Enhanced CDMA Transmission with Multiple Antennas and Joint Power Control*

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Abstract — We consider downlink transmission at high data rates in a multi-cellular code-division multiple-access (CDMA) network where signals are directed to a mobile station (MS) from antennas located at the same or different base stations (BSs). All antennas use different pilots and transmit data to individual MSs with specified powers when selected to do so. Two sources of error are found to degrade channel identification and performance: channel noise and channel variation due to the power control delay. First, we introduce a modified spatio-temporal array-receiver (STAR) that uses both the pilot and the data signals to reduce the channel identification error. Second, we formulate a power control algorithm for the signal powers transmitted by the participating antennas based on predicting the channel response variations over the power control interval. Significant performance gains are found to result from use of the techniques independently and collectively.

I. Introduction

Transmission at high data rates is becoming increasingly important in CDMA networks. Such transmissions require wide spectrum bandwidth and reduce user capacity resulting in increased per-user bandwidth costs. To increase capacity, we consider transmit antenna selection with joint power control on the forward link [1]. Antennas transmit constant pilot power and are selected for non-zero signal transmission directed at individual MSs. The total power transmitted to any mobile is divided among the active antennas so as to optimize the signal-to-interference ratio (SIR) at each MS. We have previously shown that in hexagonal cells, two of six transmit antenna selection is the best practical choice for transmission over multiple antennas on channels with fast Doppler [1]. However, several open problems remain in designing such a system. First, the relatively high power of the broadcast pilot signal degrades the system capacity on the forward link. Second, the high data rate transmission requires high signal power resulting in increased interference and degrading channel identification. Third, time delay of the closed-loop power control results in channel identification errors due to channel variation. To reduce the power control error, we introduce short-term prediction. Long-range prediction [2] requires explicit knowledge of the Doppler frequency and is computationally quite complex.

In this paper we consider two approaches to mitigate the effect of channel identification errors. The first approach to reduce both pilot power and the channel identification error due to channel noise is a modified spatio-temporal array-receiver (STAR) [3] that combines both pilot and data signals by MRC at each MS receiver. The resulting signal is used to track and estimate the channel response by a fast LMS-type tracking procedure. The second approach reduces the power control error resulting from the time delay by introducing a piecewise-linear power control technique. We propose a simple technique to predict the channel response over the time delay of the power control loop, which improves the closed-loop power control performance with low complexity.

II. Background of Multiple Antenna Selection

The transmit antenna selection system with joint power control is exploited to transmit the same information on one or more selected active antennas at multiple BSs of a CDMA network. As reported in [1], this system achieves a significant capacity gain. With fast selection, selecting two active antennas out of the six available is the best choice on a fast Doppler channel. In this section, first, we describe the system model. Second, we provide an overview of multiple antenna selection with joint power control. Finally, we introduce the main points to be dealt with in this paper.

A. System Model

We assume that the entire network consists of seven hexagonal cells with the radius R, and BSs are located at three corners of each cell. Each BS employs M antennas whose transmitted signals are assumed to arrive at the MS uncorrelated. Here, we consider a sectorization model as in IS-95 (i.e., 120° sectorization). We further assume that the transmit antenna selection is controlled by the nearest three BSs based on the channel conditions as determined by the received pilot signals. The signal with controlled power is transmitted to each MS by K active antennas simultaneously, with different PN sequences, where $K \leq 3M$, as illustrated in Fig. 1. The active antennas are located either at the same BS or at different BSs. Multiple antennas from the same BS will be activated when the MS is near that BS. Multiple antennas from different BSs will be activated when the MS is far from all the BSs.

B. Transmit Antenna Selection

The transmit antenna selection system as proposed in [1] can be briefly related as follows.

The channel estimator estimates the instantaneous channel response vectors $\hat{\underline{\mathrm{H}}}_{k,i}(n)$ for the kth transmit antenna and the ith receive MS by an LMS tracking

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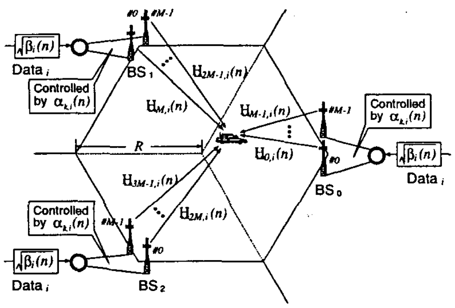

Figure 1: The model of multiple active antenna transmission with joint power control on the forward link.

loop. The resulting vectors $\hat{\underline{\mathrm{H}}}_{k,i}(n)$ are averaged over n_{as} symbols and n_{al} symbols so as to obtain short-term and long-term fading estimate vectors, where $n_{as} \ll n_{al}$. Then by reordering the resulting short-term fading vectors $\hat{\mathbf{H}}_{k,i}(n)$ according to the *norm* values of the long-term fading vectors, the channel estimate vectors $\hat{\mathbf{H}}_{k,i}(n)$ between the kth active antenna and the ith MS are determined by choosing K out of $3M$ channel vectors. The K active antennas corresponding to the K channel vectors $\hat{\mathbf{H}}_{k,i}(n)$ are selected to transmit the same data signal simultaneously.

C. *Joint Power Control*

Joint power control as proposed in [1] is exploited to achieve the optimum power allocation to multiple active transmit antennas. This power control achieves two objectives; one to control $\alpha_{k,i}^2(n)$, the relative powers transmitted on each active antenna serving the same MS, and the other to control $\beta_i(n)$ and allocate the appropriate total power across all antennas serving each MS. The former guarantees that each MS receives sufficient power, and the latter ensures that all MSs experience the same SIR level.

D. *Identification Errors*

The estimation of two vectors, $\hat{\mathbf{H}}_{k,i}(n)$ and $\hat{\underline{\mathrm{H}}}_{k,i}(n)$, that mainly affect the system performance, is made by the ith MS receiver. For the vector $\hat{\mathbf{H}}_{k,i}(n)$, since we average the channel response vector $\hat{\underline{\mathrm{H}}}_{k,i}(n)$ over n_{as} symbols, the effect of channel noise can be neglected while the time delay due to the closed-loop power control may cause a major identification error. For the vector $\hat{\underline{\mathrm{H}}}_{k,i}(n)$, comparatively, since the beamforming weight vector $\hat{\underline{\mathrm{H}}}_{k,i}(n)$ are functions of the instantaneous channel response, they are primarily affected by channel noise. In contrast, their averaged values $\hat{\mathbf{H}}_{k,i}(n)$ are less sensitive to channel noise and are more impacted by the time delay due to channel variations during the power control interval.

III. Modified STAR Receiver

To estimate the channel response on the forward link as discussed in [1], we employ a scheme in which each antenna transmits a pilot signal whose strength is estimated by each MS with the aid of a fast LMS loop. This scheme requires a large fraction of total transmission power to be devoted to pilots and reduces the system capacity. To avoid such capacity loss, a promising approach using the STAR receiver [3, 4] can be used to estimate the channel response. The STAR receiver performs a blind identification of the channel using knowledge of the desired data signal only and tracks it in space and time with low complexity.

In this section, we consider a scheme employing STAR receiver with pilot transmission. This scheme combines the pilot and desired data signals by MRC at each MS to improve the channel identification and reduce the required pilot power. We term this scheme the modified STAR receiver because it achieves the same goal as the original STAR with improved channel identification for active antennas.

A. *Transmit Pilot and Data Signals*

The pilot signal is broadcasted from each transmit antenna to all MSs to allow for accurate tracking. The pilot transmission enables estimation of the long-term fading signal and assists multiple antenna selection [1]. This selection allows antennas to be active with respect to particular MS. The active antennas transmit pilot and data directed to that MS.

With a modified STAR receiver, data signal transmission achieves two objectives. First, it carries the desired data signal from a BS to its served MS. Second, it can be used to identify the channel response. Here, we focus on the discussion of channel identification using data signal for high data rate transmission.

B. *Despread Pilot and Data Signals*

In this section, we discuss the despread pilot and data signals, and the MRC combining with modified STAR receiver. We formulate these two signals, and mathematically show how the modified STAR receiver offers a better channel identification.

1. *Despread Pilot*

Each antenna transmits a pilot signal received by each MS and despread with the aid of the corresponding PN sequence. Thus, we obtain despread pilot signal vectors $\underline{P}_{k,i}(n)$, from the kth transmit antenna to the ith MS, as given by

$$\underline{P}_{k,i}(n) = \sqrt{\mathcal{E}_k^{(p)}} \cdot \underline{\mathrm{H}}_{k,i}(n) + \underline{\mathrm{N}}_{k,i}^{(p)}(n) \qquad (1)$$

where $\mathcal{E}_k^{(p)}$ is the pilot power transmitted by the kth antenna, $\underline{\mathrm{H}}_{k,i}(n)$ is the channel response vector between the kth antenna and the ith MS, and $\underline{\mathrm{N}}_{k,i}^{(p)}(n)$ is the interference vector received by the ith MS.

2. *Despread Data*

After despreading, we obtain the data signal vector, $\underline{D}_{k,i}(n)$, from the kth transmit antenna to the ith MS, as given by

$$\underline{D}_{k,i}(n) \;=\; \sqrt{\mathcal{E}_{k,i}^{(s)}(n)} \cdot b_i(n) \cdot \underline{\mathrm{H}}_{k,i}(n) + \underline{\mathrm{N}}_{k,i}^{(s)}(n) \qquad (2)$$

where $b_i(n)$ is the BPSK data signal of the ith MS, $\mathcal{E}_{k,i}^{(s)}(n)$ is the transmission power and $\underline{\mathrm{N}}_{k,i}^{(s)}(n)$ is the received interference vector, all for the kth transmit antenna and the ith MS.

Multiplying both sides of (2) by the BPSK data signal estimate $\hat{b}_i(n)$, we have the identification signal vectors $\underline{\hat{D}}_{k,i}(n)$

$$\underline{\hat{D}}_{k,i}(n) = \sqrt{\mathcal{E}_{k,i}^{(s)}(n)} \cdot \chi_i(n) \cdot \underline{\mathrm{H}}_{k,i}(n) + \underline{\mathrm{N}}_{k,i}^{(s)}(n) \tag{3}$$

where $\chi_i(n) = 1$ if $b_i(n) = \hat{b}_i(n)$, otherwise, $\chi_i(n) = -1$.

C. *Channel Identification with MRC*

In terms of channel identification with MRC, two vectors defined in (1) and (3) are weighted for optimum combining using MRC. If we assume the MRC weight is $\eta_{k,i}(n)$ for the kth transmit antenna and the ith MS, the combined signal $\underline{\Upsilon}_{k,i}(n)$ can be represented as

$$\underline{\Upsilon}_{k,i}(n) = \underline{P}_{k,i}(n) + \eta_{k,i}(n) \cdot \underline{\hat{D}}_{k,i}(n). \tag{4}$$

Since the vectors $\underline{P}_{k,i}(n)$ and $\underline{\hat{D}}_{k,i}(n)$ are received on the same antenna at the ith MS, the received interference powers for $\underline{\mathrm{N}}_{k,i}^{(p)}(n)$ and $\underline{\mathrm{N}}_{k,i}^{(s)}(n)$ can be assumed identical. Thus, to maximize the SIR with respect to $\eta_{k,i}(n)$, we solve for the $\eta_{k,i}(n)$ and have

$$\eta_{k,i}(n) = \chi_i(n) \cdot \sqrt{\mathcal{E}_{k,i}^{(s)}(n)/\mathcal{E}_{k}^{(p)}}. \tag{5}$$

We assume that the BS communicates the combining ratio $\eta_{k,i}(n)$ to each MS periodically.

Finally, the resulting signal vector $\underline{\Upsilon}_{k,i}(n)$ is used to track and estimate $\underline{\mathrm{H}}_{k,i}(n+1)$ by the fast LMS-type tracking procedure [3].

IV. Piecewise-Linear Power Control

The piecewise-linear power control employs channel response prediction and linear interpolation. Its objective is to mitigate the effect of power control delay without excessively increasing the power control information transmitted from each MS to the BS.

A. *Predicting the Channel Response*

A linear prediction approach was proposed by Duel-Hallen *el al* [2] to reduce the MSE between the predicted and actual channel responses, but it has a high computational complexity. The prediction scheme proposed in this paper is different from [2] and approximates the response by a polynomial function defined by

$$H(t) = \sum_{m=0}^{Q-1} \zeta_m t^{Q-m-1} \tag{6}$$

where ζ_m denotes the mth coefficient and $(Q-1)$ denotes the degree of polynomial function.

For instance as in Fig. 2, if the coefficients, $\zeta_0, \zeta_1, \cdots, \zeta_{Q-1}$, are given, we can easily calculate the estimate of actual channel response, $H(T_b n + \tau)$, by

$$\hat{H}(T_b n + \tau) = \sum_{m=0}^{Q-1} \zeta_m \cdot (T_b n + \tau)^{Q-m-1} \tag{7}$$

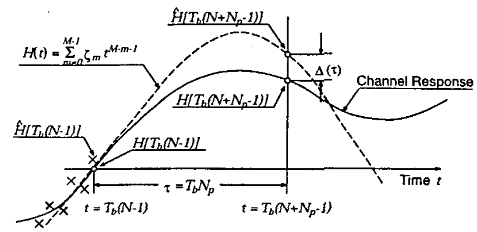

Figure 2: Pairwise observations on $(T_b n, \hat{H}(T_b n))$ constitute a scatter diagram. The relationship between $T_b n$ and $\hat{H}(T_b n)$ is approximated by a polynomial function.

where T_b is the sampling period, and in general, it can be equal to the data symbol duration.

To estimate the polynomial function with the coefficients, $\zeta_0, \zeta_1, \cdots, \zeta_{Q-1}$, we employ N previous fading samples, $\hat{H}(0), \hat{H}(T_b), \cdots, \hat{H}[T_b(N-1)]$, and calculate the MSE between the polynomial function and the previous fading samples, based on the MMSE criterion.

The proposed prediction scheme can be characterized as follows:

- It uses only a few fading samples prior to the current channel response $H(T_b n)$ to estimate the coefficients of the polynomial function. Therefore, it can be easily implemented with low computational complexity.
- It does not require estimation of the Doppler spread. However, the prediction interval τ is limited by the Doppler spread.
- It is only applicable to short-range prediction. As the prediction range increases, the MSE could be extremely large. The power control interval of 2 msec is an upper limit to the prediction interval.

B. *MMSE-Based Polynomial Function*

By using the polynomial function of degree $(Q-1)$ as defined in (6), the MSE between the polynomial function and the previous N fading samples, as illustrated in Fig. 2, is approximately given by

$$\varpi_\Delta(\zeta_0, \zeta_1, \cdots, \zeta_{Q-1}) \approx \sum_{n=0}^{N-1} \left[\sum_{m=0}^{Q-1} \zeta_m (T_b n)^{Q-m-1} - \hat{H}(T_b n) \right]^2. \tag{8}$$

To minimize the MSE, $\varpi_\Delta(\zeta_0, \zeta_1, \cdots, \zeta_{Q-1})$, with respect to ζ_m, we solve for ζ_m, that satisfies

$$\partial \varpi_\Delta(\zeta_0, \zeta_1, \cdots, \zeta_{Q-1}) / \partial \zeta_m = 0. \tag{9}$$

This yields the best $\zeta_0, \zeta_1, \cdots, \zeta_{Q-1}$, minimizing $\varpi_\Delta(\zeta_0, \zeta_1, \cdots, \zeta_{Q-1})$. Upon expanding the derivatives as in (9), and by using (8), we may obtain the optimum coefficients, ζ_m.

C. *Power Control Based on Channel Response Prediction*

The piecewise-linear power control is illustrated in Fig. 3. Based on the fading samples previous to $H(t_0)$, we first estimate the polynomial function, from which, we can predict the channel responses $H(t_1)$ at time t_1 and $H(t_2)$ at time t_2. By using such predicted channel responses $\hat{H}(t_1)$ and $\hat{H}(t_2)$, we calculate the power control factors at time t_1 and t_2, say $\gamma_j(t_1)$ and $\gamma_j(t_2)$[1], respectively, for $j = 1, 2$. Those resulting power control factors are then transmitted from each MS to its serving BS. At the BS, the power control implementation is performed by linear interpolation between the associated power control factors. The power control level for each data symbol transmission is continuously determined by the interpolated power control factor $\gamma_j(t)$, satisfying the interpolation formula

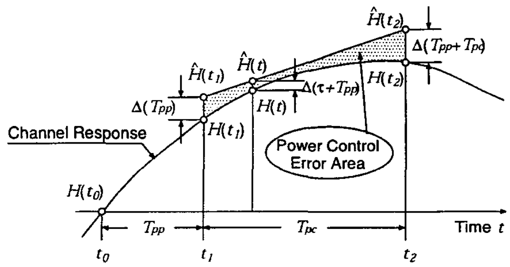

Figure 3: Piecewise-linear power control with channel response prediction.

$$\gamma_j(t) = \frac{t - t_1}{t_2 - t_1} \cdot \gamma_j(t_2) + \frac{t_2 - t}{t_2 - t_1} \cdot \gamma_j(t_1) \qquad (10)$$

where $t_1 \leq t < t_2$. This power control is termed piecewise-linear power control.

Linear interpolation is used to control the variation in transmitted power so as to reduce the information needed to be fed back from the MS to the BS. The power control implementation in the power control interval only utilizes power control factors, $\gamma_j(t_1)$ and $\gamma_j(t_2)$.

The piecewise-linear power control has the following features: *1)* it can significantly reduce the power control error as compared to the conventional piecewise-constant power control approaches; *2)* it doubles the required power control information transmitted from each MS to its serving BS as compared to the conventional piecewise-constant power control.

V. Numerical Results

A. *Simulation Model*

The network simulated consists of seven hexagonal cells, each composed of three sectors with 120° sectorization. Each BS employs two antennas located at one of three corners of each cell, resulting in twelve BSs for the entire network. Each antenna transmits data signals at a transmission rate of 115.2 kbps, and a pilot. The signals are spread by different PN sequences with a processing gain of 32. Each MS has one or two receive antennas and each receives two independent equal power multipath components. The path loss varies with distance as d^{-4} and exhibits log-normal shadowing with $\sigma_s = 8$dB. A fast Doppler spread of 90Hz is assumed. To study the probability of SIR outage, we select a 5dB threshold for the desired SIR. The simulation is performed with the antenna selection intervals of 10 msec, power control intervals of 1.25 msec, propagation and processing time of 0.625 msec. The intervals of 0.625 and 10 msec are considered for short- and long-term fading channel estimations. Table I lists the numerical parameters used in the calculations.

Table I: Numerical parameters used in the calculations

Number of sectors per cell	3
Number of BSs	12
Number of antennas per BS, M	2
Number of antennas per MS, L	1 or 2
Number of multipaths per antenna, P	2
Propagation attenuation, μ	4
Standard deviation of shadowing, σ_s	8 dB
Transmission rate	115.2 kbps
Processing gain, $\mathcal{G}$	32
Threshold for SIR outage rate	5 dB
Doppler spread, f_D	90 Hz
PN sequence chip rate	3.6864 Mcps

In terms of the short-term Rayleigh fading signal, we consider the modified Jakes' fading simulator with eight oscillators [5] to generate the fading samples at the symbol rate of the data signal.

B. *Modified STAR Receiver*

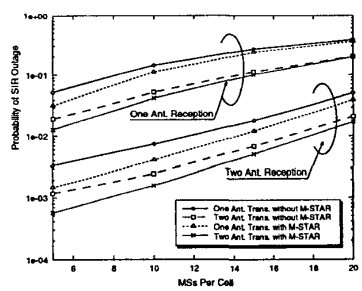

Figure 4: Effects of modifications to STAR on the probability of SIR outage vs. cell loading.

By using the optimum pilot power and the adaptative step-size of the STAR channel estimation loop, we compare the system capacity between the channel identification schemes with and without the modified STAR receiver, as shown in Fig. 4. With one receive antenna and MRC at an SIR outage rate of 5×10^{-2}, the capacity gain of using the modified STAR is about 1.2 dB for one of six active transmit antennas and 0.5 dB for two of six as opposed to the unmodified

[1] If we consider joint power control in multiple antenna selection, the power control factor $\gamma_j(t)$ should be $\gamma_1(t) = \alpha_{k,i}(t)$ and $\gamma_2(t) = \beta_i(t)$, and the transmission power ratio should be $\gamma_1^2(t)\gamma_2(t)$ for the kth active antenna and the ith MS at time t.

STAR with channel identification using only the pilot. With two receive antennas and MRC, these gains become 1.7 dB and 0.5 dB.

C. *Piecewise-Linear Power Control*

We investigate the performance of multiple antenna selection with piecewise-linear power control. For simplicity, we assume that the pilot-to-total transmission power ratio is 20%, and the step size μ is 0.048.

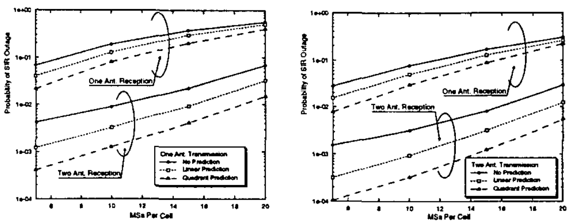

Figure 5: Probability of SIR outage as a function of the number of MSs per cell, with and without the piecewise-linear power control at the data rate of 115.2 kbps.

We show the probability of SIR outage as a function of the number of MSs per cell in Fig. 5. With one receive antenna and MRC, the piecewise-linear power control scheme with linear prediction achieves a gain of 1.8 dB for one of six active transmit antennas and 1.1 dB for two of six at an SIR outage rate of 5×10^{-2} as opposed to piecewise-constant scheme. These gains become 2.8 dB for one of six and 1.3 dB for two of six active antennas with two receive antennas at an SIR outage rate of 5×10^{-3}. With the quadratic prediction, however, those gains grow to 3.0 dB and 1.9 dB for one receive antenna, and 4.0 dB and 2.0 dB for two receive antennas, respectively.

D. *Combination of Both Identification Schemes*

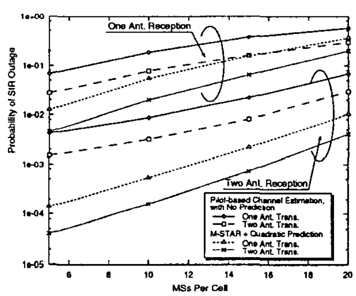

Figure 6: Probability of SIR outage as a function of the number of MSs per cell when combining the modified STAR and the piecewise-linear power control.

We now consider the benefits combining the modified STAR receiver and the piecewise-linear power control based on quadratic prediction. Fig. 6 shows the probability of SIR outage as a function of the number of MSs per cell. The combined scheme achieves a significant capacity gain as opposed to the general case that only considers multiple antenna selection with joint power control as discussed in [1]. The total capacity gain achieved by the combined scheme employing two active transmit antennas as opposed to the general case employing one active transmit antenna is about 5.3 dB at an outage rate of 5×10^{-2} for one receive antenna, and 5.4 dB at an outage rate of 5×10^{-3} for two receive antennas.

VI. Conclusions

In this paper, two sources of channel identification errors have been studied; one resulting from the channel noise, and the other resulting from the time delay. To mitigate the effects of channel noise, we considered pilot and data transmissions with the modified STAR receiver. To mitigate the effects of power control time delay, we proposed simple prediction schemes based on linear or quadratic estimation to allow the power control factors to be predicted. By interpolating the power level between the predicted power control factors, the piecewise-linear power control adjusts the power level for each data symbol transmitted. We investigated the performances and system complexity with two of six active antenna selection as follows: *1)* The modified STAR receiver with channel identification based on a pilot and data transmission offers 0.5 dB capacity gain as opposed to the conventional tracking based only on the pilot. *2)* Piecewise-linear power control with quadratic prediction achieves 2.0 dB gain as opposed to the power control with no prediction. *3)* In consideration of 2.5 dB gain achieved by two of six active antenna as opposed to one of six [1], the total gain grows to 5.4 dB. *4)* With respect to complexity, the modified STAR receiver slightly increases computational complexity as compared to the original STAR receiver. The piecewise-linear power control based on channel response prediction doubles the control information transmitted from each MS to its serving BSs as compared to the power control in [1].

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