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Performance Analysis of a Blind Adaptive Linear Minimum Mean Squared Error Receiver for use in UMTS TDD-CDMA Basestations

Y. Q. Bian, A. R. Nix and J.P McGeehan

Centre for Communications Research, University of Bristol,
Merchant Venturers Building, Woodland Road, Bristol, BS8 1UB, UK
Tel: +44 117 954 5203; Fax: +44 117 954 5206; email: Y.Q.Bian@bristol.ac.uk

Abstract

This paper presents receiver architectures and performance results relating to the UMTS (Universal mobile telecommunication system) TDD (time division duplex) mode. System performance in terms of uncoded BER (Bit Error Rate) and overall capacity are compared for MF (Matched Filter), Rake and blind adaptive LMMSE receivers. Uplink comparisons are performed in a multi-user scenario over time varying frequency selective channels. In order to achieve high performance, a modified blind adaptive LMMSE receiver is proposed. Factors such as channel variation, interference suppression and low implementation complexity are considered. The results demonstrate that the proposed receiver architecture can greatly reduce the interference floor at the basestation and thus significantly improve performance and capacity in the UMTS TDD mode.

1. INTRODUCTION

The TDD-CDMA (Time Division Duplex Code Division Multiple Access) system has been developed to offer third generation cellular services in the licensed 1900-1920 MHz and 2010-2015 MHz range [1]. The capacity of the system can be divided asymmetrically between the uplink (UL) and downlink (DL). TDD-CDMA is well suited to high rate multimedia type services. The peak data rate is at least 384 kb/s in microcells and 2 Mb/s in picocells (assuming unidirectional high rate transmissions) [2].

Multipath fading is common to both dense urban (microcell) and indoor (picocell) environments. The multipath channel degrades signal quality by introducing additional interference, thus limiting the capacity and performance of a DS (Direct Sequence) - CDMA system. The Rake receiver is believed to be the optimum DS-CDMA receiver for a single user in a multipath channel. However, in more realistic multi-user conditions, reception of the desired user code suffers interference from the presence of other user codes in the multipath channel. The cross correlation noise introduces an interference floor, and the resulting system becomes interference limited, rather than noise-limited [3]. For UL transmissions, the various mobile users are not perfectly time synchronous since each user communicates to the basestation (BS) through an independent, imperfectly time aligned channel. Each user becomes a source of interference to all other users. Therefore, practical receiver designs must consider the interference from other users in a multipath channel. Optimal multi-user detectors (MUDs) can free DS-CDMA systems from their well reported interference limitations [4], however they are generally too complex to implement. Over the last decade, research in this area has focused on the development of sub-optimal MUD solutions [5][6].

In a conventional multipath-decorrelating receiver [7], noise enhancement increases with the number of resolvable multipaths. The adaptive LMMSE [8] requires a predefined symbol level training sequence to be sent from the desired user to minimise the mean square error (MSE). Unfortunately, the TDD-CDMA standard does not support such a sequence. In addition, the LMMSE is known to suffer from phase error problems in channels suffering deep multipath fades [9]. A pre-Rake structure can be applied to either the UL or DL to enhance the performance of both FDD and TDD operation [10].

In order to improve system performance and overcome the limitations of the TDD-CDMA system, a blind adaptive LMMSE receiver with dynamic path selection (PS-LMMSE) is proposed and developed in this paper. The adaptation is based on time varying channel parameters such as signal to noise ratio (SNR) and RMS delay spread. Blind adaptation operates using decision directed (data-derived) training and aims to subtract Multiple Access Interference (MAI) prior to multipath combining. The evaluation of the BER performance and capacity versus receiver structure is presented here for a multi-user basestation.

2. SIGNAL MODEL

The simulation assumes the use of QPSK modulation. This modulation is sent over frequency selective fading channels assuming K simultaneously active users.

Individual user data is aggregated at the BS. An orthogonal Walsh code of length 16 is used in the spreading process. The wideband channel distortion is modelled using a time variant tapped delay line transformation. The time-variant UL impulse response for the k-th user, $h_k(t)$, can be written as:

$$h_k(t) = \sum_{l=1}^{L} h_{k,l}\delta(t-\tau_{k,l}) \qquad (1)$$

where $h_{k,l}$ and $\tau_{k,l}$ represent the l-th complex channel gain and excess delay respectively for the k-th multipath channel. L represents the maximum number of resolvable multipaths. The channel model consists of several path clusters (resulting from multiple reflection and diffraction). The fast fading processes on each path are statistically independent and Rayleigh distributed [11]. It is assumed that the channel multipath delay spread, $T_m \approx L/W$, is comparable or greater than the chip period T_c, where W represents the signal bandwidth. Hence, the multipath will introduce ISI (Inter Symbol Interference) and the propagation channel is affected by frequency selective fading. For the UL, the received waveform is generated as the summation of the signal from each user, which is calculated by the convolution of the user signal with its independent channel. The received signal can be mathematically expressed as:

$$r(t) = \sum_{k=1}^{K} A_k \sum_{l=1}^{L} \sum_{i=-M}^{M} h_{k,l} b_{k,i} s_k(t - iT_s - \tau_{k,l}) + n(t) \qquad (2)$$

where $2M+1$, A_k, $b_{k,i}$, T_s and $s_k(t)$ denote, respectively, the number of data symbols, the transmit symbol amplitude for the k-th user, the i-th transmitted symbol in the k-th user data sequence, the symbol period and the signalling waveform of the k-th user. $n(t)$ represents the complex zero-mean background Additive White Gaussian Noise (AWGN) with power spectral density σ^2. At the receiver, the signal $r(t)$ is passed through a matched Root-Raised Cosine (RRC) filter with a roll-off constant, α, of 0.22. The output from this filter is then sampled at the chip rate.

3. PERFORMANCE ANALYSIS

The presence of a multipath channel substantially increases the need for MUD. The correlation receiver is implemented as a bank of Matched Filters (MF) that correlate the received signal with the wanted user's code and maximises SNR by the resulting processing gain. However, this structure is only optimum in a single user, non-fading environment. The conventional detector suffers from significant performance degradation in the presence of MAI, resulting in overall inefficiency in the communication system. For the case of simplicity, the following mathematical analysis is based on BPSK (although simulations make use of QPSK). The BER of a conventional receiver for the k-th user, P_e, can be approximated by [12]:

$$P_e = Q\left(\sqrt{\frac{2E_b}{N_o}\frac{1}{1+\frac{2}{3N}\frac{E_b}{N_o}\sum_{\substack{k'=1\\k'\neq k}}^{K} v_{k'}}}\right) \qquad (3)$$

where N is the processing gain, $v_{k'}$ defines the ratio of the received signal strength of the k'-th user to the received signal strength of the desired k-th user, and

$$Q = \int \frac{1}{\sqrt{2\pi}} \cdot t \cdot e^{-t^2/2} \cdot dt \qquad (4)$$

In a single user environment, the Rake is a powerful technique for combating the effects of multipath fading. The error probability using a Rake at large SNR values (greater than 10 dB) can be approximated as [13]

$$P_e \approx \left(\frac{1}{4\bar{\gamma}_c}\right)^L \binom{2L-1}{L} \qquad (5)$$

where $\bar{\gamma}_c$ is the average SNR per channel and

$$\binom{2L-1}{L} = \frac{(2L-1)!}{L!(L-1)!} \qquad (6)$$

Once multipath effects are introduced in a multi-user environment, due to the imperfect auto-correlation properties of the Walsh codes, multipath components become correlated and diversity gain is lost. Therefore, the cross correlation noise becomes channel-dependent. The BER of a multipath decorrelator for the k-th user is calculated as [14]:

$$P_e = Q\left(\frac{1}{\sigma}\sqrt{\sum_{l=1}^{L}\frac{|A_{k,l}|}{R_{kk}^{-1}(l)}}\right) \qquad (7)$$

where $R_{kk(l)}=s_{k(l)}s_k^T$. In the absence of multipath, the k-th user is orthogonal to all other users and the decorrelator becomes equivalent to a single-user MF with $R_{kk}=I$. Otherwise, equation 7 clearly indicates that the decorrelating detector eliminates interference at the expense of noise enhancement, since $\bar{R}_{kk}(l)^{-1} \geq 1$.

The MMSE detector has the crucial advantage of adaptive implementation. In this paper, the interference suppression scheme consists of replacing the matched filter by a Q-tap LMMSE, where the number of FIR (Finite Impulse Response) filters is equal to the processing gain (PG). Path selection is also necessary in this receiver structure. The output of each selected path takes the form:

$$y_{k,l}^{(i)} = w_{k,l}^{H} \bar{r}^{(i)} \qquad (8)$$

where $\bar{r}^{(i)}$ represents the received signal vector over a processing window for the i-th symbol interval and $y_{k,l}^{(i)}$ represents the i-th symbol, on the l-th branch, for the k-th user. $w_{k,l}$ are the complex coefficients of the Q-tap LMMSE detector for the l-th branch of the k-th user and H denotes the conjugate transpose function. The coefficients are chosen to minimise the MSE, which depends on several random quantities, such as the cross-correlation, the time offsets, and the power levels of the received signals. The MSE is defined as:

$$J_{k,l} = E\left\{ \left| h_{k,l} A_k \hat{b}_k - w_{k,l}^{H} \bar{r} \right|^2 \right\} \qquad (9)$$

where $\hat{b}_k$ is the hard BPSK decision for the k-th user, and is given by:

$$\hat{b}_k^{(i)} = sign\left(\sum_{l=1}^{L} h_{k,l}^{*} y_{k,l}^{(i)} \right) \qquad (11)$$

In the simulation studies, the following QPSK hard decision rule is used for $\hat{b}_k$:

$$\hat{b}_k^{(i)} = sign[Real(\sum_{l=1}^{L} h_{k,l}^{*} y_{k,l}^{(i)})] + j \cdot sign[Imag(\sum_{l=1}^{L} h_{k,l}^{*} y_{k,l}^{(i)})] \qquad (12)$$

The filter weights are adaptively updated to achieve the minimum MSE during one symbol interval and this can be written as:

$$\begin{aligned} w_{k,l}^{(i+1)} &= w_{k,l}^{(i)} + 2\mu \bar{r}^{(i)} (h_{k,l} \hat{b}_k^{(i)} - y_{k,l}^{(i)})^{*} \\ &= w_{k,l}^{(i)} + 2\mu e_{k,l}^{*(i)} \bar{r}^{(i)} \end{aligned} \qquad (13)$$

The BER of the adaptive LMMSE for the k-th user in a multipath channel can be calculated based on the Gaussian assumption [15] as shown below:

$$P_e \approx Q\left(\sqrt{ \sum_{l=1}^{L} \frac{ \sigma_d^2 - J_{k,l}^{(\infty)} }{ J_{k,l}^{(\infty)} } } \right) \qquad (14)$$

where σ_d^2 is the variance of the desired response and $J_{k,l}^{(\infty)}$ is the final steady-state mean squared error for the adaptive algorithm. This equation can be used to estimate the impact of the noise and the interference floor on the receiver performance.

4. SIMULATION RESULTS

4.1 Medium RMS Delay Spreads (75-150ns)

Figure 1 demonstrates the UL simulation results for the different receiver structures in a medium RMS delay spread channel. K=8 users are assumed and the Power Delay Profile for the desired user is given by [-9.7dB, -10.7dB, -33.8dB]. The mean of the first path is marginally stronger than the second path, however both have similar relative strengths. MAI will result from the asynchronous multi-user UL transmissions. This largely results from the independent nature of the multipath propagation channels, which enables the strongest path to occur at different times for different users.

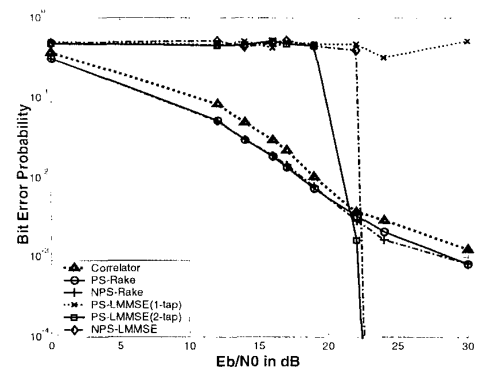

Figure 1: *BER comparison (RMS_{user1}=122ns, L=3, Threshold =-12dB, spreading gain=16, K=8, Power Delay Profile = [-9.7dB, -10.7dB, -33.8dB])*

In the above figure, the relative BER performance of the various UL receiver techniques is presented. The single tap LMMSE offers the worst performance since insufficient signal energy can be captured from the first path alone. The conventional correlation receiver offers the next level of performance, closely followed by the fixed (NPS) and adaptive Rake with path selection (PS). As discussed in the previous section, the use of Walsh spreading codes means the correlation receiver will capture the signal from all multipaths and thus add to the cross-correlation noise, which seriously degrades performance. The Rake outperforms the correlation receiver (however diversity gain is lost due to partially correlated multipaths), achieving a BER of 3×10^{-3} at 22dB E_b/N_0. For the blind LMMSE, the selection of the single strongest path is clearly unacceptable. The selection of all three paths (NPS-LMMSE) is significantly better than the Rake approach for E_b/N_0 values greater than 23dB. The dynamic selection of the two strongest paths produces the best result (PS-LMMSE–2 tap). This result confirms that all paths within a suitable power window (12 dB in this case) should be combined in the LMMSE. To achieve a target BER of 10^{-2}, the required E_b/N_0 for the PS-LMMSE (around 21.5dB) is less than that for the NPS-LMMSE (around 22.5dB). As the E_b/N_0 increases, the NPS-LMMSE has a comparable performance to that of the successful PS-LMMSE. These results indicate that adaptive path selection using a suitable power threshold is desirable.

The convergence properties of the blind adaptive LMMSE at an E_b/N_0 of 22dB are shown in figure 2. Taking just the strongest path, i.e. Path Selection (1 tap), results in poor convergence and high residual MSE. The lowest MSE occurs when the two strongest paths are combined (2 tap). For this channel, combining all three branches will cover the entire channel response. However, NPS offers no benefit in terms of reducing the cross correlation noise floor or the MSE floor. From inspection of figure 1, the use of NPS causes unreliable decisions at E_b/N_0 values less than or equal to 22dB. This is to be expected from the convergence results shown in figure 2.

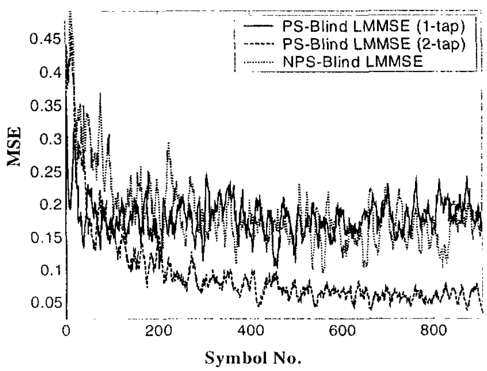

Figure 2: *Adaptive LMMSE Convergence (Eb/No=22dB, K=8)*

4.2 BER Performance versus Number of Users

Figure 3 demonstrates that the PS-LMMSE can significantly improve the performance and capacity of a multi-user TDD-CDMA system relative to the MF or Rake. At a BER of 2×10^{-3} and an E_b/N_0 of 22dB, the Rake and correlation receiver can support up to six users (37.5% of the processing gain). However, the PS-LMMSE can achieve up to nine users (56% of processing gain). For a system with three users at the lower E_b/N_0 value of 12 dB, the PS-LMMSE and NPS-LMMSE achieves a BER of 1.6×10^{-3}, which is worse than the Rake (BER of 10^{-3}). The MF offers the worst performance with a BER of 10^{-2}. These results show that both the PS-LMMSE and the NPS-LMMSE should be disabled for four or more users at E_b/N_0 levels less than or equal to 12dB.

The minimum required SNR grows as the number of users increases, as shown in figure 4. However, the required minimum E_b/N_0 for the LMMSE is less than that of the MF for small numbers of users (four or less based on figure 4). When more users enter the system, the value of $E_b/(N_0+I_0)$ reduces, where I_0 represents the interference power spectral density. The PS and NPS-LMMSE are very sensitive to low values of SNR. This sensitivity arises from the iterative use of decision directed errors.

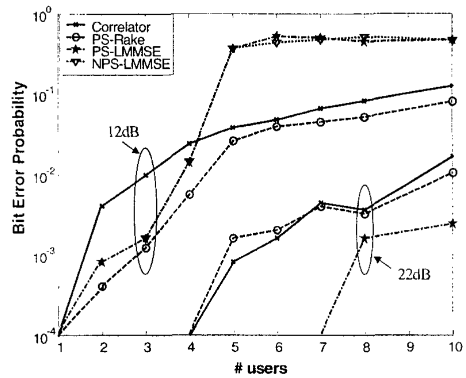

Figure 3: *BER versus number of users (RMS_{user1}=122ns, L=3, spreading gain=16)*

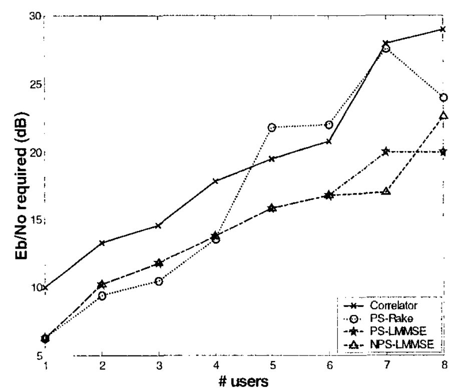

Figure 4: Required E_b/N_o comparison (BER=2 x10^{-3})

4.3 Low RMS Delay Spreads (less than 75ns)

Figure 5 shows the UL BER behaviour versus E_b/N_0 for low rms delay spread conditions. The main signal energy arrives on the first path, with other weaker paths having much lower SNR. For low values of rms delay spread, additional taps have no benefit in the Rake receiver. The results of figure 5 indicate, once again, that blind LMMSE is far more sensitive to low values of SNR than either the correlation or Rake receiver. However, as the value of E_b/N_o increases, the blind LMMSE becomes feasible, offering excellent results for E_b/N_o values of 19.5 dB or higher. This implies that a reconfigurable receiver is required, using the LMMSE at high E_b/N_o values and the MF or Rake at lower values [16]. Results show that at low delay spreads, the required minimum E_b/N_o at a target BER of 10^{-2} (15.5dB for the correlation receiver) is much lower than for larger rms delay spread channels (19-20 dB from figure 1). As mentioned above, in these channels the correlation detector offers good overall UL performance.

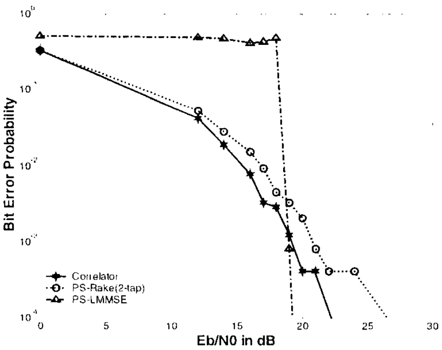

Figure 5: *BER comparison (RMS_{user1}=36.8ns, L=3, Threshold = -12dB, spreading gain=16, K=8, Power Delay Profile =[-1.15 dB, -17.39 dB, -56.87 dB])*

5. CONCLUSIONS

In this paper several interference suppression and multipath combining schemes have been presented for UL operation in the UMTS TDD mode. Simulation results demonstrate that the performance of the correlation detector and conventional Rake are often seriously corrupted by MAI and ISI. This distortion is strongly related to the characteristics of the mobile channel, with parameters such as rms delay spread and the signal to noise ratio for each resolvable multipath component playing a key role. Noise enhancement increases with the number of resolvable multipaths. Therefore, additional taps can increase the interference floor for the Rake structure and multipath-decorrelator.

Moreover, the proposed blind adaptive LMMSE has been shown to be extremely sensitive to the noise present on weaker paths. For channels with small rms delay spreads or low SNRs, results have shown that blind LMMSE decision directed training is not always desirable since poor convergence may occur. An adaptive receiver structure based on dynamic path searching has been used in this paper to improve performance. The blind adaptive LMMSE receiver reduces both MAI and ISI over frequency selective time varying channels. The method is suitable for use on both the UL and DL of TDD-CDMA. Further performance gains can be obtained by reconfiguring the LMMSE as a Rake or correlation receiver at low SNR and/or RMS delay spreads [16].

In conclusion, when suitable dynamic threshold parameters are used in the choice of tap number, impressive UL performance can be obtained with a flexible LMMSE based receiver structure. These properties make the method attractive for time varying multipath channels and the approach can be used to enhance the capacity and performance of a TDD mode UMTS network.

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