A Space-Time Pre-RAKE Transmitter Diversity Method for W-CDMA Using Long Range Prediction[1]

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Abstract– **Transmitter diversity in the downlink for Code Division Multiple Access (CDMA) systems provides a means to achieve similar performance gains as for the mobile-station receiver diversity without the complexity of a mobile-station receiver antenna array. Pre-RAKE precoding at the transmitter can be employed to achieve the multipath diversity without the need of the RAKE receiver at the mobile station. We examine feasibility of several transmitter diversity techniques for the 3rd generation Wideband CDMA (W-CDMA) systems. We also investigate an optimal method to combine transmitter diversity and precoding that achieves the gain of maximum ratio combining of all space and frequency diversity branches. We employ long range prediction to enable these methods for rapidly time varying multipath fading channels.**

I. INTRODUCTION

Wideband CDMA is a major candidate for the 3rd generation wireless communication systems. The uplink (from mobile station to base station) capacity of the proposed third generation CDMA systems can be enhanced by various techniques including multi-antenna (diversity/antenna array) reception and multiuser detection (MUD). The techniques that increase the downlink (from base station to mobile station) capacity have not been developed in recent years with the same intensity. However, it is understood that the capacity demand imposed by the projected data services (e.g. Internet) burdens more heavily the downlink channel. Hence, it is important to find techniques that improve the capacity of the downlink channel. Bearing in mind the strict complexity requirements of terminals, and the characteristics of the downlink channel, an application of advanced detectors with multiple receive antennas is not seen as the desired solution to the downlink capacity problem. Transmitter diversity in the downlink using multiple transmitter antennas provides similar performance gains as for the mobile-station receiver diversity without the complexity of a second mobile-station receiver antenna. Transmitter based methods enable to shift signal processing to the transmitter where power and computational complexity are more abundant, thus simplifying receiver units. Different solutions have been proposed suggesting that multiple antennas (or transmit diversity) at the base station will increase downlink capacity with only minor increase in terminal implementation. The proposed techniques include Space-Time Coding [1], Delay Diversity, Orthogonal Transmit Diversity, Time Switched Transmit Diversity, Selective Transmit Diversity (STD) and Transmit Adaptive Array (Tx AA) [2-5]. Some of the transmitter diversity techniques (e.g. Tx AA, STD) require feedback of the channel state information (CSI) from mobile station. We refer to them as adaptive techniques. With the help of the feedback, better performance is achieved then for non-adaptive methods. The CSI is used to calculate the complex weights required by Tx AA and to switch to the antenna with higher channel power for STD.

CDMA technology is designed to exploit the multipath characteristics of the channel. However, the RAKE receiver is required to achieve multipath diversity gain. For the downlink, this requirement increases the complexity and power consumption of the mobile station. Pre-RAKE diversity combining techniques [7,8,17] were proposed to overcome this problem. With this method, RAKE combining is performed before transmission at the Base Station so that the Mobile Station can employ a simple matched filter receiver.

While Tx AA is optimal for flat fading channels, its performance is limited for multipath fading channels by the scalar weights. Moreover it requires a RAKE receiver at the mobile station. We investigate Space-Time Pre-RAKE diversity technique for multipath fading channels and compare it with the previously studied techniques such as STD and Tx AA. This transmitter diversity combining method can achieve the full benefit of maximum ratio combining (MRC) of all space and frequency diversity branches without using the RAKE receiver at the mobile station. A similar scheme was studied in [17] for time division duplex (TDD) applications.

STD, Tx AA and pre-RAKE systems all require knowledge of the received CSI. However, in practical rapidly varying fading channels, the fed back CSI is not up-to-date which results in performance degradation. Long range prediction can be used to forecast the fading profile of the channel and improve performance [9,15,16]. The superior performance of this algorithm relative to conventional methods is due to its much longer memory span obtained by using lower sampling rate given fixed model order. In this

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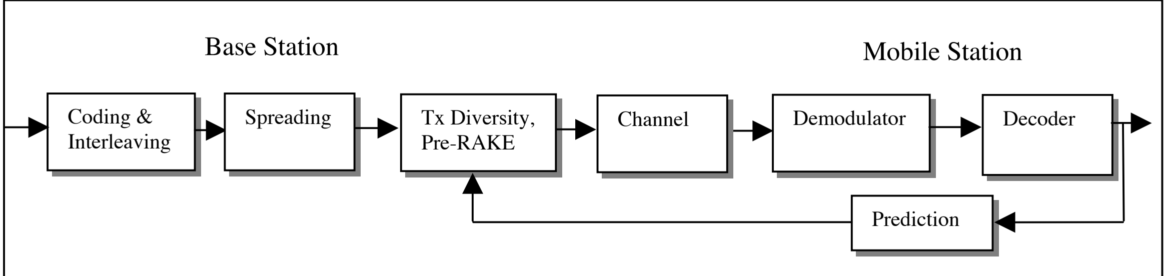

Figure 1. W-CDMA System Model

paper, we use long range fading channel prediction to improve performance of closed-loop antenna diversity methods for rapidly varying fading channels (see also [9, 15]).

In the next section, we review the W-CDMA system model, the structure of the channel and Tx AA, STD and pre-RAKE precoding techniques. The Space-time pre-RAKE is described in Section 3. Section 4 summarizes the long range prediction method, and simulation results and comparisons are presented in Section 5.

II. W-CDMA SYSTEM MODEL, TRANSMITTER DIVERSITY AND PRECODING TECHNIQUES

For simulation of performance improvements with long range prediction, a computer simulation environment is created based on proposed W-CDMA features [10]. The block diagram of the system is shown in Figure 1.

Half- rate constraint length 9 convolutional coding is used with generator polynomial parameters 561 and 753 in octal form. The minimum distance of the code is 12. The interleaving depth is 10ms. Orthogonal codes are obtained using the tree structure, explained in [10]. The channels associated with different antenna elements are assumed to be i.i.d. multipath Rayleigh fading modeled by the Jakes model with 9 oscillators [11]. The impulse response of the i^{th} antenna is given by $h_i(t) = \sum_{j=0}^{L-1} h_{ij}(t)\delta(t - jT_c)$, where L is the number of multipath components and T_c is the chip interval. The path weights are i.i.d., and the transmitter power is normalized to unity. Each channel is corrupted by Additive White Gaussian Noise (AWGN) with power spectral density (PSD) $N_o/2$, and Quadrature Phase Shift Keying (QPSK) modulation is employed.

In the discussion of the performance of various transmitter diversity techniques in this section, we will assume a single user uncoded system with the signature waveform that is orthogonal to its shifts by the chip interval T_c. We also assume that the transmitter has the perfect knowledge of received channel coefficients. In the simulation results of Section 5, the self-orthogonality assumption is removed, since the W-CDMA signature waveforms are employed, the data is coded and rapid channel variation is taken in the account in the performance evaluation.

Tx AA and STD are closed loop transmit diversity techniques and they require feedback from the mobile station. It is assumed that multiple transmit antennas are located at the Base Station (BS) and Mobile Station (MS) employs single antenna reception. Tx AA is illustrated in Figure 2. For Tx AA, each antenna transmits coherently with the same data and code but with antenna-specific weighting. Each transmitter antenna has a separate pilot signal, which enables the MS to individually estimate the channels used by each antenna [10]. The goal of this scheme is to choose the weights applied at the BS so that the total power received by the MS is maximized.

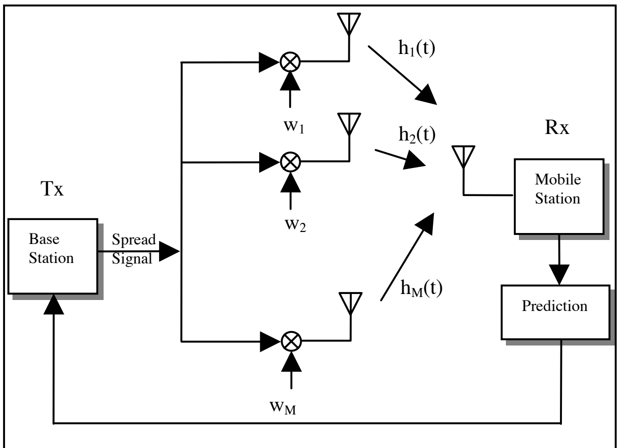

Figure 2. Tx AA Schematic

Assume M antennas with flat fading channels. Define $\underline{\mathbf{h}}=[h_1\ h_2\ \ldots\ h_M]$ as a row vector, where h_i is the fading channel coefficient for the channel between the i^{th} transmitter antenna and the MS. Then the Tx AA weights are [4]:

$$\underline{\mathbf{w}} = \frac{\underline{\mathbf{h}}^H}{\sqrt{\underline{\mathbf{h}}\underline{\mathbf{h}}^H}} \tag{1}$$

where $\underline{\mathbf{h}}^H$ is the Hermitian of the vector $\underline{\mathbf{h}}$. If there are L paths for each antenna, then the weighting vector which maximizes the total received power at the MS is the eigenvector $\mathbf{v}_{max}$, corresponding to the largest eigenvalue, λ_{max} of the MxM matrix $\mathbf{H}^{\mathbf{H}}\mathbf{H}$ [5], where $\mathbf{H}=[\underline{\mathbf{h}}_1\ \underline{\mathbf{h}}_2\ \ldots\ \underline{\mathbf{h}}_M]$ and $\underline{\mathbf{h}}_i=[\,h_{i0}\ h_{i1}\ \ldots\ h_{i(L-1)}]^T$ is the vector that contains L multipath coefficients between the i^{th} antenna and the MS. For flat fading case, the performance of the Tx AA system is equivalent to the optimal diversity case, i.e. Maximal Ratio Combining (MRC) with the order of M (number of antennas). However Tx AA cannot achieve the optimal performance in multipath fading. Moreover, it requires

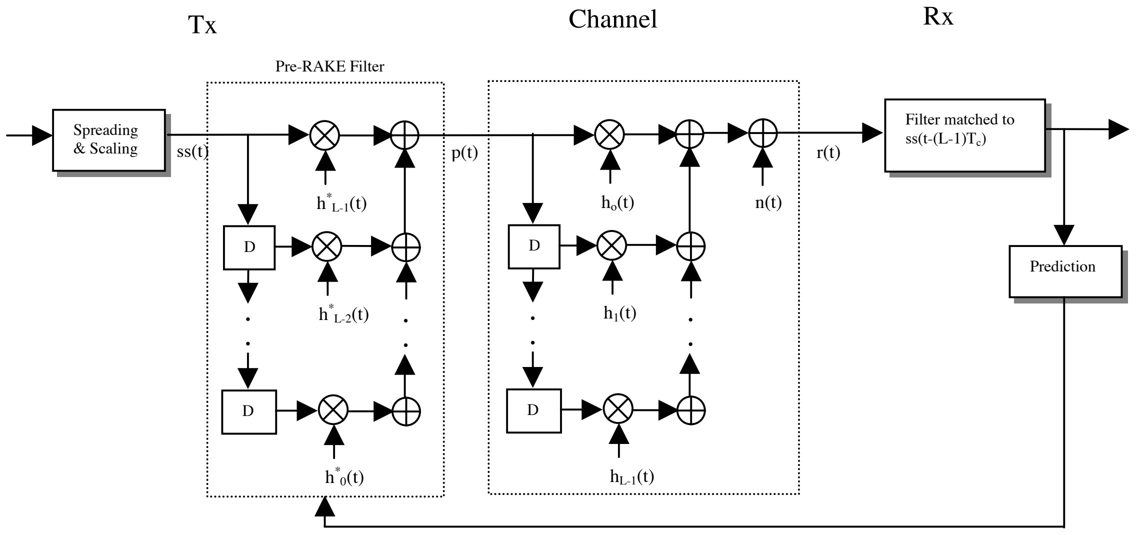

Figure 3. Pre-RAKE Diversity Combining

the RAKE receiver at the MS.

In the STD method, the dedicated channel of a given user is switched to the designated antenna with the largest received power. The ideal performance of this technique matches that of the selection diversity at the receiver. STD switching frequency determines the rate at which antenna selection signal is fed back to the BS, hence the switching between the transmit antennas. Different switching rates result in different BER performance of the system. The lower bound for the performance of this technique is achieved when the antenna switching is done for every symbol transmitted (STD Every bit). This bound is computed as follows. Suppose the RAKE receiver with MRC is employed at the MS. Then the cumulative distribution function of the fading coefficient at the output of the RAKE receiver is:

$$F_{\gamma_b^s}(\gamma) = M!\int_0^{\gamma}\int_0^{\gamma_1}\cdots\int_0^{\gamma_{L-1}} p_{\gamma_b}(\gamma_M)..p_{\gamma_b}(\gamma_1)d\gamma_M...d\gamma_2 d\gamma_1 \quad (2)$$

where $p_{\gamma_b}(\gamma) = \frac{1}{(\bar{\gamma}_c)^L (L-1)!}\gamma^{L-1}e^{-\gamma/\bar{\gamma}_c}$ is the pdf for sum of L paths' channel powers and $\overline{\gamma_c}$ is the average Signal to Noise Ratio (SNR) per path , which is assumed to be identical for all paths and defined as $\overline{\gamma}_c = \frac{\varepsilon_b}{\mathrm{N}_0}\mathrm{E}(\mathrm{h}_{\mathrm{ij}})$, where ε_b is the bit energy, No/2 is the AWGN power, h_{ij} is the fading coefficient for any of the paths and E(•) is the expectation operation. Then the probability of error is:

$$P_{STD_{LxM}}(e) = \int_0^{\infty} P^s_{\gamma_b}(\gamma)P_{BPSK}(\gamma)d\gamma \quad (3)$$

where $P^s_{\gamma_b}(\gamma)$ is the probability density function and found by differentiating (2). The $P_{BPSK}(\gamma) = Q(\sqrt{2\gamma})$ is the probability of error for the BPSK system and Q(•) is the error function defined as $Q(x) = \frac{1}{\sqrt{2x}}\int_x^{\infty} e^{-t^2/2}dt$. In particular, the probability of error for STD Every bit with flat fading i.i.d. channels and M antennas can be found from [6]:

$$P_{STD}(e) = \sum_{k=0}^{M-1}\frac{M}{2(k+1)}(-1)^k\binom{M-1}{k}\left(1-\sqrt{\frac{\bar{\gamma}_c}{k+1+\bar{\gamma}_c}}\right) \quad (4)$$

For multipath fading channels, frequency diversity can be achieved using the RAKE receiver. Pre-filtering of the transmitted signal at the base station can achieve the same performance as RAKE with MRC by employing a single matched filter at the mobile station [7,8,17]. This transmitter precoding technique is known as pre-RAKE Diversity Combining. In Figure 3, the pre-RAKE method is illustrated for a multipath single antenna fading channel with impulse response $\sum_{i=0}^{L-1} h_i(t)\delta(t-iT_c)$.

As seen in Figure 3, the coefficients of the pre-transmit filter are the conjugates of the channel path coefficients and the order of the pre-RAKE coefficients is the reverse order of the channel coefficients.

III. SPACE-TIME PRE-RAKE TRANSMITTER DIVERSITY METHOD

When Tx AA is used for the multipath fading channel, the resulting system cannot achieve the optimum performance, i.e. it cannot achieve the gain of the MRC of all space and frequency diversity branches [5]. This is due to the scalar weights used by the Tx AA. We investigate a Space-time pre-RAKE method that optimally combines multipath powers associated with all transmitter antennas using pre-

RAKE precoding and the appropriate scaling. For antenna m, we filter the spread signal *s(t)* so that the transmitter pulse shape is:

$$p(t) = \frac{1}{\sqrt{\sum_{m=1}^{M}\sum_{j=0}^{L-1} |h_{m,j}(t)|^2}} \sum_{j=0}^{L-1} h^*_{m,L-1-j}(t)\, s(t - jT_c) \quad (5)$$

where s(t) is the signature sequence and $h_{m,j}(t)$ is the fading coefficient corresponding to the jth path of the mth antenna. Assume the receiver employs a single filter matched to s(t-(L-1)Tc). The desired signal occurs at t-(L-1)Tc and is given by:

$$\sqrt{\sum_{m=1}^{M}\sum_{j=0}^{L-1} |h_{m,j}(t)|^2}\, b + z \quad (6)$$

where b is the transmitted BPSK symbol and z is the filtered noise. This is equivalent to MRC with LxM diversity branches. The probability of error is then [12]:

$$P(\varepsilon) = \left[\frac{1}{2}(1-\mu)\right]^{LxM} \sum_{k=0}^{LxM-1} \binom{LxM-1+k}{k} \left[\frac{1}{2}(1+\mu)\right]^{k} \quad (7)$$

where $\mu = \sqrt{\frac{\overline{\gamma_c}}{1+\overline{\gamma_c}}}$, and $\overline{\gamma_c}$ is the average SNR per path.

IV. LONG RANGE PREDICTION TECHNIQUE

It was shown in [9,15,16] that long range prediction based on the Minimum Mean Square Error criterion (MMSE) can be used to accurately estimate the future channel state information at least several milliseconds ahead for rapidly time varying fading channels. In this paper, MMSE prediction of individual complex channel coefficients associated with all paths is employed [9]. It is based on linear prediction method with autoregressive (AR) channel modeling. Assume we sample the channel at a rate $f_s=1/T_s$, where $f_s \geq f_d$, f_d is the maximum Doppler shift. The channel is assumed to be complex Rayleigh fading process c(t). Let $c_i=c(iT_s)$. Our aim is to predict c_n based on p previously observed channel samples $c_{n-p}, c_{n-p+1}, \ldots, c_{n-2}, c_{n-1}$. We compute the (pxp) autocorrelation matrix **R** with coefficients $R_{ij} = E[c_{n-i}c^*_{n-j}]$ and (px1) autocorrelation vector **r** with coefficients $r_i = E[c_n c^*_{n+i}]$. Then the minimum mean square error prediction of c_n is :

$$\hat{c}_n = \sum_{i=1}^{p} d_i c_{n-i} \quad (8)$$

where $\underline{d}=\{d_i\}$, i=1..p and $\underline{d}=\mathbf{R}^{-1}\underline{r}$. For the simulations, p=50 and the observation interval of 200 samples are used to compute the autocorrelation of c_n. This observation interval can be significantly reduced and matrix inversion can be aviοded if adaptive long range prediction is used [15].

For W-CDMA the sampling rate f_s is chosen as the slot rate of 1.6kHz. This results in 0.625 ms delay for calculating the channel state information. In addition, it is desirable to obtain future CSI further than one slot ahead when the antenna switching rate is lower than the slot rate (e.g. 400 Hz) [6, 9, 15]. The prediction algorithm described above is used to obtain predicted values of the current and future channel coeffients given the delayed channel samples. For the STD case, these coefficients are used to choose the antenna with the largest received power. For Tx AA, they are used to calculate the weights of each antenna. Finally, for pre-RAKE and Space-time pre-RAKE, they are utilized in filtering the spread signal prior to transmission. Both Tx AA and Space-time pre-RAKE methods require the knowledge of the CSI for every symbol transmitted. Since the CSI is fed back from the MS at 1.6kHz, it is necessary to use interpolation to obtain the intermediate coefficients of the channel. For these methods, the beginning of the current slot and the beginning of the next slot are predicted using the past values of the channel. Then these values are used to compute the intermediate values between two slots, so that the CSI at the transmission rate is obtained.

V. SIMULATION RESULTS

We removed the ideal assumptions of Section 2 and 3, and used computer simulations to evaluate the bit error rate (BER) of the schemes described above. The W-CDMA communication environment introduced in Section 2 is employed with 2 GHz carrier frequency, 60mph vehicle speed, 4.096 Mcps chip rate, and the bit rate of 128 kbps [10]. The data was coded. We assume that there is no estimation error at the MS. The results are for a single user where multiple access interference (MAI) is modeled as white Gaussian noise. In all curves, MRC, no diversity and "Every bit" results are obtained by simulation using the prefect CSI.

Figure 4 shows the comparison between STD for 1.6 KHz switching rate with RAKE receiver (no pre-RAKE diversity) and Space-time pre-RAKE. STD 1.6 KHz and Space-Time pre-RAKE methods with prediction are compared with the same techniques, but when delayed CSI is used to select antenna or to compute pre-RAKE weights. Prediction results in ~ ½ - 1 dB gain for all methods. In [6,9,15] it is demonstrated that prediction is even more helpful when switching frequency is reduced to 400Hz. It is observed that Space-Time Pre-RAKE performs better than STD for all switching rates. Space-Time Pre-RAKE provides around 1dB gain over STD 1.6kHz. Since it uses perfect CSI and is not affected by multipath interference, MRC with the same order of diversity as Space-Time Pre-RAKE is the lower bound for all methods. In a practical system like W-CDMA, orthogonal codes that are used to separate users from each other introduce multipath interference. Because of this noise and prediction errors, Space-time pre-RAKE system cannot achieve its ideal BER given by the 8-path MRC.

Figure 5 compares the BER performance of space-time pre-RAKE and Tx AA with the RAKE receiver [5]. The prediction method described above is employed to enable pre-RAKE filtering and to calculate the weights required for Tx AA. Figure 5 demonstrates that Space-time pre-RAKE system achieves better performance than Tx AA for multipath fading channels.

In the Figures, the BER is calculated in terms of the received SNR per coded bit. This SNR was evaluated theoretically for STD "Every bit" and no diversity curves,

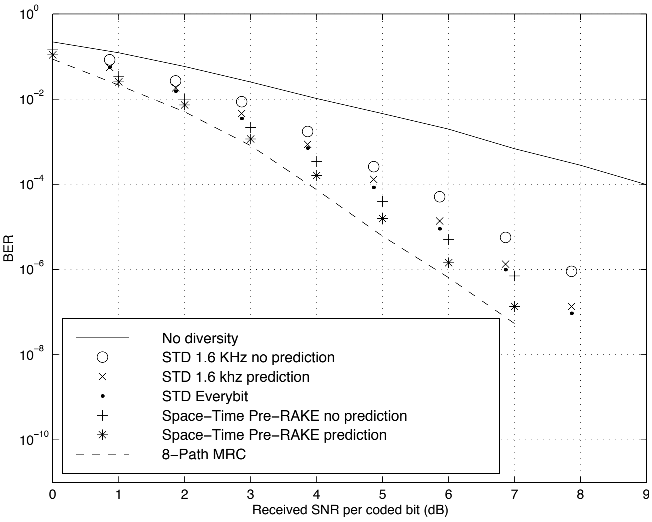

Figure 4. Comparison of STD and Space-time pre-RAKE, 4-path fading channel, 2 transmitter antennas, f_{dm}=200Hz.

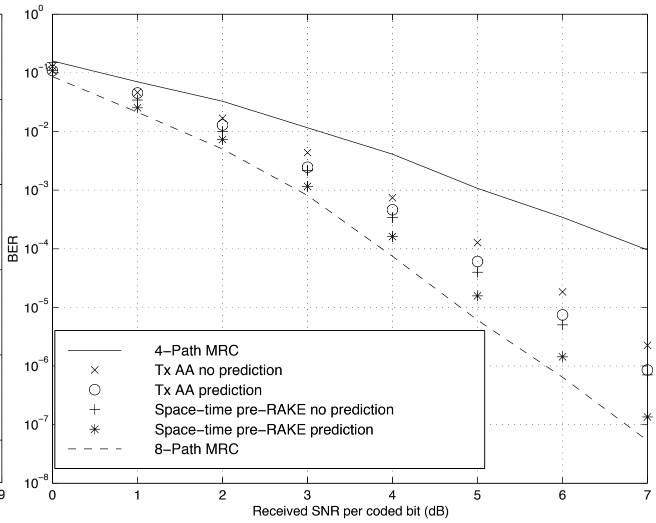

Figure 5. Comparison of Tx AA and Space-time pre-RAKE, 2 transmitter antennas, 4 paths, f_{dm}=200Hz.

and computed from simulations for other methods. The comparison in terms of received SNR per bit allows to compare directly the diversity advantages of various combining methods over different multipath channels. It is observed that employing Space-Time Pre-RAKE with long range prediction achieves near-optimal performance for a rapidly time variant multipath channel with transmission antenna array. However, this gain is achieved at the expense of significant complexity. While the feedback load is high, the RAKE filtering and prediction is performed at the BS, where this complexity can be afforded. The Tx AA method can reduce feedback load and feed back a single complex weight per antenna, provided that prediction and the RAKE receiver are performed at the MS. Thus, the complexity at the MS is higher for Tx AA than for Space-time pre-RAKE. Moreover, Tx AA does not provide significant performance gain over STD for a modest number of antennas. The complexity of STD is the lowest since it only requires the feedback of the antenna selection bits to choose the antenna with the greatest channel power. STD can be easily combined with pre-RAKE, while still retaining lower complexity than space-time pre-RAKE [17]. Thus, the methods described in this paper provide a variety of performance/complexity trade-offs, with STD being the simplest, but the least power efficient method, and Space-time pre-RAKE being more complex, and achieving near-optimal performance.

VI. CONCLUSION

A Space-time pre-RAKE transmitter diversity technique was compared to STD and Tx AA transmitter diversity methods for realistic W-CDMA channels. The performance of the Space-time Pre-RAKE method approaches the performance of MRC for all space and frequency diversity branches. It is shown that all closed loop methods depend on the long range prediction to approximate the ideal performance in the rapidly fading environment.

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