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Basestation 2-Dimensional Reconfigurable Receiver Architecture for DS-CDMA

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Abstract--In a practical DS-CDMA (Direct Sequence Code Division Multiple Access) system, the desired user suffers from significant Multiple Access Interference (MAI) resulting from the presence of other users in a time varying multipath channel. This problem is particularly limiting on the Uplink (UL), where time asynchronous users transmit over independent fading channels. This paper presents a novel receiver architecture that is reconfigurable to optimize performance adaptively in a multiuser scenario under time varying frequency selective fading channels plus Additive White Gaussian Noise (AWGN).

The UMTS TDD (Time Division Duplex) CDMA UL format is considered in this paper. System performance in terms of uncoded BER (Bit Error Rate) and overall capacity are presented. The results demonstrate that the proposed architecture can greatly reduce the interference floor at the base station (BS) and thus significantly improve performance and capacity.

Index Terms--TDD/CDMA, MAI, ISI, fading channel, blind adaptive LMMSE, adaptive receiver, diversity

I. INTRODUCTION

In a mobile cellular environment, the mobile channel exhibits considerable time variability. In addition, frequency selective fading is common to both dense urban (micro cell) and indoor (Pico cell) environments. For multi-user applications, the MAI to the desired user can be increased by multipath and fading effects from each user. On the UL, user codes are sent over independent multipath and fading channels and the cross-correlation between sequences for different transmissions are nonzero. Given this situation, a significant irreducible cross correlation interference floor occurs and system performance and capacity is seriously degraded.

The conventional Matched Filter (MF) operates efficiently in the presence of a non-faded AWGN channel by forcing the MAI to zero. In a wideband single user channel, the Rake is the optimum receiver structure [1]. In general, if the magnitude of an additional resolvable path is smaller than

approximately -10dB to -15dB with respect to the dominant path, then no errors will result [2]. However, in a multi-user DS-CDMA application, due to the imperfect auto-correlation property of the spreading codes, this weak path can result in interference in the Rake, and the multipath diversity gain is degraded by any additional interference from the undesired signals [3]. The performance degradation with increasing numbers of simultaneous users is serious since it results in the introduction of an interference floor. An optimal multiuser detector (MUD) can free DS-CDMA systems from this interference limitation, but these structures have high complexity [4]. Therefore, several sub-optimal MUD algorithms have been considered in [5, 6] with possible implementation and potential benefits for DS-CDMA systems. Nevertheless, under multipath and fading conditions, each MUD technique has its limitations. A standard Linear Minimum Mean Square Error (LMMSE) approach can be used to suppress both Inter-Symbol Interference (ISI) and MAI [7] in a non-fading (fixed) multipath channel. This method fails in a fast Rayleigh fading channel, where the system fails to track the time-varying signals encountered in such an environment [8]. The blind adaptive LMMSE (which does not require a training sequence) is suitable for the UMTS TDD/CDMA standard [9] and has been proposed in [10]. However, it is very sensitive to lower values of E_b/N_0 due to the blind decision directed (data-derived) training. In addition, the performance of Parallel Interference Cancellation (PIC) and Successive Interference Cancellation (SIC) over the UMTS multipath channel model has been presented in [11] and shows an unacceptable BER floor.

In order to improve the TDD-CDMA system performance, a Reconfigurable Adaptive Receiver (RAR) architecture with dynamic configuration control is proposed and developed in this paper to overcome the limitations of each individual MUD scheme. A novel 2-dimensional diversity combining scheme is proposed together with a blind adaptive LMMSE. Joint coefficient updates are performed between the temporal and spatial paths in the RAR operation. The evaluation of

BER and capacity performance versus various receiver structures are presented in this paper for a multi-user TDD-CDMA framework. Simulation results indicate that in Rayleigh fading (per resolvable time bin), the best choice of receiver structure depends on the instantaneous channel characteristics. Under such conditions, the RAR will be shown to substantially increase performance gain.

II. SYSTEM MODEL

The simulation assumes a multi-user environment with K active users operating with QPSK modulation over independently faded channels. The channel model consists of several time path clusters (resulting from multiple reflection and diffraction) with independent Rayleigh fading distributions. The impulse response of the UL multipath channel for the k -th user can be represented as:

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

where $h_k(t)$, L and $\tau_{l,k}$ represent the complex channel gain, the number of resolvable multipaths and the excess delay respectively. 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 wideband channel results in ISI and also introduces MAI in a multiuser environment. OVSF (Orthogonal Variable Spreading Factor) codes of length 16 are used in the spreading process. The received signal for each BS antenna element can be mathematically expressed as:

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

where $2N+1$, A_k , b_k , T_s and s_k denote, respectively, the number of data symbols, the amplitude, data sequence, symbol period and signalling waveform of the k -th user. $n(t)$ represents the complex zero-mean background 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, as shown in figure 1.

The interference suppression scheme at the receiver consists of a Q-tap LMMSE, where the number of FIR (Finite Impulse Response) filter taps is equal to the spreading factor Q . The output of the selected path at the m -th antenna element takes the form:

$$y_{k,l}^m(i) = (w_{k,l}^m)^* \cdot \bar{r}^m(i) \quad (3)$$

where $\bar{r}^m(i)$ represents the received signal vector over a processing window for the i -th symbol interval for the m -th element, $y_{k,l}^m(i)$ and $w_{k,l}^m$ represents the i -th symbol and the complex coefficients of the Q-tap LMMSE detector on the l -th branch of the m -th antenna, for the k -th user. The coefficients are chosen to minimise the Mean Square Error (MSE), which depends on several random quantities, such as

the cross-correlation function between users, the channel RMS delay spread and the Signal-to-Interference Ratio (SIR) of the desired user. The MSE is defined as:

$$J_{k,l}^m(i) = E \left\{ \left| A_k \hat{b}_k(i) (h_{k,l}^m)^* - y_{k,l}^m(i) \right|^2 \right\} \quad (4)$$

where $\hat{b}_k$ is the final QPSK hard decision after diversity, and is given by:

$$\hat{b}_k(i) = \text{sgn} \left[\text{Re} \left(\sum_{m=1}^M \sum_{l=1}^L (h_{k,l}^m)^* y_{k,l}^m(i) \right) \right] + j \text{sgn} \left[\text{Im} \left(\sum_{m=1}^M \sum_{l=1}^L (h_{k,l}^m)^* y_{k,l}^m(i) \right) \right] \quad (5)$$

Figure 1. Simulation framework for TDD-CDMA UL

The filter weights are adaptively updated to achieve the minimum MSE during one symbol interval. The step size μ is also updated based on the quantity of the estimated MAI and E_b/N_0 . Coefficient adaption uses the following rule:

$$\begin{aligned} w_{k,l}^m(i+1) &= w_{k,l}^m(i) + 2\mu \bar{r}^m(i) (h_{k,l}^m \hat{b}_k(i) - y_{k,l}^m(i))^* \\ &= w_{k,l}^m(i) + 2\mu (e_{k,l}^m(i))^* \bar{r}_{k,l}^m(i) \end{aligned} \quad (6)$$

Furthermore, in order to obtain a better diversity gain, dual antenna diversity with half wavelength spacing is also incorporated into the receiver structure. Diversity combining is performed in two dimensions, namely time and space. Maximal Ratio Combining (MRC) is used to combine the L time paths in each antenna's Rake, while Equal Gain Combining (EGC) is used to sum the spatial signals. If the channel attenuation and phase shift for $h_{k,l}^m$ contains no noise, then MRC is optimum for the single user environment [12]. A novel diversity combining scheme is proposed in this paper based on a 2-dimensional blind adaptive LMMSE (2D-LMMSE). In the 2D-LMMSE, the joint adaptation between the temporal and spatial paths employs the final

decision $\hat{b}_k(n)$ for both antennas, rather than the Parallel Independent LMMSE (PI-LMMSE), which operates separately on each antenna, as shown in figure 2. Blind adaptation operates using decision directed training and aims to subtract MAI prior to multipath combining. The dynamic parameter setup (see section IV) for the RAR is determined by analysis of the time varying channel parameters, such as signal-to-noise ratio (SNR), channel RMS delay spread and the cross-correlation function between users.

Figure 2. Block diagram of 2-dimensional adaptive receiver

III. PERFORMANCE ANALYSIS

For the case of simplicity, the following mathematical analysis is based on BPSK (although simulations make use of QPSK) and assume perfect power control (i.e., $P_j = P_i$). When no multipath fading is present, based on the central limit theorem the interference is well approximated as AWGN. However, in fading channels the interference distribution can differ from AWGN. In a DS-CDMA system with spreading factor Q , the effective E_b/N_0 can be written as [8],

$$(E_b/N_0)_{eff} = \frac{E_b/N_0}{1 + \frac{2}{3Q} E_b/N_0 \sum_{j=2}^K \frac{P_j}{P_1}} \quad (7)$$

Thus, when the modulated signals are transmitted over a non-fading multipath channel, the BER of the conventional MF is obtained by:

$$Pe = Q\left(\sqrt{2(E_b/N_0)_{eff}}\right) \quad (8)$$

and the Q function is given by:

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-t^2/2} \cdot dt = 0.5 \times \text{erfc}\left(\frac{x}{\sqrt{2}}\right) \quad (9)$$

If there are multiple Rayleigh fading channels, the BER of the conventional MF is presented as:

$$Pe^F = \frac{1}{2} \left(1 - \frac{1}{\sqrt{1 + \frac{1}{(E_b/N_0)_{eff}}}} \right) \quad (10)$$

For non-orthogonal signals in a non-fading multipath channel, the BER of the MMSE can also be approximated by assuming that the output MAI-plus-noise follows a Gaussian distribution. Hence, the BER of the LMMSE for equal-correlated ($\rho_{jk} = \rho$) signals can be expressed as [13]:

$$Pe \approx Q\left(\frac{A}{\sigma} \sqrt{1 - \frac{\rho^2(K-1)}{1 + \frac{\sigma^2}{A^2} + (K-2)\rho}}\right) \quad (11)$$

where $\rho = \rho_{jk} = \int_0^{T_b} (s_j(t) * h_j(t))^* \cdot s_k(t) \cdot dt$ is the cross-correlation of the signaling waveform between the j -th and k -th user. However, the statistics of the interference under Rayleigh fading conditions are complex and currently intractable. The performance improvement under frequency flat fading and Rayleigh fading channels has been analyzed by Barbosa [8], and can be approximated as:

$$Pe^F \approx \left(1 - \frac{1}{1 + \frac{1}{E_b/N_0}} \right) \times 10^{\xi(K-1)/Q} \quad (12)$$

where ξ represents an empirically determined parameter (related to the values of Q and E_b/N_0).

Figure 3 illustrates the theoretical BER comparison between the MF and the LMMSE. It indicates that the BER of the LMMSE is seriously degraded by Rayleigh fading compared to the non-fading case. However, the LMMSE can achieve a significant performance gain relative to the conventional MF in a non-fading channel. Moreover, the LMMSE becomes unreliable when the E_b/N_0 decreases to a certain threshold. That is, the conventional MF has better performance than the LMMSE at low E_b/N_0 values when the system load is not high (e.g., $K/Q = 26.7\%$, $E_b/N_0 = 5dB$).

For the proposed RAR in non-fading multipath channel, the approximate BER should take into account the impact of the imperfect training signal, due to the blind decision directed training. The AWGN approximation can be used as [14] [15],

$$Pe \approx Q \left(\sqrt{\sum_{m=1}^M \sum_{l=1}^L \frac{\sigma_d^2 - J_{k,l}^{m(\infty)}}{J_{k,l}^{m(\infty)}}} \right) \quad (13)$$

Where σ_d^2 is the variance of the desired response and $J^{(\infty)}$ is the final steady-state MSE for the adaptive algorithm.

Figure 3. Theoretical BER performance comparison between MF and LMMSE ($PG=15$, equal-energy users and identical cross-correlation)

The performance analysis is more complicated when each user suffers independent multipath fading. Since the fading of all paths for each user is assumed to be independent and Rayleigh distributed, according the central limit theorem, those more independent interference terms act more like additional Gaussian noise when K and L has large value. Then equation 13 can be used. Otherwise, the Gaussian assumption generates a poor result for small values of K , Q and L . The performance analysis should use the AWGN approximation and the fading property together. The BER for this case is:

$$Pe^F \approx \int_0^\infty f_\alpha(\alpha) \cdot Q \left(\sqrt{\sum_{m=1}^M \sum_{l=1}^L \frac{\sigma_d^2 - J_{k,l}^{m(\infty)}}{J_{k,l}^{m(\infty)}}} \right) \cdot d\alpha \quad (14)$$

where

$$f_\alpha(\alpha) = 2(1 + \beta^2) \alpha \exp(-(\alpha^2(1 + \beta^2) + \beta^2)) \times I_0(2\alpha\beta\sqrt{1 + \beta^2}) \quad (15)$$

is the probability density function (pdf) of the fading amplitude. The Rayleigh distribution is obtained by setting β to zero.

IV. SIMULATION RESULTS

For the specific implementation of the RAR, as shown in figure 2, several parameters are required. They are the minimum required Eb/No for the 2D-LMMSE, the estimated MAI ($\sum_{j=2}^K A_j^2 \rho_{jk}^2$), the relative power threshold for the selected resolvable multipaths, the instantaneous channel RMS delay spread and the average power delay profile (PDP). μ is determined by the value of the estimated MAI, the instantaneous RMS delay spread and the Eb/No . Figure 4 demonstrates the principle of the reconfiguring algorithm and table 1 lists the parameter setup for the different architectures in the RAR. If μ is set to zero then no adaption is possible in the LMMSE. For μ set to zero and L equal to 1, the RAR becomes a conventional MF. In the case of Rake operation, the number of Rake taps is also adapted to optimize the performance. The path search for the 2D-LMMSE can be based on the average channel PDP.

Figure 4. Basis of UL reconfiguration ($N=16$, $K=8$)

Parameters of RAR

	μ	L
MF	0	1
Rake receiver	0	>1
Adaptive LMMSE	0.05	>1

Table 1. Parameters setup for RAR

In this work, simulations are performed for a UMTS TDD/CDMA UL application. The fading environment is considered as a time varying frequency selective channel (Rayleigh fading per tap). System loading is simulated at a level of 50% ($K/Q=8/16$) of the processing gain (PG). Figure 5 presents the case study of $K=8$, where interference is fairly strong. The graph shows that the Rake achieves poor performance compared to the LMMSE. This occurs because the multipath diversity is not sufficient to overcome the fading while the desired signal is below the level of other users correlation noise. In the case of $K=2$ (25% of the PG), the performance of the Rake is similar to the 2D-LMMSE but better than the PI-LMMSE. In fact, for the previous cases the 2D-LMMSE has a better diversity gain than the PI-LMMSE.

Figure 5. BER performance for an instantaneous channel ($PDP=[-0.9, -7.2, -38.7]dB$, RMS delay spread= $95.55ns$)
(a) $MAI=-42.26dB$, (b) $MAI=-15.25dB$

Due to the MAI, a performance degradation is seen in the Rake. Figure 6 demonstrates that an irreducible BER floor (caused by interference) of 8×10^{-3} occurs, although this is better than the Rake without space diversity (BER of 3.5×10^{-2}). The PI-LMMSE and 2D-LMMSE can reduce the BER compared to the blind LMMSE without space diversity at an Eb/No of 30 dB. The later has a BER of 10^{-4} . It is worth noting that the 2D-LMMSE, which simultaneously adapts both its spatial and temporal coefficients, offers a significant performance gain (e.g. 4.5 dB more gain relative to the PI-LMMSE at a BER of 10^{-2}). However, the performance of the 2D-LMMSE and the PI-LMMSE are still sensitive to low values of Eb/No (below 19dB and 23dB respectively) relative to the Rake.

In addition, since each of the K users operates over an independent multipath UL channel, MAI is generated from each users multipath components. Results show that under Rayleigh fading, there is only a slight improvement using the 2D-LMMSE when compared to the Rake at Eb/No values between 19dB and 26dB. Hence, it is important to measure the cross correlation function between the users. If only the RMS delay spread and Eb/No are considered in the adaption

process, then the BER is very close to that of the 2D-LMMSE for Eb/No values greater than 16dB (e.g., BER of 5×10^{-3} at Eb/No of 20dB). Simulation results demonstrate that the RAR is very successful and a significant performance gain (BER of 3×10^{-4} at Eb/No of 20dB) can be achieved when considering both RMS delay spread, cross-correlation and Eb/No .

Figure 6: Uncoded BER of desired user versus Eb/No ($N=16$, $K=8$, Average RMS delay spread= $73.4ns$, Rayleigh distributed time taps)

Figure 7 illustrates the BER performance versus the number of users. Again, it indicates the noise limitation for LMMSE operation (see performance at 10dB). For an Eb/No of 20dB, the RAR demonstrates an attractive ability to suppress the interference from MAI, ISI and AWGN over fading multipath channels.

To achieve a BER of 3×10^{-3} , the 2D-LMMSE can support 8 users (50% of the PG), while the PI-LMMSE only supports 6 users (38% of the PG). It also indicates that more than 8 users can be supported by the RAR. Only 5 users are supported (31% of PG) for the Rake.

Figure 7. BER performance versus number of users

V. CONCLUSIONS

In this paper several interference suppression and multipath combining schemes have been presented for the UMTS TDD UL. In a practical mobile cellular environment, time variations in both the mobile channel and the quantity of the MAI can seriously corrupt system performance and limit the performance using a conventional MF, Rake and LMMSE (even in Down-link (DL) applications) [16]. Assuming 8-user simultaneous transmissions, this distortion can be very different when the RMS delay spread lies between 75 and 100 ns. It is strongly related to the characteristics of the mobile channel, with parameters such as RMS delay spread and signal to interference plus noise ratio playing an important role. The MAI is given by the summation of $\sum_{j \neq k} A_j^2 \rho_{jk}^2$. For a channel with small RMS delay spreads and also lower SNRs, blind LMMSE decision directed training is not always desirable since poor convergence may occur.

To overcome the above problems, in this paper a RAR structure based on dynamic configuration control is proposed. The 2-dimensional adaptive algorithm, which considers both temporal and spatial multipaths, has a significant diversity gain when compared to the PI-LMMSE. Moreover, the cross-correlation function and instantaneous channel RMS delay spread have to be considered for UL performance in a fading channel. Results have demonstrated that the proposed RAR achieves an uncoded BER of 3×10^{-4} for an E_b/N_0 of 20dB, compared to an uncoded BER of 10^{-2} for the Rake.

In conclusion, when suitable dynamic threshold parameters are used, impressive UL performance can be obtained with a flexible LMMSE based receiver structure. These properties make the method attractive for enhancing the capacity and performance of TDD mode UMTS networks.

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