PERFORMANCE ANALYSIS OF TOMLINSON-HARASHIMA MULTIUSER PRECODING IN MULTIPATH CDMA CHANNELS

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ABSTRACT

Tomlinson-Harashima multiuser precoding (THP) is a transmitter (Tx)-based multiple access interference (MAI) cancellation technique for Direct Sequence (DS) Code-Division Multiple Access (CDMA) systems. This zero forcing (ZF)-based transmitter precoding method minimizes the mean square error at the receiver. It is suitable for the downlink since the receiver is as simple as the single user matched filter receiver. For frequency-selective fading channels, by combining THP with diversity techniques, we develop two specific designs, PreRAKETHP and Multipath Decorrelating THP (MDTHP), which provide desired performance-complexity trade-off. It is shown that the nonlinear THP designs outperform linear Tx-based methods and both linear and nonlinear receiver (Rx)-based decorrelating approaches. When the received users' powers are unequal due to channel fading, the nonlinear precoders have better performance for weaker users. Therefore, they reduce total transmit power relative to linear precoders. In addition, in rapidly varying multipath fading channels, THP aided by the long-range channel prediction (LRP) method achieves almost the same performance as when the Channel State Information (CSI) is perfectly known at the transmitter.

I. INTRODUCTION

The next generation DS-CDMA systems are required to meet the increasing demands for wireless multimedia services, such as Internet and video conferencing. For these applications, the improvement of the downlink capacity becomes more important than that of the uplink. In practical wireless channels, MAI is a major limitation to the performance of DS-CDMA systems. The well-developed multiuser detection (MUD) techniques [1] require complicated receiver structure, thus are mostly suitable for the uplink. For the downlink CDMA channel, the requirements of small-size low-power mobile station (MS) have recently motivated the development of Tx-based MAI pre-rejection techniques in the base station (BS), termed transmitter precoding [2, 3]. The class of decorrelating precoding techniques is simple, efficient and satisfies the minimum mean square error (MMSE) criterion [2, 4], thus is most promising in practical applications. The linear decorrelating precoder proposed in [2, 5] can completely pre-cancel MAI by inserting a linear filter in the transmitter, but the performance is inherently degraded by transmit power scaling. For multipath fading channels, the RAKE receiver is employed for the method in [2]. An alternative method with simpler receiver is the decorrelating prefilters [4], which pre-cancels MAI by designing transmit waveforms rather than filtering the transmit data symbols. The simulation results in [4] show that there is little difference in performance between these two methods when user number is large. Two recently proposed linear techniques, Pre-RDD [6] and PreRAKE precoding [7, 8], simplify the receiver structure by replacing Rx-based RAKE combining with Tx-based diversity combining. Inspired by Tomlinson-Harashima equalization [9], the nonlinear method of Tomlinson Harashima Precoding (THP) proposed in [10] utilizes a feedback (FB) loop and a feed-forward (FF) filter to jointly cancel MAI. An independent work on THP [11] presented the significant duality between THP and the Decision-Feedback (DF) multiuser detector (MUD) [17]. Both [10, 11] assume that the non-orthogonal effective spreading codes on the downlink arise due to multipath fading. However, the channel models employed in these papers do not reflect the frequency-selective fading channel environment, and can only be viewed as flat fading non-orthogonal CDMA channels. Moreover, the issues and trade-offs of joint precoding and diversity combining are not addressed in these references.

In this paper, we analyze two novel THP designs for frequency selective fading channels, PreRAKETHP and Multipath Decorrelating THP (MDTHP) (see also [12]). PreRAKETHP and MDTHP incorporate Tx-based diversity combining techniques in different ways. In PreRAKETHP,

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the MAI cancellation is followed by the pre-RAKE combining [13]. While this precoder is the optimal THP design for multipath channels, it requires high computational complexity, since its MAI cancellation filters depend on the rapidly time variant mobile radio channel coefficients and need to be updated frequently. In MDTHP, the diversity combining is incorporated into the MAI cancellation, and the precoding filter is independent of the channel. Thus, MDTHP is simpler than PreRAKETHP, and results in moderate bit error rate (BER) loss. The essential distinction between the precoders in this paper and the methods in [10, 11] is the extension to multipath fading channels, by employing Tx-based diversity combining jointly with interference cancellation. In this paper, we not only address the duality between the Tx-based THP methods and the Rx-based DF MUD methods [15, 17], but also discuss the important relation between the proposed nonlinear precoders and linear decorrelating precoders. By theoretical and numerical analysis, it is shown that the THP outperforms previously proposed Tx- and Rx-based linear and nonlinear decorrelating methods in [2, 4-8, 14-17].

We only consider the synchronous system in the following discussion. The synchronous assumption is usually justified for the downlink channel since users employ orthogonal signature sequences, the chip interval is much smaller than the symbol interval and the multipath delay spread is on the order of a few chip intervals. Thus, in these systems multipath-induced MAI and self-interference is primarily limited to one symbol interval [4]. However, by employing the spectral factorization [18], the derivations in this paper can be easily extended to the asynchronous case. Another crucial assumption for Tx-based interference cancellation methods is that the transmitter has the knowledge of channel conditions. For rapidly time varying fading channels, the long-range channel prediction (LRP) is required to enable these techniques [19]. In this paper, we investigate transmitter precoding aided by the LRP.

In section II and III, the PreRAKETHP and MDTHP schemes are explained respectively and compared with other methods. The simulation results in section IV provide more performance comparisons among different precoding techniques. We present the concluding remarks in section V.

II. PRERAKE TOMLINSON-HARASHIMA PRECODING (PRERAKETHP)

Consider a K-user DS-CDMA system and a set of pre-assigned signature sequences $s_i(t)$, $i = 1,2,...,K$. In the symbol interval of interest [0, T), the data symbol for user i is denoted by b_i. For high-speed downlink CDMA channels, the higher-order modulation is favorable because the data transmission efficiency can be improved without increasing MAI [20]. In the following discussion, we use pulse amplitude modulation (PAM) as an example in derivation, while quadrature amplitude modulation (QAM) is also considered in numerical experiments. For an M-PAM system, $b_i \in \{-(M-1)A_i, -(M-3)A_i, \ldots, (M-1)A_i\}$, where A_i is half of the minimum Euclidean distance for the data symbols of user i. Suppose there are N resolvable multipath components for every user, and $c_{i,n} = \alpha_{i,n} e^{j\varphi_{i,n}}$ represents the Rayleigh fading gain of the nth path component over the channel between the transmitter and the ith user receiver, $\forall\, i = 1, 2, \ldots, K$ and $n = 0, 1, \ldots, N-1$. For each user, define the vector $\mathbf{c}_i = [c_{i,0}, c_{i,1}, \ldots, c_{i,N-1}]$. By assuming the multipath spread is small relative to the symbol duration, the inter-symbol interference (ISI) is minor and therefore ignored in the remaining discussion. Without transmitter precoding, the equivalent baseband received signal at the ith mobile user receiver site can be expressed as

$$r_i(t) = \sum_{k=1}^{K} \sum_{n=0}^{N-1} c_{i,n} b_k s_k (t - nT_c) + n_i(t), \tag{1}$$

where T_c is the chip duration and $n_i(t)$ is the complex white Gaussian noise.

First, consider the CDMA system that utilizes preRAKE combining [13]. To avoid the transmit power increase due to preRAKE processing, we use the normalized fading channel coefficients in the Tx. For the ith user, the normalized fading coefficient is $\hat{c}_{i,n} = c_{i,n} / \|\mathbf{c}_i\|$, $n = 0, 1, \ldots, N-1$, and the normalized vector corresponding to $\mathbf{c}_i$ is $\hat{\mathbf{c}}_i = [\hat{c}_{i,0}, \hat{c}_{i,1}, \ldots, \hat{c}_{i,N-1}]$. For all K users, define a K-row, $(K \times N)$-column channel gain matrix $\mathbf{C} = diag\{\mathbf{c}_1, \mathbf{c}_2, ..., \mathbf{c}_K\}$ and the corresponding normalized matrix $\hat{\mathbf{C}} = diag\{\hat{\mathbf{c}}_1, \hat{\mathbf{c}}_2, ..., \hat{\mathbf{c}}_K\}$. The cross-correlations between delayed signature sequences are represented as $M_{i,k}^{m} \equiv \int_0^T s_i(t) s_k(t + mT_c)\, dt$, $m \in \{-(N-1), \ldots, (N-1)\}$. For $\forall\, i, k \in \{1, 2, \ldots, K\}$, define the $N \times N$ correlation matrix $\mathbf{M}_{i,k}$ with the jth row given by $[M_{i,k}^{1-j}, M_{i,k}^{2-j}, ..., M_{i,k}^{N-j}]$, j=1, 2,…, N. Then we can construct the $(K \times N)$-row and $(K \times N)$-column matrix $\mathbf{M}$ by superimposing the $K \times K$ non-overlapping submatrices $\mathbf{M}_{i,k}$, $i, k \in \{1,2,\ldots,K\}$. Suppose the inputs of the preRAKE combiner for the K users are represented by $\mathbf{w} = [w_1, w_2, \ldots, w_K]^T$, then the matched filter (MF) outputs in the K users' receivers are given by

$$\mathbf{y} = \hat{\mathbf{R}}\mathbf{w} + \mathbf{n}, \tag{2}$$

Where $\hat{\mathbf{R}} \equiv \hat{\mathbf{C}}\mathbf{M}\hat{\mathbf{C}}^H$. The matrix $\hat{\mathbf{R}}$ is positive definite. Thus, it can be factored into two triangular matrices $\mathbf{F}_{\mathrm{P}} = \{f_{\mathrm{P}ij}\}_{K \times K}$

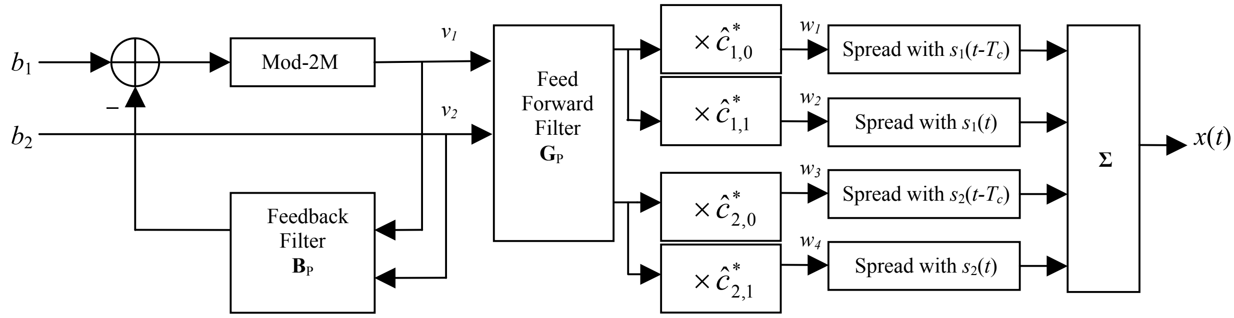

Fig. 1 The Transmitter of PreRAKETHP for Multipath Fading Channels (a 2-user 2-channel path/user system)

and $\mathbf{F}_P^H$ using the Cholesky factorization. Denote the normalized matrix corresponding to $\mathbf{F}_P$ as $\hat{\mathbf{F}}$.

The PreRAKETHP transmitter structure is shown in Fig. 1. Prior to the pre-RAKE combiner, a FB loop followed by a FF filter is used to cancel multipath-induced MAI. The output of the FB filter is fed to a bank of mod-2M operators to limit the transmit power. The FB and FF filters in PreRAKETHP are defined as $\mathbf{B}_P \equiv diag(\hat{\mathbf{F}})^{-1}\hat{\mathbf{F}}^H - \mathbf{I}$ and $\mathbf{G}_P \equiv \hat{\mathbf{F}}^{-1}$, respectively. With THP processing, the input to the preRAKE combiner is $\mathbf{w} = \mathbf{G}_P(\mathbf{B}_P + \mathbf{I})^{-1}(\mathbf{b} + 2M\mathbf{Ad})$, in which the term $2M\mathbf{Ad}$ is generated by the mod-2M operation [11]. Following the preRAKE combining, the transmitted signal is given by

$$x(t) = \sum_{k=1}^{K} \sum_{l=0}^{N-1} \hat{c}^*_{k,l} w_k s_k (t - (N - n - 1)T_c). \qquad (3)$$

The equivalent baseband received signal at the ith user receiver site is given by

$$r_i(t) = \sum_{k=1}^{K}\sum_{n=0}^{N-1}\sum_{l=0}^{N-1} c_{i,n} w_{kN-l} s_k(t - lT_c - nT_c) + n_i(t). \qquad (4)$$

Each user's receiver is simply composed of a filter matched to that user's signature sequence and a mod-2M operator that cancels the effect of the modulo operation in the Tx. The output of the MF is sampled at $t = (N–1)T_c$, and for the ith user is given by

$$y_i = \int_{(N-1)T_c}^{T+(N-1)T_c} r_i(t) s_i(t - (N-1)T_c) dt. \qquad (5)$$

We assume the channel gains and, therefore, f_{Pii} are estimated in the receivers. Then for the ith user, we have $f_{Pii}^{-1} y_i = b_i + 2MA_i d_i + f_{Pii}^{-1} n_i$. The term $2MA_i d_i$ will then be cancelled by mod-2M operation. The instantaneous ideal SER of the ith user is given by

$$Pe_i(\gamma_{bi}) = \frac{2(M-1)}{M} Q\left(\sqrt{\frac{6(\log_2 M) f_{Pii}^{\ 2}}{M^2 - 1}\gamma_{bi}}\right) \qquad (6)$$

Since the THP precedes the preRAKE combiner that is essentially the filter bank matched to the signature waveforms convolved with the multipath channel responses, the PreRAKETHP is the optimal decorrelating THP method. In [12], we proved that the PreRakeTHP outperforms the linear methods RDD, Pre-RDD and MDD.

III. MULTIPATH DECORRELATING TOMLINSON-HARASHIMA PRECODING (MDTHP)

One drawback of the PreRAKETHP is that the coefficients of the FB and FF filters depend on the channel gains. Consequently, the matrix factorization and inversion required for the computation of these coefficients have to be performed frequently, especially for rapidly varying fading channels. To alleviate this problem, we present an alternative THP design, MDTHP.

The transmitter diagram for the MDTHP is shown in Fig. 2. Note that the $(K\times N)$-row $(K\times N)$-column positive definite matrix $\mathbf{M}$ is only determined by the spreading sequences and not related to channel gains. We can decompose $\mathbf{M} = \mathbf{F}_M^T\mathbf{F}_M$ by Cholesky factorization, where $\mathbf{F}_M$ is a lower triangular matrix. Divide $\mathbf{F}_M$ into $K\times K$ blocks, where each block is an $N\times N$ submatrix; and represent the block on the ith row and jth column as $[\mathbf{F}_M]_{ij}$, $\forall\, i, j = 1, 2,\ldots, K$. The FB loop works in the following way. First, the N-dimensional vector $\mathbf{v}_K$ is computed by applying N weights to the input symbol of the last user, $\mathbf{v}_K = b_K \cdot ([\mathbf{F}_M]_{KK}\hat{\mathbf{c}}_K^H)$. The interference caused by user K is calculated from $\mathbf{v}_K$, and fed back to be canceled from the signals of other users. This procedure is repeated consecutively for $k = K–1, K–2, \ldots, 2$, thus forming vectors $\mathbf{v}_k$. For user i, $\forall i = 1, 2, \ldots, K–1$, the feedback from user j, $j = i+1, i+2, \ldots, K$, is given by $\frac{\hat{\mathbf{c}}_i [\mathbf{F}_M]_{ji}^T \mathbf{v}_j}{\sqrt{\beta_i \beta_j}}$, where

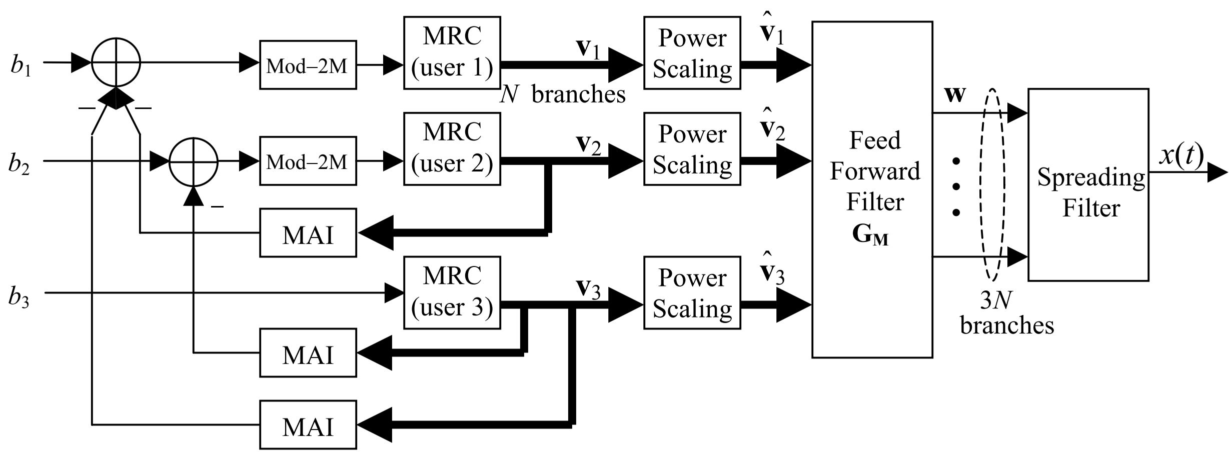

Fig. 2 The Transmitter of MDTHP for Multipath Channels (a 3-user *N*-channel path/user System)

$\beta_i \equiv \hat{\mathbf{c}}_i[\mathbf{F}_\mathrm{M}]_{ii}{}^T[\mathbf{F}_\mathrm{M}]_{ii}\hat{\mathbf{c}}_i{}^H$. Thus, for users 1 through $K-1$, the output of the FB loop is

$$\mathbf{v}_i = \left(b_i - \sum_{j=i+1}^{K} \frac{\hat{\mathbf{c}}_i[\mathbf{F}_\mathrm{M}]_{ji}{}^T \mathbf{v}_j}{\sqrt{\beta_i\beta_j}} + 2MA_i d_i \right) \cdot [\mathbf{F}_\mathrm{M}]_{ii}\hat{\mathbf{c}}_i{}^H, \quad (7)$$

The output power is normalized by multiplying $\mathbf{v}_i$ by the scaling factor $S_{vi} = (\hat{\mathbf{c}}_i[\mathbf{F}_\mathrm{M}]_{ii}{}^T[\mathbf{F}_\mathrm{M}]_{ii}\hat{\mathbf{c}}_i{}^H)^{-1/2} = \beta_i^{-1/2}$. Let $\hat{\mathbf{v}}_i = S_{vi} \cdot \mathbf{v}_i$, $i = 1, 2, \ldots, K$. Represent the input of the FF filter by the vector $\hat{\mathbf{v}} = [\hat{\mathbf{v}}_1{}^T, \hat{\mathbf{v}}_2{}^T, \ldots, \hat{\mathbf{v}}_K{}^T]^T$. The normalized outputs of the FB loop pass through the FF filter and are finally spread with the signature sequences. The FF filter output is $\mathbf{w} = \mathbf{G}_\mathrm{M}\hat{\mathbf{v}}$, where the filter $\mathbf{G}_\mathrm{M}$ is defined as $\mathbf{F}_\mathrm{M}{}^{-1}$. Following the derivation similar to that for the PreRAKETHP above, we obtain the matched filter bank output in the receivers as $\mathbf{y} = \mathbf{CMw} + \mathbf{n}$. For user i, this output is

$$y_i = \sqrt{\beta_i} \big/ S_i (b_i + 2MA_i d_i) + n_i, \quad (8)$$

where $S_i = \left(\sum_{n=0}^{N-1} \left| c_{i,n} \right|^2 \right)^{-1/2}$. Consequently, the ideal instantaneous SER for the ith user is

$$Pe_i(\gamma_{bi}) = \frac{2(M-1)}{M} Q\left(\sqrt{\frac{6(\log_2 M)\mathbf{c}_i[\mathbf{F}_\mathrm{M}]_{ii}{}^T[\mathbf{F}_\mathrm{M}]_{ii}\mathbf{c}_i{}^H}{M^2-1}\gamma_{bi}} \right). \quad (9)$$

The MDTHP method significantly simplifies transmitter precoding compared to the PreRAKETHP, since it employs the factorization of the channel gain-independent matrix **M**. Thus even for rapidly varying mobile radio channels the matrix factorization and inversion operations do not have to be performed frequently. These filters depend only on the signature sequences and the order of the users. From the theoretical symbol error rate (SER) of the PreRAKETHP and MDTHP, it is observed that they have the same performance for the last user, which is the same as for an isolated single user with RAKE receiver; for other users, theoretical performance analysis indicates better performance for the PreRAKETHP [22].

In [22] we describe a linear multipath decorrelating precoder closely related to the MDTHP. This linear precoder can be regarded as the Tx-based counterpart of the Multipath Decorrelating Detector (MDD) [16]. Therefore we call it Multipath Decorrelating Precoding (MDP). Compare the decision statistic of the MDTHP with that of the MDP and MDD. Based on the theorem for the inverse of a partitioned symmetric matrix, it is easy to prove that for user 1, the MDTHP, MDP as well as MDD have the same performance; and for other users the MDTHP outperforms the MDP and MDD [22].

IV. PERFORMANCE ANALYSIS

The practical performance of THP schemes for M-PAM/QAM systems is degraded when M is small due to the power penalty and end effect of mod-2M operation [9]. In the proposed multiuser THP methods, the first user suffers the worst degradation and the last user is not influenced at all. Moreover, similarly to DF-MUD, as the users' order increases, the benefit of the THP becomes more pronounced (note that error propagation degrades the performance of the DF methods, but does not affect the error rate of the THP techniques [9, 11, 12]). Consider a 4-user 3-channel paths/user BPSK system, where the transmit

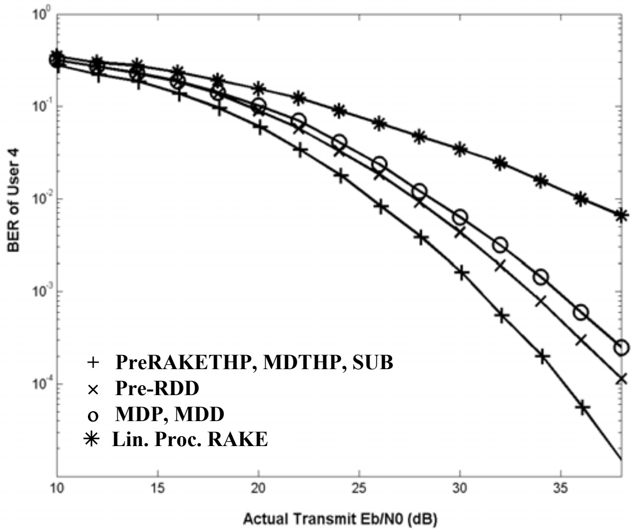

Fig. 3 Performance of the user with the weakest received signal power in large scale lognormal multipath fading channels, 4 users, 3 channel paths/user, equal transmit power for all users, the ratio of the received signal powers is 8:4:2:1, BPSK.

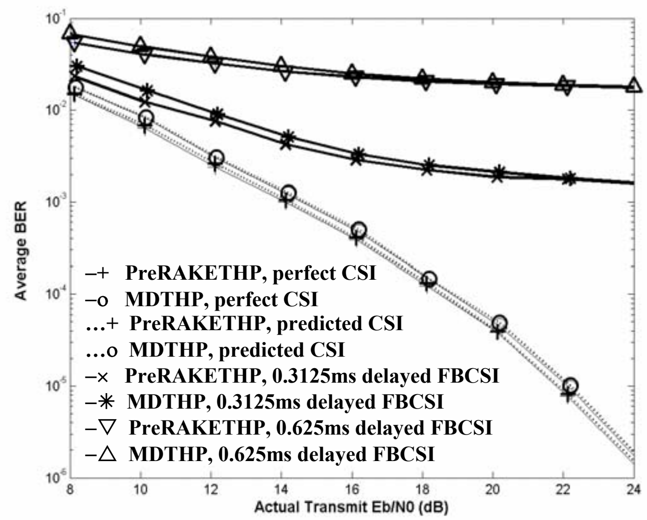

Fig. 4 Performance comparison of precoding aided by CSI prediction and by CSI feedback, 4 users with equal transmit powers, 3 channel paths/user, BPSK, data rate 128kbps, carrier frequency 2GHz, maximum Doppler frequency 200Hz, channel sampling frequency 1600Hz.

powers for all users are equal. In addition to short-term multipath Rayleigh fading, the transmitted signal is also subject to long-term shadow fading modeled by log-normal distributionwith variance 6dB [23]. Suppose the average received signal powers for the four users satisfy the ratio of 8:4:2:1. Fig. 3 demonstrates the BER of the weakest user. The proposed two nonlinear techniques, linear techniques Pre-RDD, MDP, MDD and the linear precoder with RAKE receiver [2] (labeled as "Lin. Prec. RAKE") are compared. As expected, for the last user PreRAKETHP and MDTHP result in the same performance as for the isolated single user with RAKE receiver (SUB), while other methods have poorer performance. Equivalently, the users that experience greater propagation loss will require lower power to satisfy the target BER. Thus, in practice the overall transmit power can be reduced when THP methods are employed.

We also investigate the performance of the THP techniques under the condition that the CSI is not perfectly known at the Tx. Consider a BPSK modulated 4-user 3-channel paths/user wideband-CDMA (W-CDMA) system with the data rate 128kbps. The rapidly varying frequency selective Rayleigh fading is simulated using the Jakes model [21]. In Fig. 4, the average BER of the proposed precoding methods is shown for three different cases: CSI is perfectly known at the Tx; CSI is predicted by 3-step LRP algorithm [19]; CSI is estimated at the Rx and fed back to the Tx (no prediction is used). In the case of delayed fed back CSI (FBCSI), the channel gains are fed back with the delays of 0.3125ms and 0.625ms. Note that transmitter precoding aided by channel prediction achieves almost the same performance as for the case when the channel is perfectly known at the Tx, while feeding back delayed CSI without prediction results in significant performance degradation. Thus, accurate LRP is required for reliable precoding in practical mobile radio channels. While Fig. 3 and 4 illustrate the advantages of the THP over linear precoders, we also observed that the proposed THP methods outperform linear and non-linear MUDs in [14-17] (see [11,12, 22]).

V. CONCLUSIONS

Using theoretical analysis and simulation examples, it was shown that THP has better performance than previously proposed linear precoders, and linear and nonlinear MUDs with similar complexity. Furthermore, when the received users' powers are unequal, THP can significantly improve the performance of weaker users compared to linear precoding methods, thus enabling reduction of total transmit power. It is also shown that the

LRP enables performance of THP in practical W-CDMA channels.

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