# Performance Analysis of Space-Time Transmitter Diversity Techniques for W-CDMA Using Long Range Prediction[1]

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***Abstract– Transmitter diversity in the downlink of Code Division Multiple Access (CDMA) systems achieves similar performance gains to 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 and precoding for the 3rd generation Wideband CDMA (W-CDMA) systems. In particular, Selective Transmit Diversity, Transmit Adaptive Array and Space-Time Pre-RAKE techniques are compared. It is demonstrated that the Space-Time Pre-RAKE (STPR) method is the optimal method to combine antenna diversity and temporal precoding. This method achieves the gain of maximum ratio combining of all space and frequency diversity branches when perfect channel state information (CSI) is available at the transmitter. We employ the long range fading prediction algorithm to enable transmitter diversity techniques for rapidly time varying multipath fading channels.***

## I. INTRODUCTION

In the downlink of mobile radio systems, transmitter-based methods enable to shift signal processing from the Mobile station (MS) to the Base station (BS), 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 mobile 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]. Closed-loop transmitter diversity techniques (e.g. Tx AA, STD) achieve better performance than open-loop methods, but they require feedback of the CSI from the MS. We refer to these closed-loop methods as adaptive techniques.

CDMA technology is designed to exploit the multipath characteristics of the channel. The RAKE receiver is utilized to achieve multipath diversity gain [12,14]. For the downlink, the RAKE receiver increases the complexity and power consumption of the MS. Pre-RAKE diversity combining techniques [7,8,17] were proposed to overcome this problem. With this method, the RAKE filtering is performed before transmission at the BS so that the MS can

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employ a simple matched filter receiver. In this paper and [17,18,21], the pre-RAKE filtering is extended to transmitter antenna array systems. We investigate the Space-Time Pre-RAKE (STPR) diversity combining method for multipath fading channels and compare it with the previously studied techniques such as STD and Tx AA. While Tx AA is optimal for flat fading channels, its performance is limited for multipath fading channels by the scalar weights. Moreover it requires the RAKE receiver at the MS. We will show that the STPR is the optimal transmitter diversity method since it achieves the full benefit of maximum ratio combining (MRC) of all space and frequency diversity branches without using the RAKE receiver at the MS. A similar scheme was independently studied in [17] for time division duplex (TDD) applications, but little detail was provided on performance comparison with other methods and performance issues. In independent research reported in [21], the pre-RAKE scheme and selective diversity methods were utilized for multiple transmitter antennas for uncoded TDD systems. We compare these methods and Tx AA for coded W-CDMA channel, aided by the long range prediction algorithm. Since we normalize transmitted and received power for all techniques, our performance comparison reflects the gain due to the diversity, and our conclusions differ from those in [21].

STD, Tx AA and pre-RAKE systems all require the 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. The long range fading prediction algorithm (LRP) 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 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 discuss the CDMA system model, the structure of the channel and Tx AA, STD and Space-time pre-RAKE precoding techniques. In section III, the long range prediction method is summarized and its performance is analyzed. Simulation results and comparisons are presented in Section IV.

## II. TRANSMITTER DIVERSITY AND PRECODING TECHNIQUES FOR CDMA SYSTEMS

Consider a CDMA system with M antennas at the BS and a single antenna at the MS. An example of this system is shown in Figure 1. The channels associated with different antenna elements are assumed to be independent and identically distributed (i.i.d.) multipath Rayleigh fading. The impulse response of the channel from the $i^{th}$ antenna to the MS is given by:

$$h_i(t)=\sum_{j=0}^{L-1} h_{ij}\delta(t-jT_c) \quad (1)$$

where L is the number of multipath components, and $T_c$ is the chip interval. The path weights are i.i.d. complex Gaussian random variables, and the transmitter power is normalized to unity. The received signal is corrupted by complex Additive White Gaussian Noise (AWGN) with power spectral density (PSD) $N_o$, and Binary Phase Shift Keying (BPSK), or equivalently, Quadrature Phase Shift Keying (QPSK) modulation is employed, with energy per bit $E_b$. The average signal-to-noise ratio (SNR) per path is defined as:

$$\bar{\gamma}_c=\frac{E_b}{N_o}E(|h_{ij}|^2) \quad (2)$$

In the discussion of the performance of various transmitter diversity techniques in this section, we assume a single user uncoded system with the signature waveform s(t) orthogonal to its shifts by integer multiples of $T_c$. We also assume that the transmitter has perfect knowledge of the received channel coefficients. In the simulation results of Section IV, 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. The multiuser interference is modeled as additive Gaussian noise throughout the paper.

The Tx AA system is illustrated in Figure 1. In this method, 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 that 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. Assume M antennas with flat fading channels. Then the channels in (1) reduce to $h_i(t)=h_i\delta(t)$, where $h_i$ are i.i.d. Rayleigh fading random variables, and $\bar{\gamma}_c=\frac{E_b}{N_o}E(|h_i|^2)$ . Define $\underline{\mathbf{h}}=[h_1\ h_2\ .\ .\ .\ h_M]$. Then the optimal Tx AA weights are [4] $\underline{\mathbf{w}} = \frac{\underline{\mathbf{h}}^H}{\sqrt{\underline{\mathbf{h}}\,\underline{\mathbf{h}}^H}}$, where $\underline{\mathbf{h}}^H$ is the Hermitian of the vector $\underline{\mathbf{h}}$. If there are L paths for each antenna as in (1), then the weighting vector that maximizes the total received power at the MS is given by $\underline{\mathbf{w}} = (\underline{\mathbf{v}}^H_{max}/\sqrt{\underline{\mathbf{v}}_{max}\,\underline{\mathbf{v}}^H_{max}})$, where $\underline{v}_{max}$ is the eigenvector corresponding to the largest eigenvalue, $\lambda_{max}$ of the MxM matrix $\mathbf{H}^{\mathbf{H}}\mathbf{H}$ [5], $\mathbf{H}=[\underline{\mathbf{h}}_1 \;\; \underline{\mathbf{h}}_2 \; . \; . \; . \; \underline{\mathbf{h}}_M]$ and $\underline{\mathbf{h}}_i=[\, h_{i0} \; h_{i1} \; . \; . \; . \; h_{i(L-1)}]^T$. For the flat fading case, the Bit Error Rate (BER) of the Tx AA system is given by the BER of the MRC with the order of M (the number of antennas) [12]:

$$P_{MRC}(e) = \left[\tfrac{1}{2}(1-\mu)\right]^M \sum_{k=0}^{M-1} \binom{M-1+k}{k} \left[\tfrac{1}{2}(1+\mu)\right]^k, \tag{3}$$

where $\mu = \sqrt{\bar{\gamma}_c/(1+\bar{\gamma}_c)}$. Therefore, Tx AA is the optimal transmitter diversity method for flat fading channels. We demonstrate later that Tx AA cannot achieve the optimal performance in multipath fading. Moreover, it requires 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. The switching frequency of the STD method determines the rate at which the antenna selection signal is fed back to the BS, hence the rate of 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 performed 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 received SNR at the output of the RAKE receiver is:

$F_{\gamma^s_b}(\gamma)=M!\int_0^{\gamma}\int_0^{\gamma_1}\cdots\int_0^{\gamma_{M-1}} p_{\gamma_b}(\gamma_M)..p_{\gamma_b}(\gamma_1)\,d\gamma_M..d\gamma_2\,d\gamma_1$, where the instantaneous received SNR $\gamma^s_b=\frac{E_b}{N_o}|c^s|^2$ and $|c^s|^2=\max_i(\sum_{j=0}^{L-1}|h_{ij}|^2)$ is the power of the channel for the selected antenna, $p_{\gamma_b}(\gamma) = \frac{1}{(\bar{\gamma}_c)^L (L-1)!}\gamma^{L-1}e^{-\gamma/\bar{\gamma}_c}$ and $\gamma_b=\frac{E_b}{N_o}\sum_{j=0}^{L-1}|h_{ij}|^2$ is the instantaneous SNR of the channel of the $i^{th}$

antenna. Then the BER is $P_{STD_{LxM}}(e) = \int_0^\infty p_{\gamma^s_b}(\gamma)\, p_{BPSK}(\gamma) d\gamma$ , where $p_{\gamma^s_b}(\gamma)$ is the probability density function (pdf) found by differentiating $F_{\gamma^s_b}(\gamma)$ with respect to $\gamma$, $P_{BPSK}(\gamma)=Q(\sqrt{2\gamma})$ is the BER of the BPSK system, and $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2/2} dt$. In particular, the BER for STD Every bit with flat fading i.i.d. channels and M antennas is [6]:

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

The transmitter diversity systems described above have suboptimal performance for multipath channels and require the RAKE receiver at the MS. We investigate the Space-Time pre-RAKE (STPR) method that optimally combines multipath and space diversity components. This method extends the pre-RAKE precoding to multiple antenna systems as shown in Figure 2. In this structure, L delayed versions of the signature waveform are weighted by pre-RAKE weights corresponding to each antenna. For antenna m, the transmitter pulse shape is:

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

Assume the receiver employs a single filter matched to s(t-(L-1)Tc). The desired signal occurs at time t-(L-1)Tc and is given by $\sqrt{\sum_{m=1}^{M}\sum_{j=0}^{L-1} |h_{mj}|^2}\, b + z$ where $b$ is the transmitted BPSK symbol and $z$ is the filtered noise. The BER associated with this system is equivalent to the BER of MRC in (3) with LxM diversity branches. Thus, the STPR method is the optimal transmitter diversity technique for the multipath fading channel.

## III. THE LONG RANGE PREDICTION (LRP) ALGORITHM

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 time-varying complex channel coefficients $h_{ij}$ associated with individual paths in (1) is employed [9]. It is based on linear prediction method with autoregressive (AR) channel modeling. Assume the channel is sampled at the rate $f_s=1/T_s$, where $T_s$ is the sampling interval.

This rate is much lower than the date rate and is on the order of the maximum Doppler shift $f_{dm}$. The channel is assumed to be complex Rayleigh fading process c(t), where c(t) represents $h_{ij}(t)$. Let $c_i=c(iT_s)$. Our aim is to predict $c_n$ based on p previously observed channel samples $c_{n-p},c_{n-p+1},\ldots,c_{n-2},c_{n-1}$ . The algorithm computes the (pxp) autocorrelation matrix **R** with coefficients $R_{ij} = E[c_{n-i}\, c^*_{n-j}]$ and the (px1) autocorrelation vector $\underline{\mathbf{r}}$ with coefficients $r_i = E[c_n\, c^*_{n+i}]$. Then the minimum mean square error prediction of $c_n$ is :

$$\hat{c}_n=\sum_{i=1}^{p} d_i c_{n-i} \tag{6}$$

where $\underline{\mathbf{d}}=(d_1,\ldots, d_p)$ are the coefficients for the Minimum Mean Square Error (MMSE) solution and $\underline{\mathbf{d}}=\mathbf{R}^{-1}\underline{\mathbf{r}}$ . The MMSE is given by:

$$E[|e_n|^2]= E[|c_n-\hat{c}_n|^2]= r_0-\sum_{i=1}^{p} d_i r_i \tag{7}$$

For the simulations, p=50 and the observation interval of 200 samples are used to compute the autocorrelation of $c_n$. We utilize multi-step prediction to predict more than one sample ahead [15]. Noiseless observations are used in (6). In practice, noise in the observations can be reduced by combining prediction with adaptive tracking. The observation interval can be significantly reduced and matrix inversion can be avoided if adaptive long range prediction is used [15].

For W-CDMA the sampling rate $f_s$ is chosen as the slot rate of 1.6 kHz [10]. This results in at least 0.625 ms delay for calculating the channel state information. The prediction algorithm described above is used to obtain predicted values of the current and future channel coeffients in the next slot or block of slots, given the delayed channel samples. For STD, these coefficients are used to choose the antenna with the largest received power. The number of predicted samples depends on the switching frequency [6,9,15]. For Tx AA, they are used to calculate the weights of each antenna. Finally, for STPR, they are utilized in filtering the spread signal prior to transmission. Both Tx AA and STPR methods require the knowledge of the CSI for every symbol transmitted. Since the CSI is fed back from the MS at 1.6 kHz, 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 and past values are used to compute the intermediate values for the next slot, so that the CSI at the transmission rate is obtained.

To analyze the performance of the LRP algorithm in diversity systems, we apply results of [19,20] as follows. The lower bound on the BER of a BPSK system with M i.i.d. Rayleigh fading diversity branches, MRC combining and imperfect MMSE channel estimates is:

$$P^{est}_{M}(e) = \left[\frac{1}{2}(1-\mu_e)\right]^{M} \sum_{k=0}^{M-1} \binom{M-1+k}{k} \left[\frac{1}{2}(1+\mu_e)\right]^{k} \tag{8}$$

where $\mu_e = \sqrt{(1-\Gamma)/(1+1/\bar{\gamma}_c)}$ and $\Gamma$ is the normalized estimation error variance for each branch, defined by: $\Gamma = (E\{|e|^2/E\{|c|^2\})$, where e=c-ĉ and ĉ is the MMSE estimate of the branch weight c. The MMSE of the LRP (see (7)) was computed for the individual paths and appropriate prediction ranges using simulations. It was then averaged to obtain an estimate of Γ and used in (8) to bound performance of transmitter diversity methods, as discussed in section IV.

## IV. SIMULATION RESULTS

We removed the ideal assumptions of Section II, and used computer simulations to evaluate the BER of the schemes described above. A computer simulation environment was created based on proposed W-CDMA features [10]. 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 modeled by the Jakes model with 9 oscillators [11]. The carrier frequency is 2 GHz, the vehicle speed is 60 MPH, $f_{dm}$=200 Hz, the chip rate is 4.096 Mcps, and the bit rate is 128 kbps [10]. For coded data, MRC, no diversity and “Every bit” results are obtained by simulation using the prefect CSI.

In Figure 3, performance of Tx diversity aided by LRP is illustrated for uncoded W-CDMA system. For flat fading channel with M=4 antennas, the Tx AA is used. The ideal performance of Tx AA with perfect CSI is that of MRC with 4 branches, and the lower bound on performance with LRP is given by (8). For the 4-path multipath channel, STPR is utilized with M=2 antennas. Equation (8) with 8 branches provides a lower bound on its performance with LRP. For STPR, the deviation from this bound is due to multipath induced self-interference due to non-orthogonality between shifted signature sequences and non-ideal interpolation of predicted channel coefficients. Simulation results for both Tx AA and STPR without prediction are also included in Figure 3. When prediction is not employed, the delayed CSI at the beginning of the previous slot is used during the next slot, and these fixed coefficients are used to calculate the weights and pre-RAKE coefficients associated with the Tx AA and the STPR methods. It is observed that, for both cases, the performance with prediction is near optimal, approximately equivalent to MRC with LxM diversity branches. The gain due to accurate channel prediction is approximately 1 dB.

In Figures 4-6, simulation results are presented for coded systems with 2 Tx antennas. Figures 4 and 5 compare STD methods for different switching frequencies. Results for flat fading channel are presented in Figure 4. It is observed that significant performance improvements (1-2 dB) are possible when prediction is used. For low switching frequencies, antenna selection based on averaging predicted channel state information for the duration of the future switching interval is utilized since it results in improved BER. The Tx AA with perfect CSI provides a lower bound on performance of STD systems. Note that the performance of STD with higher switching rate approaches ideal performance (STD Every bit) and is very close to the performance of Tx AA with perfect CSI. Since STD is much simpler to implement than Tx AA, it represents a very attractive solution for Tx antenna diversity systems.

Figure 5 shows the comparison between the STD with RAKE receiver and the STPR methods for a 4-path channel. The gain due to prediction is lower here than in figures 3-4 (around 0.5 dB). In general, as diversity gain due to multipath and coding increases, the channel becomes less time-variant, resulting in reduced benefit of prediction. It is observed that the STPR performs better than STD for all switching rates. The gain is around 1dB gain for 1.6 kHz switching rate. Note that MRC with LxM branches is the lower bound for all methods. Due to multipath-induced interference and prediction errors, the STPR system cannot achieve its ideal BER given by the 8-path MRC.

Figure 6 compares the BER performance of Space-time pre-RAKE and Tx AA with the RAKE receiver [5]. Comparison of Figures 5 and 6 demonstrates that performance of Tx AA is similar to that of STD, and that the STPR method significantly improves upon both Tx AA and STD 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", no diversity and MRC curves, and computed from simulations for other methods. The comparison in terms of the received SNR per bit allows to compare directly the diversity advantages of various combining methods over different multipath channels. It is observed that employing STPR with LRP 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 and feedback load that reduces the throughput of the uplink channel. 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 (improve the throughput) since it feeds 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 STPR. Moreover, Tx AA does not provide significant performance gain over STD for a modest number of antennas. The complexity of STD is the lowest and the throughput is the best 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 STPR [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 the STPR technique being more complex, and achieving near-optimal performance.

## V. CONCLUSION

Various transmitter diversity techniques for realistic W-CDMA channels were investigated. The Space-time pre-RAKE transmitter diversity technique was compared to STD and Tx AA transmitter diversity methods and performance/complexity trade-offs of these techniques were examined. It was demonstrated that the performance of the STPR method approaches the performance of the 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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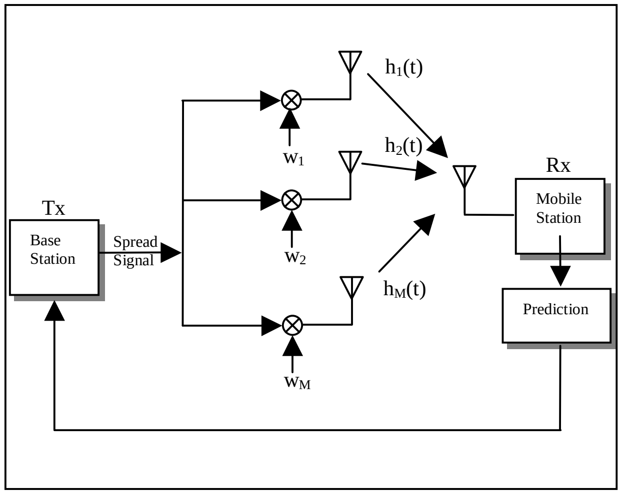


**Figure 1. Tx AA transmitter diversity system aided by long range prediction**

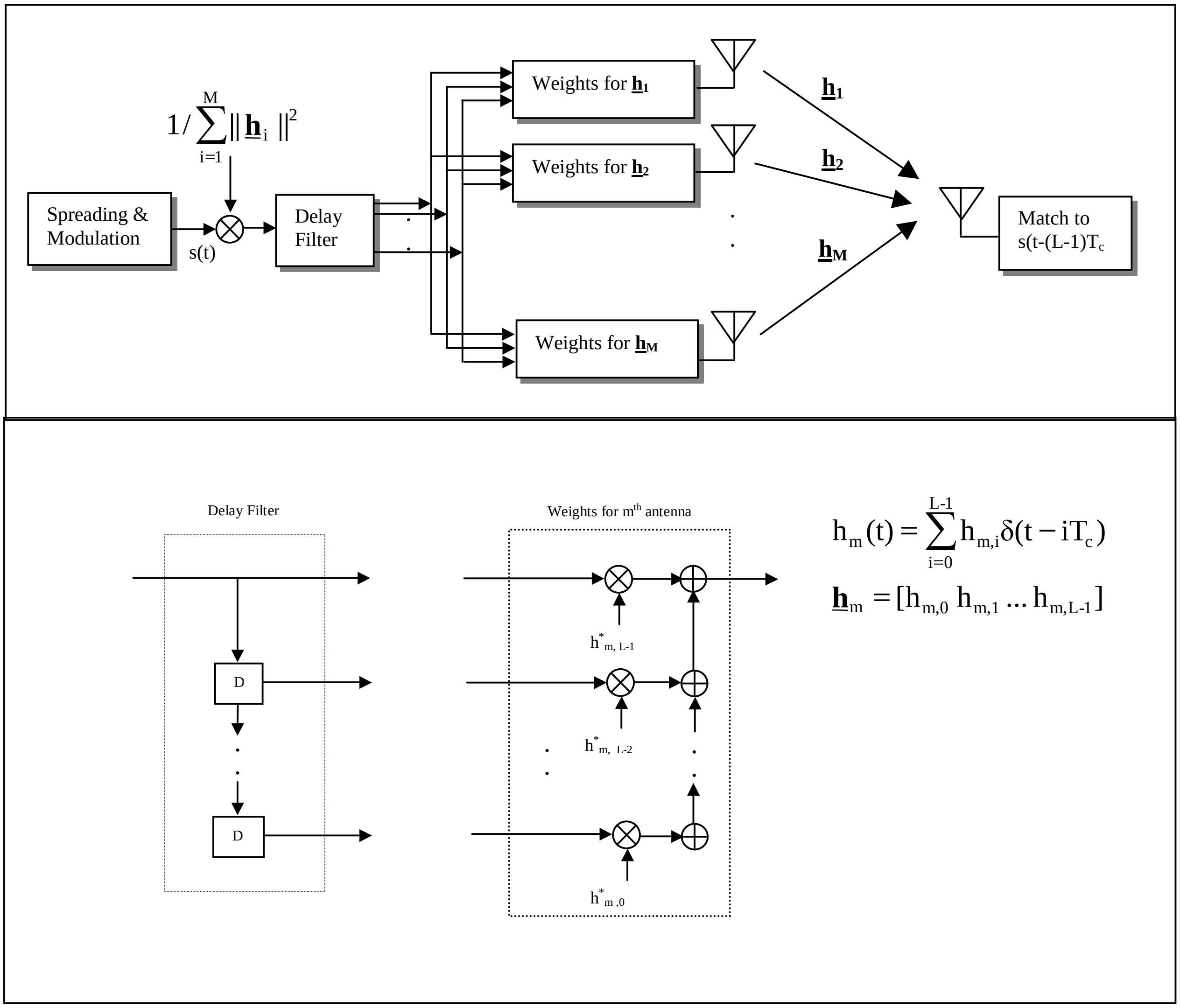


**Figure 2. Space-Time Pre-RAKE diversity combining**

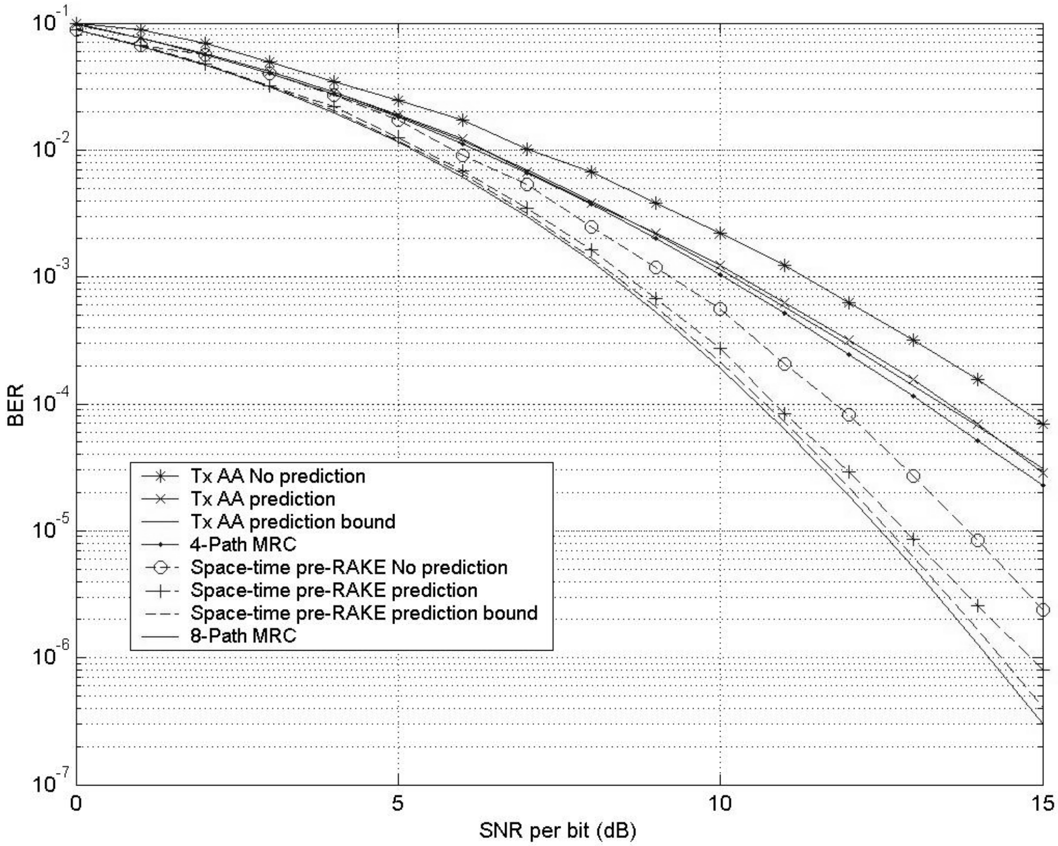


**Figure 3. Simulated performance and theoretical bounds for long range prediction, $f_{dm}$=200Hz. Uncoded W-CDMA, Tx AA: 4 antennas, flat fading, STPR: 2 antennas, 4 paths.**

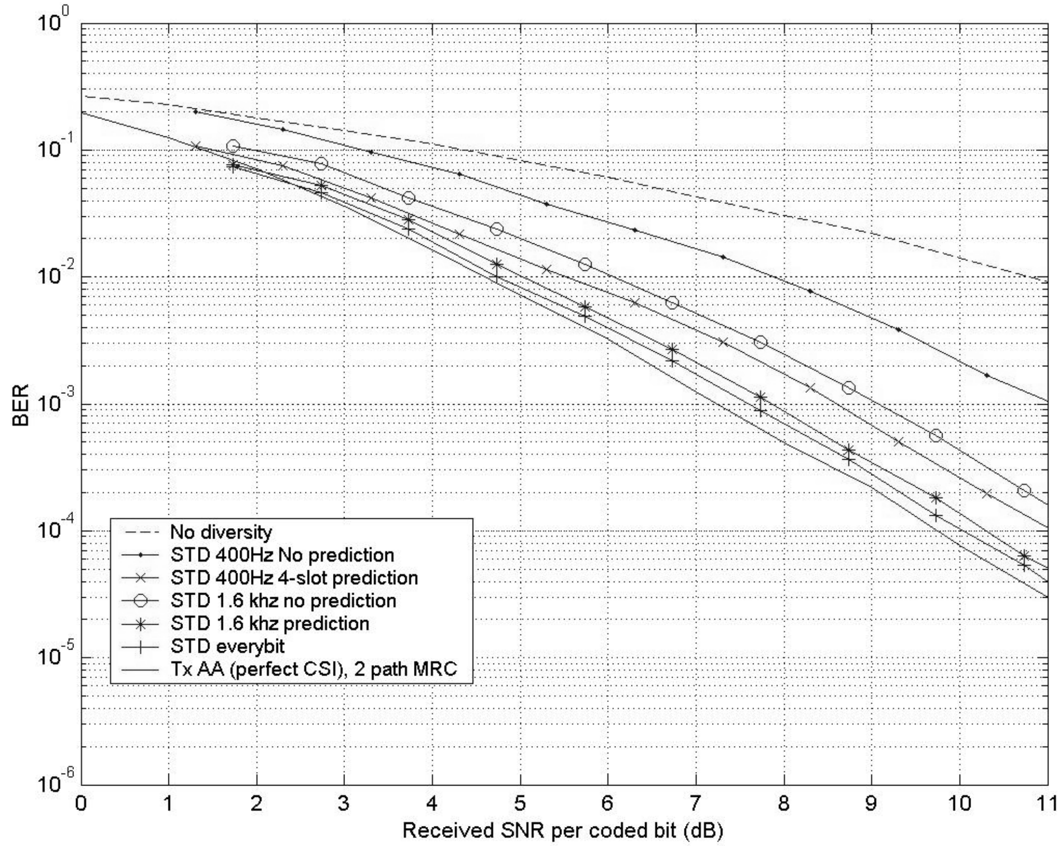


**Figure 4. Performance of the STD, flat fading channel, 2 transmitter antennas, $f_{dm}$=200Hz, coded W-CDMA.**

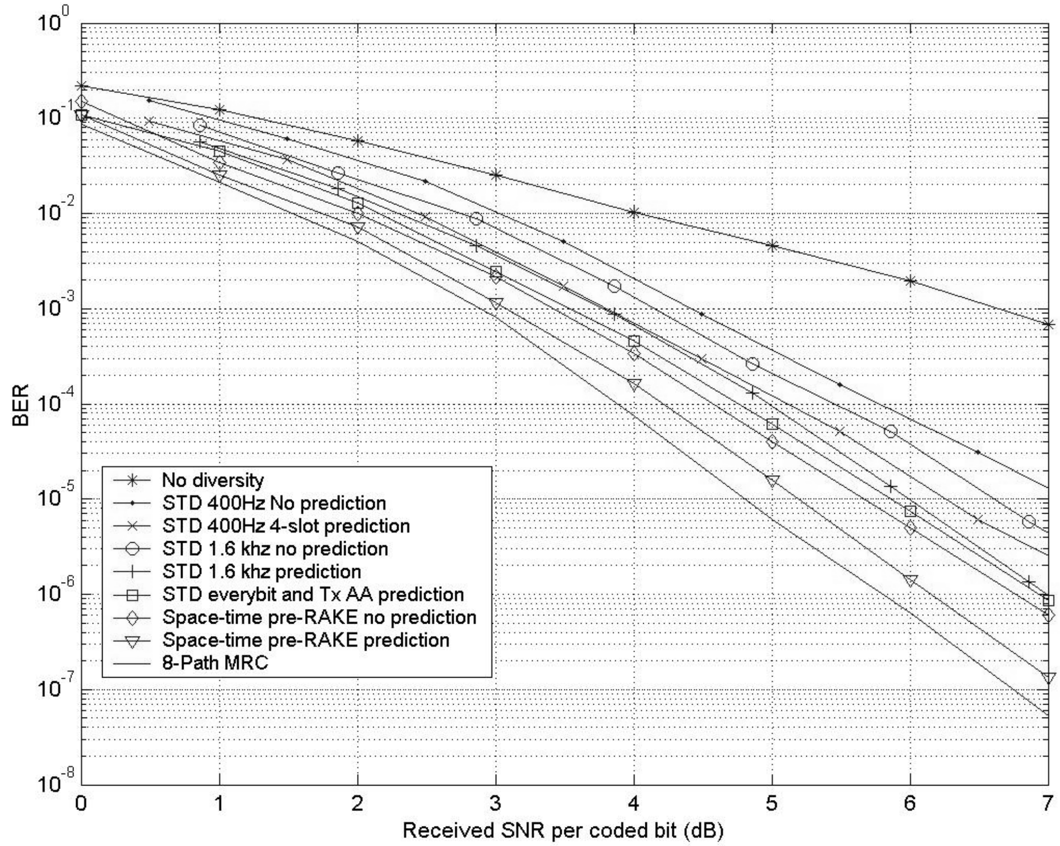


**Figure 5. Comparison of STD, Tx AA and Space-time pre-RAKE, 2 transmitter antennas, 4 paths, $f_{dm}$=200Hz. Coded W-CDMA.**

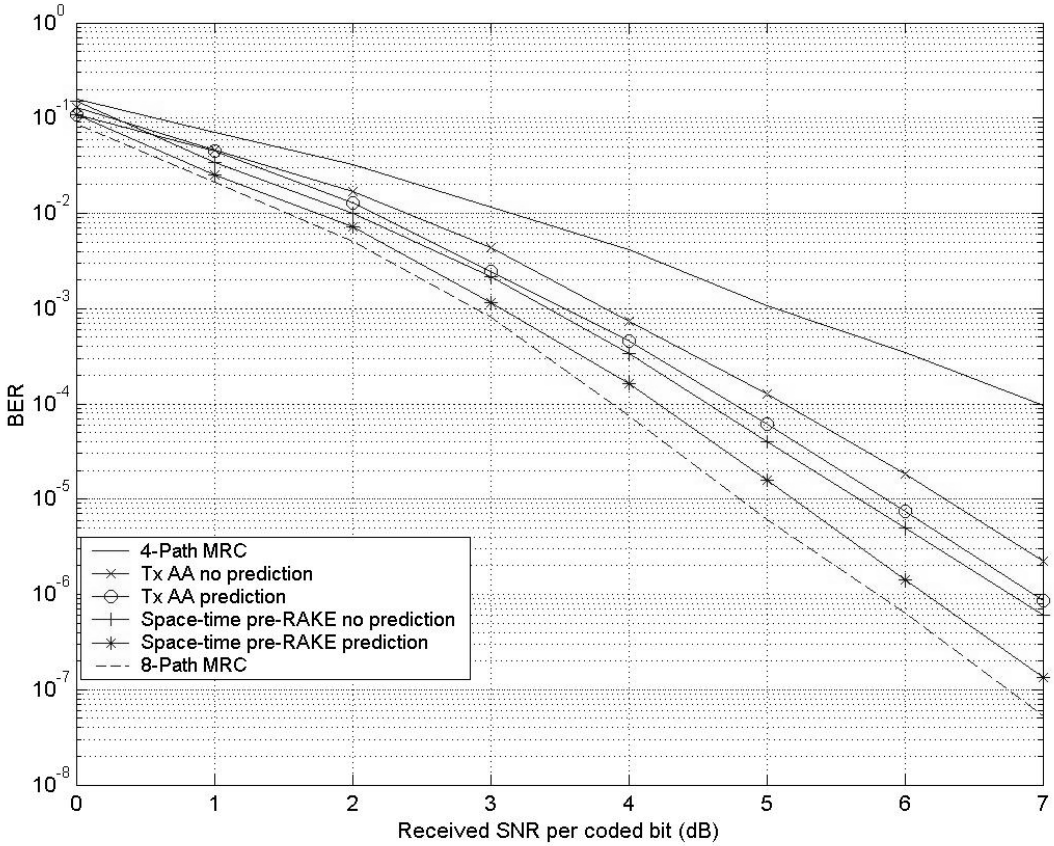


**Figure 6. Comparison of Tx AA and Space-time pre-RAKE, 2 transmitter antennas, 4 paths, $f_{dm}$=200Hz. Coded W-CDMA.**