Return Link Code Acquisition with DS-CDMA for High Capacity Multiuser Systems under Realistic Conditions

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***Abstract*— Acquisition of the code timing in a direct-sequence code-division multiple-access system at the base station must take place before signal detection and decoding is possible. Code acquisition under severe multiple access interference conditions with time varying codes makes the task even more difficult. Inefficient designs lead to large number of false alarms and/or missed detections. This paper details a realistic powerful code acquisition technique for the uplink of direct-sequence code-division multiple-access systems under high loaded situations, where the number of users is greater than the processing gain. Under this high multiple access interference condition the DS-CDMA acquisition problem becomes very difficult and conventional search methods simply fail. The method discussed utilises soft data from a multiuser detector to reduce the interference received by the acquisition unit. Numerical results validate performance under realistic conditions with amplitude, phase and frequency impairments.**

***Index Terms*— Synchronisation, Code division multiple access, cochannel interference, multiuser channels**

I. INTRODUCTION

The introduction of cellular wireless systems in the 1980s has resulted in a huge demand for personal communication services. This demand has increased the need for efficient systems, which has been partially satisfied by the introduction of second generation digital systems, some of which are based on direct-sequence code-division multiple-access (DS-CDMA). New third generation systems, almost all based on DS-CDMA, are now being deployed and will require even more efficient utilisation of the limited spectrum if the high bandwidth features are to become a reality.

In the Uplink of a DS/CDMA cellular communication system it is well known that the limiting factor on performance is interference from other users, i.e. Multiple Access Interference (MAI). To mitigate this effect a large body of research work has been performed to find receiver methods for minimising the MAI [1], [2], [3], [4]. A very promising receiver technique that has been recently developed is based on the “Turbo Principle” from Turbo Codes [5]. The technique is known as iterative multiuser detection (IMUD) and iteratively reduces interference. These techniques can achieve single user (no interference) performance even when the number of users is greater than the processing gain. Although there are many variations on the IMUD technique the low complexity interference cancellation based approach was first published in [2] and was analysed in [3]. Although these receiver techniques bring large improvements, further performance improvement is sought. Antenna arrays at the receiver can be included in the iterative MUD scheme and performance has been shown in [6]. System performance in terms of capacity and cell size improvements was shown in [4]. This paper focuses on acquisition of multi-user DS/CDMA where both a single antenna element and an antenna array is used by the receiver.

Efficient timing acquisition in single antenna DS-CDMA systems [7], [8], [9] is essential to minimise false alarms and missed detections. The acquisition function is to determine the code timing to within a half-chip interval prior to passing the timing information to a tracking function such as a delay lock loop. It has been shown that the acquisition task in the presence of MAI can significantly reduce the capacity of the system [10]. In [11] the authors defined the capacity of multiple users while maintaining acceptable acquisition performance. In [10] the authors suggested a multiple dwell solution, consisting of a search mode and a verification mode, in this paper the number of users was significantly less than the processing gain. Intuitively the sensitivity of the acquisition unit is reduced due to the MAI, which appears as noise like interference.

In this paper we develop acquisition techniques that work under high interference scenarios. The situations we are interested in is where the number of users is significantly greater than the processing gain. Previous work on 1-D code acquisition with the presence of MAI includes [12] which studied acquisition performance in the presence of MAI and the near-far problem. The authors compared the performance of approximate maximum likelihood, MUSIC and correlator performance, where the number of users was only one third the spreading factor. In [13] a constant modulus algorithm was proposed, however the number of users was also always less than the processing gain. In [14] an investigation into parallel acquisition in DS-CDMA systems with MAI and other effects was performed, however no suggestions on how to reduce MAI were discussed. In [8] an improved acquisition technique was introduced which is useful for channels with low SNR or MAI. The paper treated the MAI as noise and is therefore not in the same class as the technique we propose.

Most techniques in the literature try to perform acquisition for a number of users simultaneously. In a practical implementation this is never needed. Users, or paths from users, are detected (and lost) one at a time as a user enters (or exits) the

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particular cell of interest. For example when a base station is switched on there are no users present and one by one they are acquired, detected and received by the base station.

We describe in this paper a data directed acquisition system where the current users' information is used to improve the signal used for detecting new users or new paths from current or new users. We include results with and without phase and amplitude impairments to show robustness to errors. We also include realistic frequency offset impairments. The method is demonstrated utilising an iterative multi-user detector for data detection and a correlator for the acquisition unit. The technique is, however, more general and could be applied to a number of different multi-user detection schemes (MMSE, SIC) and to higher performance acquisition approaches. For the results in this paper we use simple correlator techniques [15]. The technique described has been patented under [16], [17] and has been analysed for synchronous chip and symbol systems in [18], [19].

II. SYSTEM MODEL

We assume that K users each transmit data symbols $d_t^{(k)}$ via BPSK modulation of the length N spreading codes $\mathbf{s}'_{c,t} \in \{\pm 1/\sqrt{N}\}^N$, where t is the time index and c is a chip index and bold type represents vector notation. We also assume that the pilot signal is transmitted using BPSK modulation, orthogonal to the data signal with spreading code length N and spreading codes $\mathbf{s}''_{c,t} \in \{\pm 1/\sqrt{N}\}^N$. This is similar to the modulation methods used in 3GPP [20].

The signal of interest, representing the transmitted preamble, uses random complex spreading codes which is a short code (repeated every symbol interval. In this model we assume no modulation or data encoding for the user of interest (i.e. $d_t^{(1)} = \pm 1$), as would be the case for the preamble of 3GPP [20].

For the generalised case (for both 1-D and 2-D) the model for a signal received by an L element array for all users at time t and chip interval c is then

$$\begin{aligned}\mathbf{y}_{c,t} &= \sum_{k=2}^{K+1} \mathbf{e}^{(k)} (s_{l,c,t}^{'(k)} P_d d_t^{(k)} + j s_{l,c,t}^{''(k)} P_p p_t^{(k)}) + \mathbf{e}^{(1)} s_{c,t}^{(1)} + \mathbf{n}_{c,t} \\ &= \sum_{k=2}^{K+1} \mathbf{e}^{(k)} g_{c,t} + \mathbf{e}^{(1)} s_{c,t}^{(1)} + \mathbf{n}_{c,t} \qquad (1)\end{aligned}$$

where k is the user number, l is the antenna element number $l = 1, \ldots, L$. P_d and P_p are constant and are the amplitude of the data and pilot signal, respectively. The channel adds zero mean complex white Gaussian noise (AWGN) with variance $\sigma^2 = N_0/2$, where N_0 is the single sided noise power spectral density. Using vector notation to represent the antenna array the steering vector is therefore

$$\mathbf{e}^{(k)} = \Big[1, \exp\{-j\pi l \sin(\theta^{(k)})\}, ., \exp\{-j\pi(L-1)\sin(\theta^{(k)})\}\Big]^T$$

for the k'th user and $\mathbf{n}_{c,t} = [n_{1,c,t}, .s, n_{L,c,t}]$ is a vector of L independent, identically distributed zero mean Gaussian noise terms, with variance σ_n^2. We shall measure angles relative to the broadside direction of the array.

Our system performs non-coherent detection. We assume we will be testing a finite number of code epochs obtained by discretizing the time uncertainty region into cells, where correct detection results when the H_1 cell is above the threshold and is the maximum. Likewise a missed detection is when the H_1 cell is below the threshold. A false alarm occurs when a H_0 cell (all other cells except the H_1 cell) is above the threshold. The false alarm probability (P_{fa}) is defined as the probability of the H_0 cell being above the threshold per symbol interval. The missed detection probability (P_{md}) is defined as the probability of the H_1 cell being below the threshold per symbol interval. We allow asynchronous chip and symbol timing and utilise random spreading codes for interfering users. We also include frequency uncertainty. The system model also assumes no multi-path and no time variation during acquisition, such as time drift.

III. ACQUISITION WITH ITERATIVE MUD UNDER HIGH MULTIPLE ACCESS INTERFERENCE

For given acquisition requirements the system capacity has been shown to be limited by the acquisition techniques [10], this means that as the ratio of users to processing gain increases traditional code acquisition techniques fail. This is because the system is interference limited and no amount of integration time will allow correct detection of the timing position. In the uplink of a mobile cellular system the base-station receiver is assumed to use a high performance multi-user receiver. This receiver contains information about the signals from the users that are currently being detected. These signals cause the MAI in the acquisition unit which is looking for new (unknown) users and new paths for currently known users in the multi-path case.

A. The Acquisition Concept

Initially the base station is turned on and no terminals are connected, over time callers connect and disconnect. The receiver detects the data for all users connected. The iterative MUD techniques [3], [6] possess a very good estimate of the baseband spread signal at the receiver input. If the receiver cancels the input baseband signal against the receiver estimate for every connected user then what is left is system noise, noise from incorrect estimation of interfering users, and signals from unknown users, or unknown paths of currently tracked users.

If the signal estimates from the currently tracked users are "good" then the remaining cancelled signal may be processed with a conventional correlator to find new users or new paths of currently tracked users. The definition of a "good" signal from the receiver is subjective, however, the received signal must be of a high enough signal to noise ratio after interference cancellation that the frame error rate conditions (QoS conditions) are met. If this were not the case this user would be dropped by the receiver as part of the Radio Resource Controller (RRC) function. Figure 1 shows a block diagram of the technique, here soft information from the multi-user receiver (which is the receiver's best guess at the input signals) is subtracted from the input signal. A correlator may then be used to acquire these signals. Figure 1 also highlights the need for a delay between the input signal and the cancellation process. The delay is needed because the IMUD requires a certain amount of time to determine its estimate of the received signal.

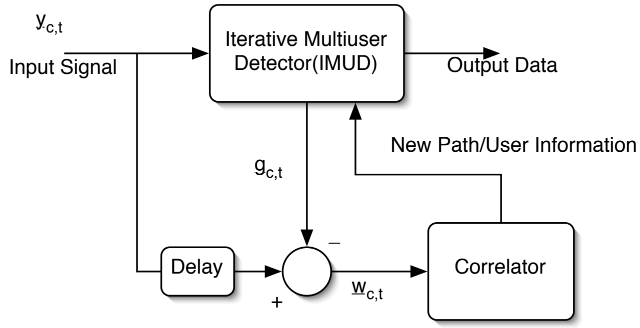

Fig. 1. Decision Directed Acquisition Unit.

We now show the formulation of the technique for the generalised case, which applies to both 1-D (single antenna reception) and the 2-D case (multiple antenna reception). We assume the received spread signal, $\mathbf{y}_{c,t}$, consists of signals that are being tracked by the receiver $\mathbf{g}_{c,t}$ plus one new signal $\mathbf{s}^{(1)}_{c,t}$. The decision directed approach then computes

$$\mathbf{w}_{c,t} \quad = \quad \mathbf{y}_{c,t} - \tilde{\mathbf{g}}_{c,t} \tag{2}$$

where $\tilde{\mathbf{g}}_{c,t}$ is the sum of an estimate of the spread signal sent by users $k = 2, \ldots, K + 1$ on each antenna element. The iterative multiuser detection technique discussed in [4], [6] is well suited to this decision directed approach as the receiver has available the spread signal estimates as they are needed for the receiver implementation. The added complexity of the implementation is therefore very low as shown in Section IV. This paper says nothing about the architecture of the correlating searcher unit only that it should be implemented following the cancellation of the input signal against the receiver estimate of the input signal.

Beamforming is performed prior to correlation (if more than a single antenna array exists). This is achieved by multiplying by the transpose of the steering vector, and is equivalent to maximum ratio combining [21] and is

$$w_{c,t} \quad = \quad \left(\mathbf{e}^{(p)}\right)^T \mathbf{w}_{c,t} \tag{3}$$

where $\mathbf{e}^{(p)}$ is the steering vector for the p^{th} sub-sector of interest. The cell is divided into sub-sectors, where time correlation is performed before moving to the next sub-sector.

Following beamforming the received signal is convolved with the time reversed complex conjugate of the wanted transmitted sequence such that the timing position can be determined. This method is based on the conventional correlation approach. The resultant signal is

$$r_{c,t} = \left| \sum_{c=1}^{N} w_{c,t} (s^{(1)}_{c,-t})^T \right| \tag{4}$$

where the absolute value is taken as the phase of the signal is unknown.

IV. MAXIMUM LIKELIHOOD ACQUISITION WITH MULTIUSER INTERFERENCE CANCELLATION

To understand the complexity and size of the acquisition problem it is beneficial to describe the Maximum Likelihood (ML) problem where there is multiuser interference. The ML solution is described here where this is compared to the computational complexity of our proposed method.

The maximum likelihood solution for timing synchronization of user $K + 1$ given K users exist in the system already will be described. This analysis is independent of the search algorithm used and only describes the complexity based on the search space. The assumption is that hypotheses are taken for all users over all data symbols that are currently being detected. The assumption is that the data hypotheses are hard, therefore the data to correlate against is based on

$$\hat{w}_{c,t} \quad = \quad y_{c,t} - \hat{g}_{c,t} \tag{5}$$

where

$$\hat{g}_{c,t} \quad = \quad \sum_{k=2}^{K+1} s^{(k)}_{c,t} P_d \hat{d}^{(k)}_t \tag{6}$$

and $\hat{d} \in \{+1, -1\}$. We assume the pilot signal is known at the receiver and already cancelled.

This is described by the following equation

$$\{\tau, \hat{\mathbf{d}}^{k=1:K}\} = \arg \max_{\tau, \mathbf{d}^{k=1:K}} \sum_{t=1}^{T} \left| \sum_{c=1}^{N} \hat{w}_{c,t} (s^{(1)}_{c,-t})^T \right| \tag{7}$$

here the solution is to maximise a correlation for the known spread sequence and data set, where all combinations of timing offset and data symbol possibilities for the other users is searched. If the data symbols involved in the correlation are T then the order of the complexity of this search is $O(N_s D.2^{TK})$, where the first $N_s T$ is for the number of timing positions that need to be checked, and 2^{TK} are the number of different data combinations of data combinations that need to be hypothesised.

A. Computational Complexity for 1-D and 2-D Acquisition

In this section we describe the computational complexity of the proposed solution as discussed. The optimisation cannot be described as the maximisation of the argument as soft values are taken from the detector and cancellation is performed. Therefore the computational complexity for the 1-D system is simply $O(N_s.T.K)$ cancellations and for the 2-D case the complexity is $O(P.N_s.T.K)$.

The computational complexity is therefore linear with the spreading factor and the number of symbols for the 1-D case and for 2-D this is extended to include the number of antenna elements. The complexity is trivial compared to the exponential search over the number of symbols and the number of users for the ML solution.

Figure 2 shows the computational complexity as a function of the number of users. For this example the integration time was $T = 3$, the number of Antenna sub-sectors for the 2-D case

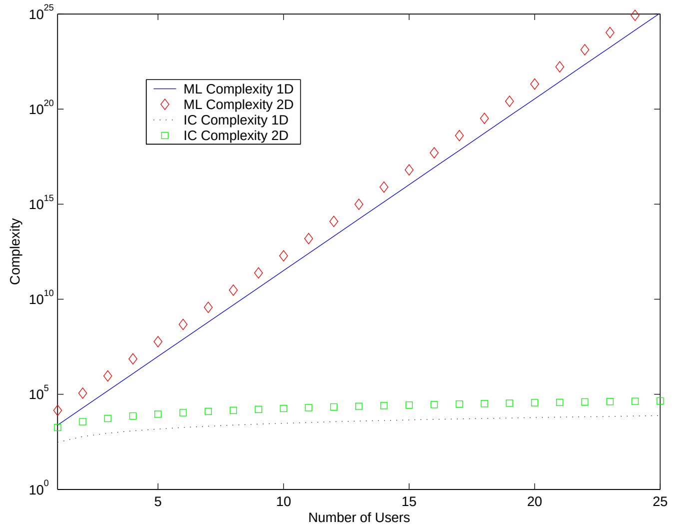

Fig. 2. Computation Complexity Comparison between ML and Interference Cancellation.

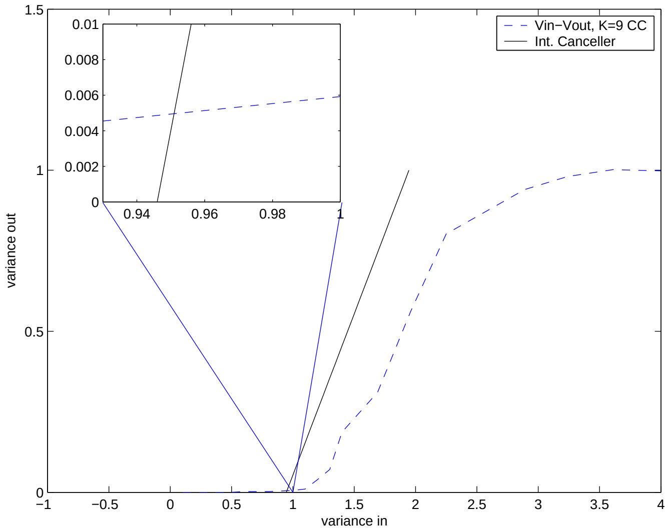

Fig. 3. Variance in vs. Variance Out Plot for Conv. Code and Interference Canceller.

was $P = 6$, the spreading factor was $N = 100$, and the number of users was $K = 150$. As can be expected the maximum liklihood (ML) computational complexity increases exponentially with the number of users, while the interference cancellation (IC) computational complexity only increases linearly with the number of users. For more than about 10 users the ML approach is not realizable.

V. DETERMINING RESIDUAL INTERFERENCE LEVELS

The residual interference from the MUD receiver will determine the performance of the acquisition unit under the proposal we have detailed here. The purpose of this section is to determine a typical residual interference value (σ_x^2), which can be used in showing the expected performance of the system. The typical frame error rate (FER) that maximises capacity has been determined to be FER = 0.1 [20][p.270]. We assume that the bit error rate required is $P_e = 10^{-3}$. Using the rate 1/3 $K = 9$ convolutional code from 3GPP [22][p.166] the $E_b/N_0 = 1.8$ dB. Allowing headroom we select $E_b/N_0 = 2$ dB, which equates to an $E_s/N_0 = -2.7$ dB. If the pilot is 6dB lower than the data signal (typical) then the pilot $E_s/N_0 = -8.7$ dB. Assuming the preamble is at $E_s/N_0 = 1$ dB we can therefore set the amplitude of the data/pilot signals based on an fixed amplitude of 1 for the real/imag. value of the preamble. The data and pilot signals amplitude for this configuration are therefore $0.653 = 10^{-3.7/20}$ and $0.327 = 10^{-9.7/20}$, respectively.

To determine σ_x^2 we utilise the variance in/variance out analysis approach [3] of the $K = 9$ rate $R = 1/3$ convolutional code, along with the interference canceller function line with user loading of $K/N = 1.5$. As can be seen in Figure 3 the residual variance is where these two curves cross. We can see that this value is $\sigma_x^2 = 0.005$ when the noise variance is $\sigma_n^2 = 0.946$, this value of noise variance is computed for a $E_b/N_0 = 2$ dB for the code rate 1/3 convolutional code.

Although the individual values of $\tilde{d}$ are not Gaussian the sum of a large number of these values will be and we utilise this assumption throughout our work. It turns out from comparing the simulation to the analysis that this assumption is very close to correct.

VI. ASYNCRONOUS NUMERICAL RESULTS

In this section we show results in Figure 4 when the correlation process is allowed to be asynchronous for the 1-D case. Each users timing position is randomly selected with a uniform distribution over the symbol, the spreading codes are random, the phase of each user is uniformly distributed $[0 - 2\pi]$ and the oversampling rate is $O_s = 4$. For this example the number of users was $K = 150$, and the processing gain was $N = 100$. The signal power of the preamble was $E_s/N_0 = 10.54$ dB, or alternatively with integration of three symbols at $E_s/N_0 = 1$ dB. The interference power was as described in Section V. The transmitter and receiver pulse shaping filter is a root raised cosine filter of length 24 chips, providing overall raised cosine filtering. Under these conditions analysis of the system, to the authors' knowledge, is not possible as this would require knowing the distribution of signals that have been low pass filtered.

As the terminal removes the large initial frequency offsets [23] the remaining frequency offset is typically less than 571Hz, consisting of 200Hz frequency error from the terminal, and the addition of 371 Hz, which is due to a vehicle traveling at 200 km/hr. In the result in Figure 4 the interfering users have a random frequency offset between ±571 Hz, uniformly distributed, while the signal of interest has a +571Hz frequency offset. The effect of this, as will be shown, is insignificant, as acquisition occurs within a few symbol intervals, where the rotation in this time interval is less than 16 degrees.

The results in Figure 4 show the same trend as those for the chip synchronous solution [19]. The results are shown in terms of the false alarm probability (x-axis) P_{fa}, which defines when an invalid timing point is determined from the acquisition unit, and the missed detection probability (y-axis) P_{md} which is the probability of occurrence that the correct timing position is missed. The performance shows that the partial cancellation is essential to acquire signals under the given conditions,

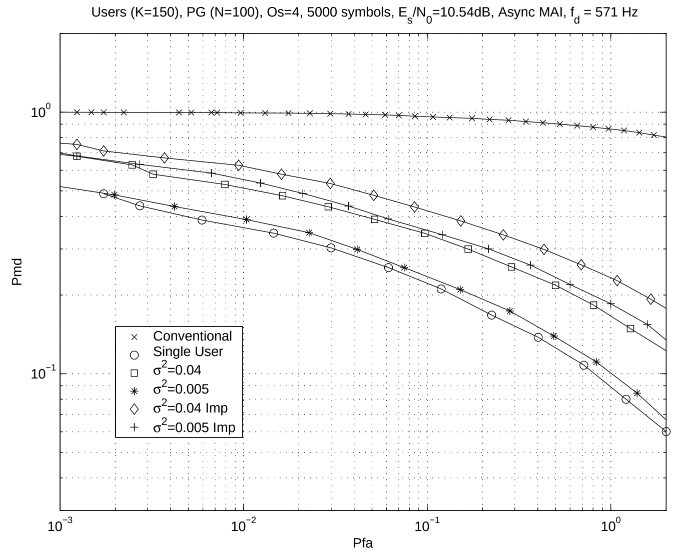

Fig. 4. Acquisition Performance for a single antenna with 4 times oversampling

where the conventional approach has 100% missed detections. We also can note as the reliability of the data from the receiver degrades so to does the performance of the acquisition system.

Figure 4 also shows results with impairments "Imp" with the rest of the parameters the same as before. As expected the acquisition performance degrades but the results are still very good. Here the amplitude error variance of the sum of the multiple access interference is $\sigma_a^2 = 0.005$ and the phase error variance is $\sigma_p^2 = 0.09$ radians. These interference levels are an estimate based on a mean multiple access interference amplitude of 0.3, which equates to a mean square error of MSE = 0.038, this is equivalent to an operating point of $E_b/N_0 = 2$dB in [24] and therefore is a pessimistic value, where [24] evaluates the channel estimation performance in terms of MSE within an iterative multiuser detector.

VII. SUMMARY

In this paper we have investigated a low complexity acquisition technique based on a soft data directed assistance from the receiver. This has been performed under severe multiple access interference, where the number of users is greater than the processing gain. The tests have been performed with realistic phase, amplitude and frequency impairments.

We show a generalised channel model for both the 1-D and 2-D cases and illustrate the concept of using a data directed interference cancellation approach to minimise multiple access interference with acquisition. We detail a complexity study and show the low complexity of our solution. We also show numerical results with and without impairments to indicate the benefits of our technique.

This paper demonstrates that for high performance multiuser detection designs that information sharing between the acquisition unit (searcher) and the receiver is essential to maximise the capacity of the system and achieve acquisition of new users, or new paths of current users. Based on the reliability expected from our receiver, this technique significantly improves the capacity of the return link system.

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