INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS
Int. J. Commun. Syst. 2007; **20**:661–668
Published online 8 September 2006 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/dac.841

A multipath interference cancellation technique for WCDMA downlink receivers

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SUMMARY

In this paper, we present a simple interference cancellation technique for the downlink of wideband code-division multiple-access (WCDMA) systems in multipath environment. With the same knowledge required by a RAKE receiver, the present method acts as an equalizer and cancels the interfering multipath signals from the received signal to retrieve the orthogonality property of the received signal. The present receiver has a simple structure and it has significant performance gain against the RAKE receiver. In addition, the noise enhancement is negligible when there is a line of sight path or the channel power delay profile has an exponential decaying form. Copyright © 2006 John Wiley & Sons, Ltd.

Received 15 October 2005; Revised 26 May 2006; Accepted 17 July 2006

KEY WORDS: CDMA/WCDMA; downlink receiver; multiuser detection; equalization; multipath channel

1. INTRODUCTION

In the new generation of wireless systems, due to the asymmetric capacity requirement of uplink and downlink of wideband code-division multiple-access (WCDMA) systems, the deployment of efficient low complexity downlink receivers is important. In the downlink of direct-sequence code-division multiple-access (DS-CDMA) systems, the spreading sequences of users are mutually orthogonal, which is effective against co-channel interference. However, multipath propagation distorts the codes' orthogonality, thus degrading the performance and capacity of the system. On the other hand, higher bandwidth usually corresponds to a smaller chip period which increases the multipath resolution, thus increasing the interference within the cell.

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Contract/grant sponsor: National Science Foundation; contract/grant number: ANI-0203063

There are several techniques for interference cancellation and multiuser detection in CDMA systems that improve the performance and increase the capacity of the system at the expense of higher complexity at the receiver [1]. Most of these techniques are designed for the uplink of CDMA systems, where it is assumed that the receiver knows the spreading codes of all users. However, this assumption does not hold for the downlink where mobile units only know their own spreading codes. Two promising approaches for the downlink receivers are the RAKE receivers [2] and equalizers [3, 4]. In situations where a small number of users are active, the RAKE receiver may provide acceptable performance, and more complex signal processing is not required. However, as the number of users increases, the performance of RAKE receivers degrade due to the non-zero cross correlation between the spreading sequences with arbitrary time shifts. As an alternative to the RAKE receivers, equalization techniques have been proposed [3, 4] to enhance the performance of the downlink receivers. Although the chip level equalizers (zero-forcing, MMSE) and the generalized RAKE receiver [5] have significant performance improvement compared to the conventional RAKE receiver, they suffer from high complexity. In this paper, a new technique for multiple access interference (MAI) cancellation based on successive cancellation of interfering multipath signals from the received signal is presented. The present method has the capability to completely cancel the MAI with only a slight increase in complexity compared to the conventional RAKE receiver. The three basic assumptions often used in some literature under which the application of the present method is feasible include: (1) there is a guard interval at the beginning of each transmitted frame so that there is no interference between two consecutive frames, though this guard interval may used for different purposes [6]; (2) the multipath delays are integer multiples of the chip interval, this assumption is easily achieved by sampling the data in multiple integer of the chip rate; and (3) there exists a line of sight path (a relatively strong first path), or the channel power delay profile has an exponential decaying form [7].

2. SYSTEM MODEL

Consider the downlink of a synchronous orthogonal CDMA system with K active users. The transmitted baseband signal due to the kth user is given by

$$x_k(t) = A_k \sum_{m=0}^{M-1} b_k(m) s_k(t - mT), \quad k = 1, 2, \ldots, K \tag{1}$$

where M is the number of data symbols per frame, T is the symbol interval, $b_k(m) \in \{+1, -1\}$ is the mth transmitted symbol by the kth user, and A_k and $s_k(t)$ are the amplitude and normalized signature waveform of the kth user. The signature waveform of the kth user has the form

$$s_k(t) = \sum_{j=0}^{N-1} c_k(j)\Psi(t - jT_c), \quad 0 \leqslant t \leqslant T \tag{2}$$

where N is the processing gain equal to T/T_c, $c_k(j)$ is a spreading sequence of ± 1 that is assigned to the kth user, and Ψ is a chip waveform of duration T_c. It is assumed that $s_k(t)$s are zero outside the interval $[0, T]$, have unit energy and have zero cross correlation. Furthermore, we assume that new users can join the system at the beginning of a frame and the transmission strategy is such that there is no interference between two consecutive frames by adding a guard

DOI: 10.1002/dac

interval to each frame. Since the transmissions starts from the base station (BS) these assumptions can be justified because the BS can manage when start transmitting to each one of the users. The baseband multipath channel between the BS antenna and the kth user's antenna is modelled as a tapped delay line and is written as

$$h(t) = \sum_{l=1}^{L} \alpha_l \delta(t - \tau_l) \tag{3}$$

where L is the number of resolvable paths in each user's channel, and α_l and τ_l are the complex-value channel coefficient and the delay, respectively, of the lth path. The channel parameters are assumed to be known in the demodulation process and they remain constant over the time period of a frame. Furthermore, it is assumed that the chip rate is high enough so that the multipath delays become integer multiples of the chip time interval T_c [3, 4], i.e. it is assumed that $\tau_l = p_l T_c$ for $l = 1, 2, \ldots, L$, where p_l are integers. The received signal can be expressed as

$$\begin{aligned} r(t) &= \sum_{k=1}^{K} x_k(t) * h(t) + n(t) \\ &= \sum_{k=1}^{K} \sum_{l=1}^{L} \alpha_l x_k(t - \tau_l) + n(t) \\ &= \sum_{m=0}^{M-1} \sum_{k=1}^{K} \sum_{l=1}^{L} \alpha_l A_k b_k(m) s_k(t - mT - \tau_l) + n(t) \end{aligned} \tag{4}$$

where $n(t)$ is assumed to be white and Gaussian with one-sided power spectral density N_0 which models the intercell interference and the thermal noise.

3. A NEW TECHNIQUE FOR WCDMA DOWNLINK INTERFERENCE CANCELLATION

Without loss of generality assume that the delay of the first path, τ_1, is zero (i.e. $p_1 = 0$) and the rest are indexed in increasing order. With due attention to the system model explained in Section 2, it is clear that the first $p_2 = \tau_2 / T_c$ chips at the beginning of each frame are free from multipath interference (assuming a guard interval slightly larger than τ_L). We use these chip samples with the knowledge of the channel coefficients to estimate the corresponding interfering chips and then cancel the multipath effect from the second p_2 chip samples of the received signal. Similarly, we can use these second p_2 chips to cancel the multipath effect from the third p_2 samples of the received signal. This procedure can be continued until the end of the frame to cancel the multipath effects from the whole frame. With the perfect knowledge of the channel coefficients, it is possible to cancel all multipath effects and recover the orthogonality property of the received signal. Clearly this algorithm is not complex and does not consume much time since each information bit can be detected after the interfering chip cancellation is done in a bit interval. It should be noted that the simplicity of the algorithm with the perfect cancellation of MAI comes at the expense of noise enhancement. Although this noise enhancement causes a loss of few dBs in SNR compared to the single user system, the performance of the receiver, as the

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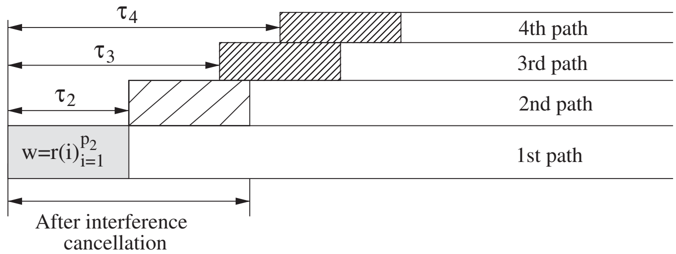

Figure 1. The present interference cancellation process for $j = 1$.

simulation results show, is much higher than the RAKE receiver and is free from any error floor.

The aforementioned procedure can be mathematically formulated as follows. Let $\mathbf{w}$ be a $p_2 \times 1$ vector and $\mathbf{y}$ be a $p_L \times 1$ vector. After sampling the received signal at chip rate or a multiple of the chip rate, the receiver will begin the following steps for data detection.

1. Initialization: Set $j = 0$ and $\mathbf{w} = \mathbf{r}(i)_{i=1}^{p_2}$, where $\mathbf{r}$ is the sampled received signal.
2. Set $j = j + 1$, $\mathbf{y}_l = [\mathbf{O}_{p_l - p_2}, \mathbf{w}^{\mathrm{T}}, \mathbf{O}_{p_L - p_l}]^{\mathrm{T}}$ for $l = 2, 3, \ldots, L$, and
$$\mathbf{r}(i)_{i=j\times p_2+1}^{j\times p_2+p_L} = \mathbf{r}(i)_{i=j\times p_2+1}^{j\times p_2+p_L} - \sum_{l=2}^{L} \frac{\alpha_l}{\alpha_1} \mathbf{y}_l$$
where $\mathbf{O}_{p_l - p_2}$ is a $1 \times (p_l - p_2)$ vector of zeros and $\mathbf{O}_{p_L - p_l}$ is a $1 \times (p_L - p_l)$ vector of zeros.
3. Set $\mathbf{w} = \mathbf{r}(i)_{i=j\times p_2+1}^{(j+1)p_2}$. Go to Step 2.

These steps are continued until the multipath effect is canceled from the whole frame. The procedure is illustrated in Figure 1. As shown in the figure for $j = 1$, the first p_2 bits (corresponding to delay of τ_2) of the arrived signal will be scaled (cf. the cross-hatched parts) and then subtracted successively from the received signal. We then have the first $2 \times p_2$ bits free of interference. This process can be continued by using the second p_2 bits until the whole frame is free of interference. Finally, the output will be despreaded according to the spreading sequence of the desired user in one finger RAKE receiver,

$$z(m) = \alpha_1^* \mathbf{r} \cdot \mathbf{s} \quad \text{and} \quad b(m) = \operatorname{sign}\{\operatorname{Re}(z(m))\}, \quad m = 0, 1, \ldots, M - 1$$

Since the above procedure has the capability to cancel the interfering paths completely, the received signal retrieves the orthogonality property and as a result there is no MAI at the output of the correlator. Although the present technique can remove MAI, needless to say this property comes at the expense of accumulating the Gaussian noise which has a crucial effect on the performance of the system. Therefore, the application of this method is feasible in some propagation environments where there exists a line of sight path (a relatively strong first path), or in an environment with Ricean channel characteristics in which the power delay profile has exponential decaying form.

4. PERFORMANCE ANALYSIS

In this section we briefly analyse the performance of the designed receiver. With the assumption of having knowledge of the channel time delays and coefficients the bit error rate (BER) only

DOI: 10.1002/dac

depends on the Gaussian noise. As we mentioned the drawback of the algorithm is the accumulation of the Gaussian noise. Let us assume that the channel model has the property such that the power received from the first path is strictly greater than total sum of power received from other paths, i.e.

$$\sum_{l=2}^{L} \alpha_l^2 < \alpha_1^2 \;\Rightarrow\; \sum_{l=2}^{L} \frac{\alpha_l^2}{\alpha_1^2} < 1$$

Let $\alpha_l/\alpha_1 = \beta_l$ and assume that the noise samples are independent then after one step cancellation of interferer chips the noise samples becomes:

$$n_1 = n_1 - \sum_{l=2}^{L} \beta_l n_0$$

after the second step we have

$$n_2 = n_2 - \sum_{l=2}^{L} \beta_l n_1$$

However, this noise accumulation is negligible for a few first steps it increases as the procedure passes the bits across the frame. The worst case is that we assume that the amount of the noise accumulation for the whole frame is fixed and is equal to the accumulated noise at the last step of the interferer chips cancellation of the last bit of the frame ($b(M-1)$). Then for the frame of the length M and number of chip sample per bit N, the maximum number of steps in each frame would be $q = \lceil M \times N/p_2 \rceil$, therefore the variance of the maximum accumulated noise is

$$var(n_q) = 1 + \sum_{l=2}^{L} \beta_l^2 + \left(\sum_{l=2}^{L} \beta_l^2\right)^2 + \left(\sum_{l=2}^{L} \beta_l^2\right)^3 + \cdots + \left(\sum_{l=2}^{L} \beta_l^2\right)^q$$

According to the assumption of $\sum_{l=2}^{L} \beta_l^2 < 1$ the above series is bounded above by the value which depends on the parameter N, M and mostly on the parameter $\gamma = \sum_{l=2}^{L} \beta_l^2$, the less close this value to 1 the less accumulated noise power. This increase in noise power due to accumulation just shifts the error probability graph of the single user system to the right, as the simulation result also shows, which can be compensated by increasing the signal power. The above derivation of noise power is for the worst case scenario (the assumption that we used for the sake of simplicity of derivation) and the real power of accumulated noise is comparably less than this.

5. SIMULATION RESULTS

In this section, we study the performance of the present technique using computer simulation. We consider the downlink of a wideband CDMA system with a chip rate of 3.84 Mbps and a saturated load with $K = 64$ active users. The users' spreading codes consist of orthogonal Walsh codes of length 64 followed by a common random scrambling code. QPSK modulation with raised cosine pulse shaping is used and perfect knowledge of multipath channel parameters is assumed at the receiver. The multipath propagation channel consists of four paths, one at zero propagation delay and the others with propagation delays randomly chosen in the range

DOI: 10.1002/dac

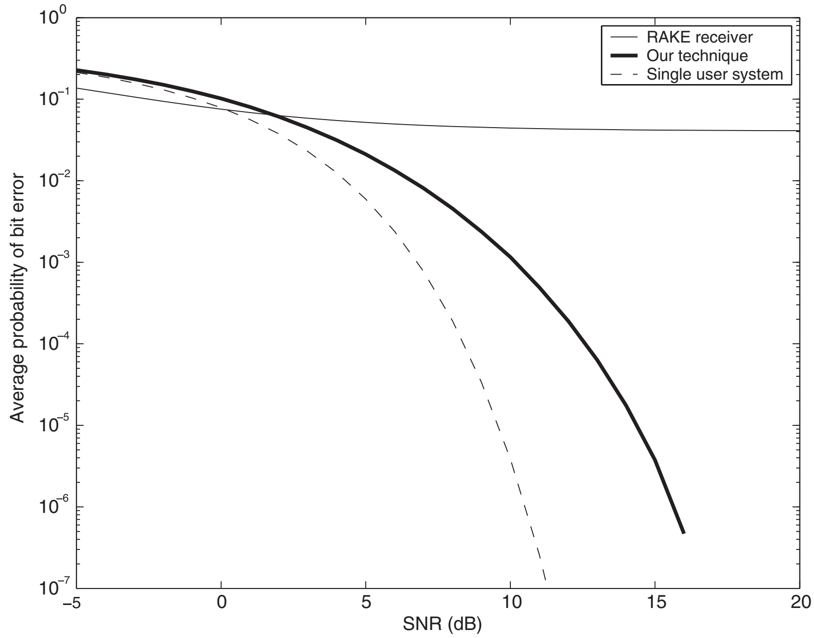

Figure 2. Average probability of detection error for all active users.

$[T_c, 25T_c]$, which are feasible for outdoor propagation environment where the maximum delay spread is up to 7 μs [8, 9]. The channel paths are assumed to have powers of 0, −3, −13, −25 dB and the path phases are chosen uniformly between 0 and 2π. The simulation is done for a frame length of 500 bits, and the BER are obtained by averaging over 300 simulation runs. Figure 2 compares the BER performance of the present method, the RAKE receiver, and the single user system for different SNR (E_b/N_0). It is clear that the present technique significantly outperforms the RAKE receiver and it just has the loss of few dBs compared to single user system, which results entirely from the noise accumulation.

6. CONCLUSIONS

We have presented a new technique for multipath interference cancellation in the downlink of WCDMA systems. In the downlink of frame synchronous CDMA systems all signals undergo the same propagation channel, and depending on time delays of multipath, a few chips at the beginning of each frame will be immune from multipath interference. In the present method the receiver cancels the signals of interfering paths using these chips and the knowledge of channel parameters. The only disadvantage of this technique is the noise accumulation that could have a crucial effect on the receiver performance. However, in situations where there exists a line of sight signal, or the channel power delay profile has the exponential decaying form, this noise enhancement is negligible and the method has significant performance gain against the RAKE receiver according to our simulation results.

DOI: 10.1002/dac

Our future work will be to investigate the effect of any noise reduction technique to see if it can increase the performance by reducing the level of the noise resulting from noise accumulation.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation under Grant ANI-0203063.

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DOI: 10.1002/dac

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DOI: 10.1002/dac