Space-Time Pre-RAKE Multiuser Transmitter Precoding for DS/CDMA Systems

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Abstract: *A novel linear precoding method that combines Multiuser Interference (MAI) cancellation, pre-RAKE filtering and Transmitter (Tx) antenna diversity is proposed for the downlink of the Code Division Multiple Access (CDMA) channel. It is demonstrated that this method has better performance than single user space-time pre-RAKE precoding with relatively low increase in complexity. In addition, several novel and previously proposed MAI cancellation methods for the uplink and downlink are compared. Long range prediction is employed to enable performance of Tx precoding for rapidly time varying fading CDMA channels.*

I. INTRODUCTION

Multipath-induced MAI severely degrades performance of bandwidth efficient CDMA systems. While receiver-based multiuser detection (MUD) techniques are suitable for the uplink [1,9,10,17-19], Tx-based MAI cancellation techniques have been proposed for the downlink to shift computational complexity and power consumption from the Mobile Station (MS) to the Base Station (BS), where they can be afforded [2,3]. However, these methods are complex since MAI cancellation filters need to be updated continuously as fading coefficients vary.

CDMA technology greatly benefits from exploiting the multipath diversity of the channel. Pre-RAKE diversity combining [8] was proposed for the downlink channel to achieve multipath diversity without the burden of the RAKE receiver at the mobile. In [6,15,16], space-time pre-RAKE (STPR) technique was investigated for transmitter antenna diversity systems. The ideal performance of this method approaches that of the maximal ratio combining (MRC) of all space and frequency diversity branches.

In [13], we proposed the pre-RAKE multiuser precoding (pre-RAKE decorrelator) method. In this algorithm, the functions of pre-RAKE combining and MAI cancellation are separated. Thus, the MAI cancellation matrix does not depend on rapidly time-varying fading coefficients. This method has similar performance to other previously proposed linear precoding techniques [2,3] and the pre-RDD method recently investigated in [14], but the complexity is much lower.

In this paper, we extend the pre-RAKE decorrelator [13] to antenna array systems by combining it with the STPR approach of [6,15,16]. The proposed space-time pre-RAKE multiuser precoding (STPR MUP) has low computational complexity, and the receiver for each user is a simple matched filter.

Precoding and transmitter diversity techniques require the knowledge of the received Channel State Information (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 channel prediction (LRP) can be used to forecast the fading profile of the channel and improve performance [4-6]. We use the LRP to enable performance of precoding techniques in rapidly time variant channels.

In the next section, we describe the DS/CDMA system, channel model and the pre-RAKE diversity combining. Section III describes several previously proposed and new linear MAI cancellation methods for multipath channels. The proposed space-time precoding method is introduced in Section IV. Numerical and simulation results are presented in Section V.

II. SYSTEM MODEL AND PRE-RAKE FILTERING

First, consider the downlink of the synchronous DS/CDMA system with K active users and a single transmitter antenna. The transmitted equivalent lowpass signal x(t) at the BS is $x(t) = \sum_{k=1}^{K} A_k b_k s_k(t),\ 0 \le t \le T_b$, where for the k^{th} user, A_k is the amplitude, $b_k \in \{-1,1\}$ is the data bit, $s_k(t)$ is the unit energy normalized signature waveform and T_b is the bit duration. We assume the observation interval $0 \le t \le T_b$ throughout the paper. The transmitted signal can be expressed in vector notation as $x(t) = \mathbf{s}^T\mathbf{A}\mathbf{b}$, where $\mathbf{A}=\mathrm{diag}(A_k)_{KxK}$ is the diagonal amplitude matrix, $\mathbf{b}=[b_1,..,b_K]^T$ is the vector of the data bits of K users, and $\mathbf{s}=[s_1(t)..s_K(t)]^T$ is the vector of signature waveforms. Binary Phase Shift Keying (BPSK), or alternatively, Quadrature Phase Shift Keying (QPSK) is employed. The passband energy of k^{th} user's bit is given by $E_k=A_k^2/2$.

The frequency selective channels associated with different users are assumed to be independent and identically distributed (i.i.d.) multipath Rayleigh fading. If there are L resolvable paths, the impulse response of the k^{th} user's channel is given by:

$$h_k(t)=\sum_{l=0}^{L-1} h_{kl}\delta(t-lT_c) \qquad \textbf{(2.1)}$$

where, h_{kl} is the time varying complex Gaussian fading coefficient corresponding to the l^{th} path of the k^{th} user, and T_c is the chip interval. The received signal at the k^{th} MS is given by $r_k(t) = \sum_{j=1}^{K}\sum_{l=0}^{L-1} A_j b_j h_{kl} s_j(t-lT_c) + n_k(t)$**,** where $n_k(t)$, k=1…K are i.i.d. complex valued zero-mean white Gaussian noise processes (AWGN) with power spectral density (PSD) N_o. The signal to noise ratio (SNR) per bit for user k is $A_k^2/2N_o$. Similarly, for the uplink CDMA system, the received signal at the BS is $r(t)=\sum_{k=1}^{K}\sum_{l=0}^{L-1} A_k b_k h_{kl} s_k(t-lT_c)+ n(t)$, where n(t) is AWGN with PSD N_o [13].

This paper assumes synchronous transmission for both the uplink and the downlink. In the downlink, the spreading codes associated with different users are generated to be orthogonal to each other and the transmission is synchronous. For the multipath DS-CDMA channel, the delay spread is on the order of several chip intervals, and $T_c \ll T_b$. Thus, the intersymbol interference (ISI) and the MAI due to adjacent symbol intervals are negligible. As a result, the MAI and self-interference are mostly due to the effects of the multipath in the current symbol interval, and the synchronous model is appropriate. The uplink signal is often asynchronous in practice. However, in this paper we use the uplink model primarily for performance comparison with the proposed downlink methods, so the synchronous assumption is sufficient.

We utilize the *pre-RAKE* filtering method [8] at he BS that was shown to achieve performance of the RAKE receiver, while employing a single matched filter at the MS. The block diagram of the method is shown in Figure 1, where D is a delay of T_c seconds. The transmitted signal for the k^{th} user is:

$$p_k(t) = \frac{1}{\sqrt{\sum_{j=0}^{L-1} |h_{kj}|^2}} \sum_{j=0}^{L-1} A_k b_k h^*_{k(L-1-j)} s_k(t-jT_c) \qquad \textbf{(2.2)}$$

These signals are summed and sent to individual users. The receiver of the k^{th} user employs a filter matched to $s_k(t-(L-1)T_c)$. For ideal spreading codes (when multipath-induced interference is not present), the output signal achieves full Maximal Ratio Combining (MRC) diversity benefit without using the RAKE receiver at the MS.

The channel model in (2.1) can be easily extended to multiple transmitter antenna systems. Assume there are M transmitter antennas and a single receiver antenna. The channel associated with each antenna is given by:

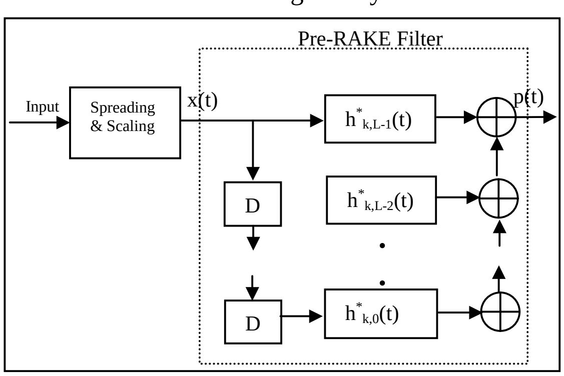

Figure 1. Pre-RAKE Diversity Combining

$$h^m_k(t)=\sum_{l=0}^{L-1} h^m_{kl}\delta(t-lT_c) \qquad \textbf{(2.3)}$$

and we assume that the channels are i.i.d. Rayleigh fading with the same characteristics as in (2.1). In [6,15,16], the pre-RAKE filter was extended to multiple transmitter antenna systems. In this case, a pre-RAKE filter specific to each antenna is applied prior to transmission. This system achieves the gain of MRC for MxL diversity branches for ideal spreading codes.

III. LINEAR MAI CANCELLATION METHODS FOR MULTIPATH FADING CHANNELS

The performance of the conventional single-user RAKE receiver and the pre-RAKE filter degrades due to multipath-induced MAI. Linear multiuser detectors for multipath fading channels include the *Multipath Decorrelating Detector (MDD)* [9] and the *RAKE Decorrelating Detector (RDD)* [10]. RDD achieves the optimum performance over all linear multiuser detectors for multipath signals of unknown energy [10]. MDD has slightly worse performance, but lower complexity than RDD.

As an alternative to Rx based methods, pre-filtering can be applied on the downlink at the BS transmitter to "precode" the transmitted data in order to eliminate MAI at every individual receiver while employing a simple single user receiver. *Linear multiuser precoding* methods have been previously proposed in, e.g. [2,3], and, more recently, in [14], where the MAI cancellation matrix that has the same structure as in the RDD MUD is placed prior to the pre-RAKE filtering. The method described in [2] requires the RAKE receiver at each MS, whereas the techniques proposed in [3,14] eliminate the need for the RAKE receiver. For these methods, inversion of KxK matrices is necessary. The elements of these matrices depend on the CSI, so recalculation of the inverse matrix is required at the rate of variation of the channel fading.

A simpler pre-RAKE multiuser precoding method was proposed in [13] (Fig. 2). In this method, the functions of the pre-RAKE filtering and multiuser precoding are separated and the multiuser cancellation matrix is independent of channel fading. First, the tap delay line filter as in the pre-RAKE structure (Fig. 1) is applied to the non-spread input signal of each user, i.e., L delayed components of the input signal are created and weighted appropriately. The linear multiuser decorrelating filter **G** then processes jointly the KL outputs of these filters. The resulting signal is spread using a bank of KL spreading filters of all users expressed in the matrix form as:

$$\mathbf{S}=[\mathbf{s}_1..\mathbf{s}_K]_{1xKL}, \text{ where } \mathbf{s}_k=[s_k(t-(L-1)T_c..s_k(t)] \qquad \textbf{(3.1)}$$

The outputs of the spreading filters are summed, the resulting signal is scaled to keep the total transmitted power normalized and the resulting signal is sent to all mobile stations. The decorrelating filter **G** removes all multipath-induced interference. For rapidly varying fading channels, the pre-RAKE coefficients and scaling factors need to be updated for each transmitted symbol. However, the decorrelating matrix depends only on the signature sequences and the number of multipath components, not on channel gains [13]. Thus the matrix inverse does not have to be updated as the channel gains vary at the fading rate, and the complexity is much lower than for linear precoders in [2,3] and for the pre-RDD method [14]. Note that the structure of this precoder is related to that of the low complexity MDD receiver [9].

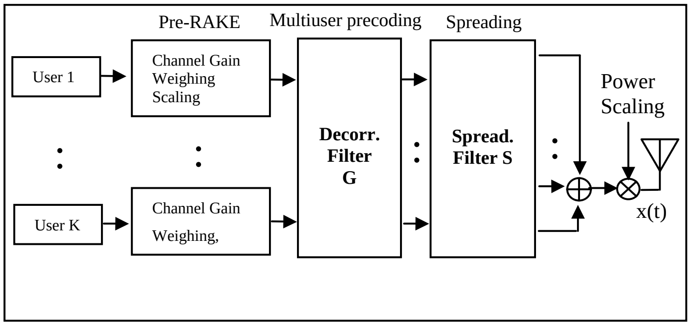

Figure 2. Pre-RAKE Multiuser Precoding

All linear recoding methods require scaling of transmitter signals to normalize the transmitter power. Therefore, performance of these techniques is degraded by the scaling factor, similarly to the noise enhancement in the receiver-based MUDs. Expressions for the BER of the precoding methods and MUDs discussed above result from averaging the corresponding BER for the AWGN. This AWGN BER is given by the Q-function with the argument that depends on the received SNR and the scaling factor or the enhanced noise variance for linear precoders and MUDs, respectively.

It was shown in [17-19] that combining linear multiuser detection with multiple receiver antennas improves the BER performance for multipath fading multiuser CDMA channels. In [17], the MDD structure [9] is extended to multiple antennas. First, the MAI at each antenna is removed through decorrelating. Then the resulting signals from all antennas are whitened and optimally combined using MRC. In [19] the optimal combining of received signals is performed first, followed by multiuser decorrelation, resulting in the extension of the RDD receiver [10].

MUD with multiple antennas is suitable for the uplink channel, given the limitations of the MS. Alternatively, multiuser precoding can be extended to multiple antennas to achieve similar gains for the downlink.

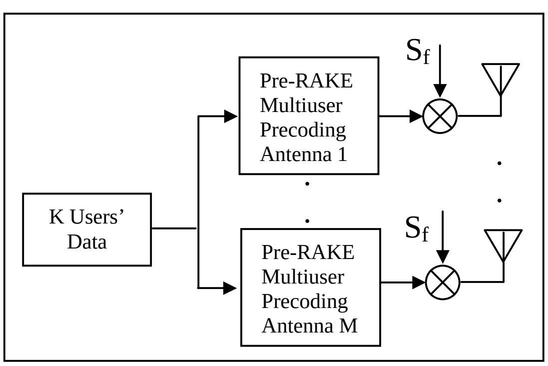

Figure 3. Block Diagram of Space-Time Pre-RAKE Multiuser Precoding

IV. SPACE-TIME PRE-RAKE MULTIUSER TRANSMITTER PRECODING TECHNIQUE

Assume multiple transmitter antenna channel model (2.3). Consider the transmitter for the proposed precoding method shown in Figure 3. Antenna-specific pre-RAKE multiuser precoding is applied prior to transmission at each antenna. The transmitted signal at the m[th] antenna is given by

$$x_m(t)=S_f\mathbf{S}\mathbf{G}\mathbf{C}^{\mathbf{H}}_{\mathbf{m}}\mathbf{A'b}, \tag{4.1}$$

where $\mathbf{G}$ is the KLxKL precoding matrix and $\mathbf{S}$ is given in (3.1). The pre-RAKE weighting matrix for the m[th] antenna is:

$$\mathbf{C}_m^{H} = \begin{bmatrix} \mathbf{h}_1^m & 0 & .. & 0 \\ 0 & \mathbf{h}_2^m & .. & : \\ : & : & : & 0 \\ 0 & .. & 0 & \mathbf{h}_K^m \end{bmatrix}_{KLxK} \tag{4.2}$$

where the vector $\mathbf{h}^m_k=[h^m_{k,0},\dots,h^m_{k,L-1}]^H$, and $\mathbf{A}'=\mathbf{S}_p\mathbf{A}$ is the scaled version of the diagonal amplitude matrix $\mathbf{A}$. The diagonal pre-RAKE scaling matrix $\mathbf{S}_p$ = $\mathbf{S}_p = \text{diag}\,\{1/\sqrt{\sum_{m=1}^{M}\sum_{l=0}^{L-1}|h_{kl}^{m}|^2}\}_{KxK}$, k=1..K. The transmitted signal $x_m(t)$ in (4.1) is convolved with the channel response (2.3) for each m, and the received signals are superimposed at the each MS. The receiver of the k[th] user employs a filter matched to $s_k(t-(L-1)T_c$. The received K-dimensional signal vector that corresponds to the outputs of all users can be expressed as: $\mathbf{y}=\sum_{m=1}^{M}(\mathbf{C}_m\mathbf{RGC}_m^H\mathbf{Ab})+\mathbf{n}$, where $\mathbf{n}$ is zero mean white Gaussian noise vector with the covariance matrix $N_0\mathbf{I}$ and the KL x KL matrix $\mathbf{R}$ is the matrix of cross-correlations between the multipath components of all users. It that can be defined in terms of its LxL sub-matrices $\mathbf{R}_{ik}^{lm} = \int_{-\infty}^{\infty} s_i(t-(L-1+l-m)T_c)\, s_k(t-(L-1)T_c)dt$, $m,l\in\{0,\dots,L-1\}$, $i,k\in\{1,\dots,K\}$. To cancel MAI, we let $\mathbf{G}=\mathbf{R}^{-1}$. Note that this matrix is the same as in the pre-RAKE multiuser precoding system for single antenna [13]**.** To normalize the transmitter power, the scaling factor in (4.1) is given by:

$$S_f^2 = \frac{\sum_{k=1}^{K} A_k^2/2}{\sum_{m=1}^{M}\sum_{k=1}^{K}\left[\frac{A_k^2/2}{\sum_{j=1}^{M}\sum_{l=0}^{L-1}|h_{kl}^{j}|^2}\right](\mathbf{C}_m\mathbf{GC}_m^{H})_{kk}} \tag{4.3}$$

For the k[th] user, the output of the matched filter at the receiver is $y_k = S_f\sqrt{\sum_{m=1}^{M}\sum_{l=0}^{L-1}|h_{kl}^{m}|^2}A_k b_k+n_k$. Then the instantaneous probability of error for user k is given by:

$$P_k = Q\left(\sqrt{\left(\sum_{m=1}^{M}\sum_{l=0}^{L-1}|h_{kl}^{m}|^2\right) S_f^2\frac{A_k^2}{N_o}}\right) \tag{4.4}$$

Note that for an ideal system without MAI, this BER is equivalent to MRC with MxL-order of diversity and the precoder reduces the space-time pre-RAKE method [6,15,16].

The performance degradation is caused by S_f and depends on the autocorrelation and cross-correlation properties of the spreading codes. For a single antenna system, this precoding technique reduces to the pre-RAKE multiuser precoding in [13]. This system is related to the multiple receiver antenna MDD system [17].

V. NUMERICAL AND SIMULATION RESULTS

In the simulations and numerical results, orthogonal spreading codes of W-CDMA [11] are used, and error control coding is not employed. We assume perfect CSI at the receiver. Total average channel power is normalized to one. The BER of MRC in the plots is evaluated analytically [7] and gives the lower bound on the BER of all methods. The order of diversity for each plot is given by the number of paths times the number of antennas.

In Figure 4, we investigate the performance of linear multiuser precoding methods described in section III for single transmitter antenna system. BER performance of Rx based MUD schemes and Tx based precoding methods is compared. The models associated with uplink and downlink are different, as described in section II. However, noise enhancement of Rx decorrelating MUDs is analogous to the transmission power scaling of Tx precoders. Furthermore, it can be shown that the performance of the linear MUDs and corresponding linear transmitter precoders is the same for simplified channel parameters, and duality exists between these structures. Therefore, it is meaningful to compare their performance.

The BER of the RAKE receiver with MRC is determined by simulation. The MDD and RDD are employed at the BS on the uplink, and the RAKE receiver at the MS on the downlink. The precoding methods are utilized at the BS for the downlink channel. Numerical results are presented for the precoding methods assuming that ideal CSI is available at the BS. These results are computed by averaging the instantaneous BER of each method over the statistics of the fading channel. In this example, high numbers of users and paths result in large MAI, and the performance of the RAKE receiver is severely degraded. It is observed that all multiuser methods significantly improve upon the RAKE receiver and perform similarly. However, the level of complexity is not the same. Among the precoding techniques, the precoding+RAKE method [2] has the highest complexity, since it requires the RAKE receiver at the MS. Moreover, the matrix inversion at the BS needs to be updated as channel coefficients vary. The prefilters no RAKE method [3] and pre-RDD [14] are simpler, since only a matched filter is needed at the MS. However the matrix inversion based on the CSI is still necessary. The pre-RAKE multiuser precoding method in [13] is the simplest among the four precoding techniques. The matrix to be inverted is not dependent on the CSI, and a single matched filter is required at the MS. Only computation of the tap weights in the pre-RAKE and the scaling factor needs to be updated as the channel varies.

In Figure 5, we remove the assumption of perfect CSI and explore realistic rapidly varying fading multiple antenna CDMA channels where the CSI needs to be fed back and predicted far ahead to enable adaptive transmission. It was shown in [4-6] that long range prediction (LRP) 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, the LRP of the coefficients h_{kl}^m in (2.3) associated with individual paths is employed [4]**.** The LRP model order is p=50, and the observation interval of 200 samples is used to compute the autocorrelation of each path (see, e.g. [6]). We utilize multi-step prediction to predict more than one sample ahead [5]. Noiseless observations are used in prediction.

A simulation environment based on the W-CDMA parameters was created with 2 GHz carrier frequency, 60mph vehicle speed, 4.096 Mcps chip rate, and 1.6kHz slot rate [11]. The frequency selective Rayleigh fading channels experienced by the users are modeled by the Jakes model [12]. We assume perfect power control, so that both users transmit with the same power. Scaling factors computed from simulations are used at the BS to keep the transmit power normalized for all Tx based methods. We assume that perfect channel state information is fed back to the BS at the end of each slot. The sampling rate of the LRP is chosen as the slot rate of W-CDMA. This results in 0.625 ms delay for calculating the channel state information. The prediction algorithm is used to obtain predicted values of the current and future channel coefficients given the delayed channel samples. 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 this method, the beginning of the current slot and the beginning of the next 2 slots are predicted using the past values of the channel. Then these values are filtered using a lowpass interpolating filter to compute the intermediate values between two slots, so that the CSI at the transmission rate is obtained. This CSI is used to update the coefficients of the pre-RAKE filters and scaling factors. When prediction is not employed, the CSI delayed by 0.625ms relative to the beginning of the slot is used to update these coefficients.

In Figure 5, performance of the space-time pre-RAKE multiuser precoding (STPR MUP) method (with and without prediction) is compared to the performance of space-time pre-RAKE transmitter diversity method [6] without multiuser precoding (STPR no MUP) (with prediction). The optimal performance is achieved by MRC of order 4=LxM. The BER of STPR MUP with perfect CSI is obtained under the assumption of perfect knowledge of the CSI at the Tx. Note that prediction results in approximately 1dB gain relative to precoding with delayed CSI and similar BER to the perfect CSI (no delay) case. When multiuser precoding is not employed, the STPR MUP reduces to STPR. We observe that MUP provides significant performance gain. Similar relative performance results were obtained for an 8-user system, although the BER of all precoding methods is poorer due to higher MAI and self-interference. The STPR MUP has relatively low complexity, since the precoding matrix does not depend on the fading coefficients and the inverse does not have to be updated at the fading rate. Further simplification results from employing the same precoding matrix for all antennas,

VI. CONCLUSION

Tx based multiuser precoding schemes and Rx based MUD techniques were investigated and compared. Novel STPR MUP scheme was proposed for realistic frequency selective fading CDMA channels. It was shown that this method effectively cancels MAI at relatively low complexity. The long range fading prediction was employed to enable Tx precoding techniques for rapidly fading channels.

SUPPORT

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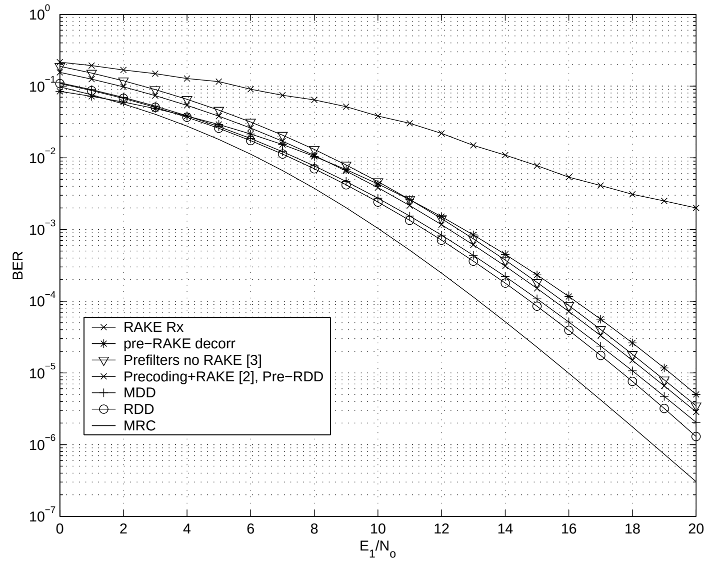

Figure 4. BER of user 1 in 4 path 8 users system with 32 chip spreading. Perfect CSI. Equal energies.

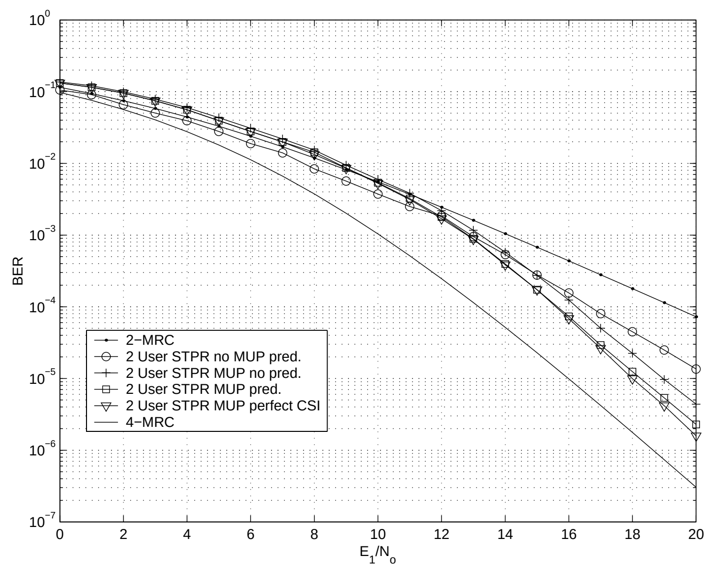

Figure 5. BER of user 1 in 2 antennas 2 paths, 2 users system with 8 chip spreading. Equal energies.