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RAKE Decorrelation as an Alternative to Rapid Power Control in DS-CDMA Mobile Radio

S.S.H Wijayasuriya, J.P McGeehan and G.H Norton
University of Bristol
Centre for Communications Research
Queens Building, University Walk
Bristol BS8 1TR, United Kingdom
Email *hans@uk.ac.bristol.comms-research*, Fax : +44 272 255265

Abstract

The Sliding Window Decorrelating Algorithm (SLWA) for asynchrnous multi-user DS-CDMA systems was propsed in [1], and its performance in various propagation environments investgated. In mobile radio networks, the feasibility of overcoming the near-far problem using power control strategies is questionable at practical vehicle speeds [2]. This is especially so in an urban time dispersive channel, where power control is unlikely to achieve satisfactory compensation over all significant multi-paths. In this paper we propose an alternative to rapid power control which incorporates both the RAKE diversity reception concept and the SLWA. Decorrelation is thus achieved between individual users and their significant multi-paths. In this paper we present a mathematical model for the receiver in conjunction with simulation and numerical results, which show capacity enhancements over the Conventional Linear Correlation Receiver (CLCR) or (CR) and lead to ideas on a positioning strategy for decorrelating solutions in DS-CDMA mobile radio.

1 Introduction

The nature of a mobile radio environment leads to reception of several signals with widely different power levels over a multiplicity of fading paths. The impact of Multi-User (MU) interference as perceived by a single user detector could then be attributed to the following effects: **(1)** Propogation loss and shadowing **(2)** Fast fading **(3)** Multi-Path (MP) propogation. Effects **(1)** and **(2)** were addressed in [1], and it was shown that the SLWA ameolirates them without the requirement for closed loop (rapid) power control. In this letter we seek to combat effect **(3)**.

We consider a wide band frequency selective channel [3]. Each of the MP's linking transmitter and receiver are assumed to fade independently, separated in time by a variable delay. This MP situation is replicated for each user in a MU network. The self interference is clearly dependent on autocorrelation properties of the codes, whereas the inter-user (path) interference will depend on partial cross correlations as discussed in [1]. Conceptually it is possible to model each MP as an additional user in the system, each adding to the total MU interference and hence limiting the multiple access (MA) capability of the network. For a system with K users, each of whose transmissions arrive via S paths, we have a situation analogous to a KM user system operating in a single path fading environment. The fading of correlation noise and its manifold replication due to MP propogation causes an aggravated version of the NF problem. It is shown in [2] that in this situation, ideal power control and MP combining techniques are required if the CLCR is to be useable.

2 The RAKE-SLWA Receiver Architecture

The RAKE receiver for a DS-CDMA system is described in [3]. Clearly the 'taps' of the RAKE receiver are based on the CLCR. We have shown [1], in agreement with [2], that the CLCR is unusable for fading links in the absence of ideal power control. In urban environments where several multi-paths could arrive with similar energy but anti-phase fading patterns, power control based on the primary received path is likely to enhance the interference component from the an anti-phase fading path. It follows that power control could prove to be self defeating in a dense multi-path environment. Considering each MP to be an additional user in the system, decorrelating techniques could be applied to retrieve the significant MP's. Decorrelated outputs of the RAKE taps would then be largely NF resistant subject to residual interference from undecorrelated MP energy. We recognise the fact that fast fading (Doppler) effects, oscillator phase instability, and dynamically evolving positions of transmitter and re-

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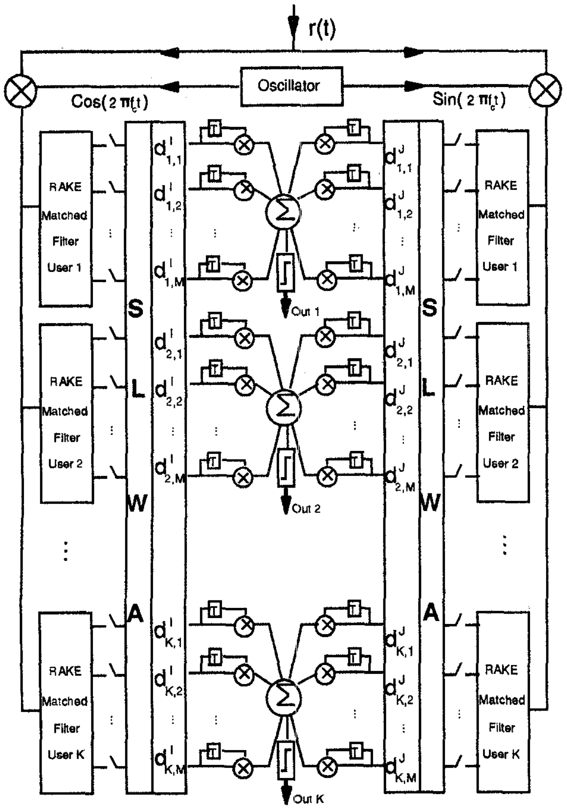

Figure 1: Multi-User SLWA-RAKE Receiver

ceiver are strong deterents to coherent communication in a MU environment. Using the SLWA algorithm in conjunction with a non-coherent modulation scheme requires that the algorithm be applied independently on quadrature channels. This strategy overcomes problems of phase aligning RAKE outputs, and removes performance dependency on absolute phase. The performance achieved is identical to that using maximal ratio combining [3]. Our decision variable for the i^{th} symbol of the k^{th} user can then be written for M path combining as

$$D_k = \sum_{n=1}^{M} d_{k,n}(i).d^*_{k,n}(i-1) \qquad (1)$$

where $d_{k,n}(i)$ is a complex decorrelator output for the n^{th} path of the k^{th} user over the i^{th} symbol interval. If the SLWA outputs on the quadrature branches are denoted by d^I and d^J, we can write

$$d_{k,n}(i) = d^I_{k,n}(i) + j.d^J_{k,n}(i)$$

In this letter we focus on Binary-DPSK though the architecture and analysis which follows is easily extended to any Differential Phase Modulation scheme. In the B-DPSK case the only possible transmitted phase differences are 0 or π, equation (1) reduces to

$$\begin{aligned} D &= Re\left[\sum_{n=1}^{M} d_{k,n}(i).d^*_{k,n}(i-1)\right] \qquad (2) \\ &= \sum_{n=1}^{M} d^I_{k,n}(i).d^I_{k,n}(i-1) + \sum_{n=1}^{M} d^J_{k,n}(i).d^J_{k,n}(i-1) \end{aligned}$$

A schematic of the resulting receiver architecture is given by Figure (1). A decorrelating algorithm is probably the most inexpensive interference cancellation technique on a per-iteration (symbol) basis, and is analagous to applying a Zero Forcing (ZF) equaliser to the CLCR outputs. However there is a significant cost of recomputation of the linear system solution [1], in reponse to changes in timing, selective combining of MP's, addition of users or if voice activity is to be exploited. It is clear that this imposes a limit to MP decorrelation, and the system will be left with residual MP interference which will accumulate to limit system capacity. Additional users will hence degrade the system by contributing to residual MP interference.

3 Analytical Model

Here we discuss some key points of an analytical model for RAKE Sliding Window Decorrelator which will help explain the functioning of the algorithm in a MP scenario. The development of the model will be the subject of a future publication. We assume a B-DPSK, phase stationarity over the sliding span, perfect edge correction, and M path combining ($S >= M$). In terms of the second central moments of the k^{th} path define

$$\lambda_n = \begin{cases} M^k_{xy} + \sqrt{M^k_{xx}M^k_{yy}} & \text{for } n \text{ odd, } k = \frac{n+1}{2} \\ M^k_{xy} - \sqrt{M^k_{xx}M^k_{yy}} & \text{for } n \text{ even, } k = \frac{n}{2} \end{cases} \qquad (3)$$

Here $1 \leq n \leq 2M$. We define

$$\Gamma i = \prod_{\substack{i=1 \\ k \neq i}}^{2M} \frac{\lambda_i}{\lambda_i - \lambda_k} \qquad (4)$$

giving the probability of error

$$P_e = \sum_{i,\lambda_i<0} \Gamma_i \qquad (5)$$

The quadrature matched filter output for the k^{th} path of the j^{th} user consists of three components

$$y_{j,k}(t - \lambda T) = \alpha_{j,k}(\lambda) + \beta_{j,k}(\lambda) + \eta_{j,k}(\lambda) \qquad (6)$$

In (6) $\alpha_{j,k}$ represents the energy spanned by the RAKE decorrelator and is replaced by the desired signal due to the zero forcing action of the SLWA. $\beta_{j,k}$ and $\eta_{j,k}$ are the interference terms due to the $(S-M)K$ residual MP's and the thermal noise respectively. The central moments for the j,k^{th} path have the form

$$\begin{aligned}\frac{M^{y}_{xx}}{2N_0T} &= \gamma_{x,y}+\frac{1}{W^2}\sum_{i=1}^{W}\sum_{j=1}^{W}\mathbf{h}^T_{W-i}.\mathcal{M}^{xx}(i,j).\mathbf{h}_{W-j}\\ &+\frac{1}{W^2}\sum_{i=1}^{W}\sum_{j=1}^{W}\mathbf{h}^T_{W-i}\mathcal{D}(i-j)\mathbf{h}_{W-j} \qquad (7)\end{aligned}$$

where $\gamma_{x,y}$ is the SNR of the x,y^{th} (desired) path and W is the window span. $\mathbf{h}_i$ is the i^{th} decorrelating detector within the window for the desired user. The elements of the residual interference correlation matrix $\mathcal{M}$ are of the form $E\left[\beta_{j,k}(i).\beta^*_{m,n}(j)\right]$ where as the elements of the noise variance matrix are taken from the zero symbol delay partial correlation matrix $R(0)$. Exact expressions for the evaluation of the matrix have been derived. However an approximation based on the Gaussian noise approximation [4] allows the variance of this term to be given by

$$\psi_{j,k}=\frac{4}{3}N\sum_{p=1}^{K}\sum_{q=S-M}^{S}\gamma_{p,q}.T \qquad (8)$$

where T is the symbol period and N the spreading factor or Processing Gain (PG).

4 Simulation Results

The performance of the proposed receiver was evaluated by Monte-Carlo simulation using a tapped delay line urban mobile radio channel model [5]. A coded data rate of 20 kbps (accommodating a half rate code cf [1]) is used. For clarity we show only undecoded error rates. It has been verified that decoded error rates for the SLWA decorrelator (DR) are in the range 0.0% - 0.4% over the regions of interest. In the light of equations (7),(8) the total interference variance is clearly dependent on three factors. **(a)** Magnitude of cross correlations (hence elments of $\mathcal{D}, \mathcal{M}$) determined by the PG **(b)** Absolute dimension of the zero forcing problem **(c)** Relative magnitude of the residual interference (C/I) ratio. The relationship between the last two factors will depend largely on the delay profile of the channel. Effects **(a)** and **(b)** are manifested in the level of interference enhancement due to the ZF action.

By using delay profiles based on measured data as opposed to the worst case (rectangular) profile assumed in [6] we have found that the interplay of these factors lead us to performance criteria significantly different to those specified in that publication. In terms of RAKE decorrelation, decorrelating additional paths reduces **(c)** but increases **(b)**. Similarly increasing PG for a fixed number of RAKE taps decreases **(a)** while increasing **(c)**. It is clear that adding users contributes to both **(b)** and **(c)**. Figure (2) clearly demonstrates the capacity improvements offered by increasing the combining depth in the case of the DR. In contrast the CR performance is not improved once MA limited, though an improvement is evident when the number of users is extremely small. Processing of additional paths gives the decorrelator deterministic access to a larger proportion of the total MP energy. As the combining depth is reduced, accumulated MP energy affects the DR performance resulting in it eventually becoming MA limited as well, and approaching the performance of the CR. Figure (3) is an equivalent set of results for a Processing Gain (PG) of 127. The overall error rates are lower due to (a) being the dominant factor for both the DR and the CR. However since the impact of **(c)** is hence reduced, the incremental benefit of combining additional paths is less than in the former (PG 63) case. Figure (4) provides a comparison between the two PG's for combining depths of 2,3,4 paths. It can be seen that the diference in performance for the two PG's decreases as the number of paths is increased (effect **(c)** is reduced). In this set of results for a delay (1-r sloping profile) spread of $3.2\mu s$, it is clear that the interference enhancement effect dominates, ie the superior correlation properties of the degree 7 code more than compensates for the decreased C/I. This ceases to be true for the 4 path case. Here **(c)** is very small for a PG of 63, whereas the C/I for the PG 127 case decreases as users are added, and inspite of lower correlation, performance falls below that for the latter case. Figure (5) shows the SNR performance for selected numbers of users and combined paths. Figure (6) is a generated error probability curve based on the analytical model described. The analysis is based on several assumptions (Section 3), resulting in differences between predicted and simulated performance, in the high interference regions. Note the cross over between the 3 and 4 path cases as **(b)** overides **(c)** in the high interference region of the idealised case. This cross-

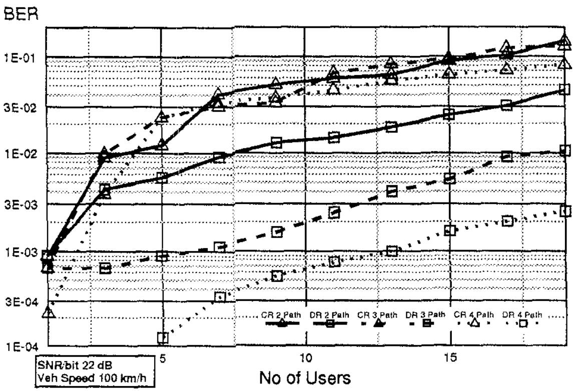

Figure 2: Effect of Combining Depth - PG 63

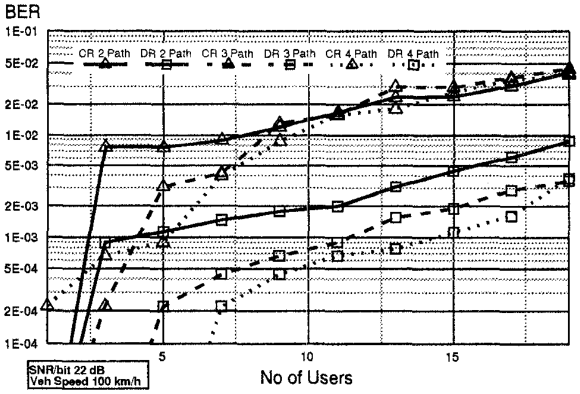

Figure 3: Effect of Combining Depth - PG 127

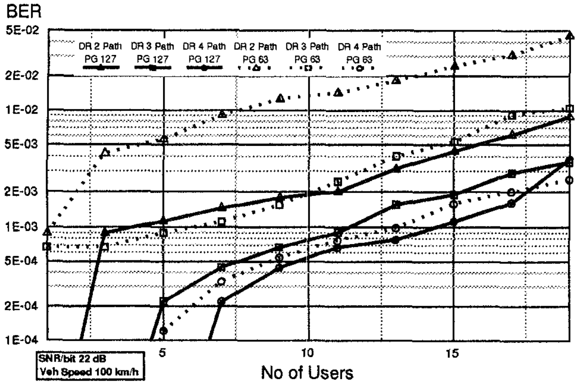

Figure 4: Effect of Processing Gain

over takes place at lower SNR in the simulated (non ideal) case.

5 Conclusions

We have proposed a SLWA-RAKE decorrelating receiver for DS-CDMA mobile radio networks, and evaluated its performance by simulation and an idealised mathematical model. The algorithm outperforms the CR and ameolirates the requirement for rapid power control, especially when the correct choice of combining depth and PG is used. The results have shown that it is benefitial to increase PG at high C/I (low combining depth and complexity), to achieve band width efficient capacity improvements. Little or no advantage is available in the low C/I region. These findings for a real-world channel augur well for the application of decorrelation for wider BW's. In the limit this should allow primary (single path) decorrelation for wide band CDMA.

6 Acknowledgements

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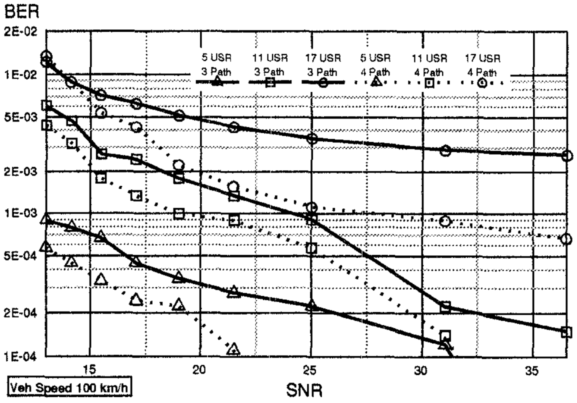

Figure 5: Noise Performance - PG 127

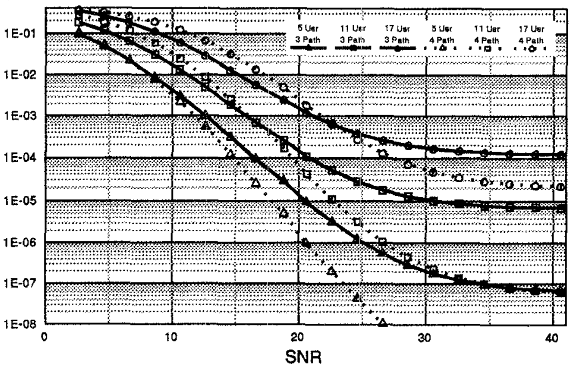

Figure 6: Noise Performance - Numerical Result

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