omni-directional case. For the linear array, the directivity results in a narrower field of view. SOI's in the field of view will have high SINR, but other angles will have low SINR.

Reduced-Dimension Receiver

The results above demonstrate that the circular array can perform very well in a ST Rake receiver. Here, for the purpose of easing computation and to train the receiver more rapidly, we propose a reduced-dimension receiving structure that can reduce dimension efficiently with small performance loss. Due to the directivity of the antenna elements , only adjacent antennas are closely correlated. Based on this property, reduced dimension receiving can be done by dividing the full dimension array into several sub-arrays.

Fig. 2 shows the simulation results for the reduced-dimension receiver compared with the results for the full-dimension receiver. The figures demonstrate that with omni-directional antennas, the full-dimension receiver outperforms the reduced-dimension receiver. This is because the architecture of the reduced-dimension receiver does not match the correlation structure observed by a system with omni-directional antennas. However, as antenna elements become more directive, the performance of the reduced-dimension receiver approaches the performance of the ideal, full-dimension receiver.



(a) SINR vs Number of Users

(b) SINR CCDF for 19 users

Figure 2: Performance of Circ. Array VS Reduced Dim. Circ. Array

CONCLUSION

Simulation results show that directive antennas can be applied in a ST-Rake receiver with small performance differences in both average SINR and SINR distribution. With directive antennas in a conformal arrangement, the interference covariance matrix will be more "locally" correlated than that of the omni-directional antennas. The full-dimension receiving array can be divided into several reduced-dimension sub-arrays based on this unique property of the interference covariance matrix. The reduced-dimension receiver loses little performance but will have a great advantage in computation savings compared to the full-dimension receiver. Furthermore, in a time-varying environment, the reduced-dimension receiver will outperform the full-dimension receiver due to the reduced data required for covariance training.

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