Real-Time DSP Implementation of a Coherent Partial Interference Cancellation Multiuser Receiver for DS-CDMA *

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Abstract- **This paper presents a baseband real-time DSP implementation of a multiuser receiver built upon an improved strategy for parallel interference cancellation. Significant performance gains are obtained by using a partial parallel interference cancellation scheme that mitigates the negative effects of biased estimation and imperfect MAI cancellation that are intrinsic to the complete interference cancellation approach. An attractive feature of the implementation is that it has a computational complexity that is linear in the number of users. Experimental test results confirm substantial improvements over the conventional receiver.**

1 Introduction

The conventional receiver for DS-CDMA corresponds to a matched filter demodulator and is optimal for single user communications over AWGN channels. In a multiple access situation this receiver is no longer optimal and requires power control. The optimum multiuser detector for Gaussian channels was derived in [1] and corresponds to a bank of matched filters followed by a Viterbi algorithm. The complexity per bit decision of this technique is $O(2^K)$ where K is the number of simultaneous users. For most applications this level of complexity precludes its practical implementation. Alternate lower-complexity sub-optimal multiuser receiver structures have been proposed. Good descriptions of proposed receiver structures are found in [2, 3].

Our intent is to develop a practical implementation of a multiuser receiver. In previous work, we have examined the performance of several major receiver structures for a variety of situations and channel conditions. Comparative performance and computational complexity results based on theoretical and simulation analysis are presented in [4]. Figure 1 shows the probability of error vs. the number of users K for several multiuser detection schemes. The multistage partial parallel interference cancellation approach provides an excellent tradeoff between computational complexity and performance. It is also robust to phase and synchronization errors [5]. As a result the parallel partial interference cancellation approach was selected for implementation. In this paper, we present the practical details of implementation for this type of receiver.

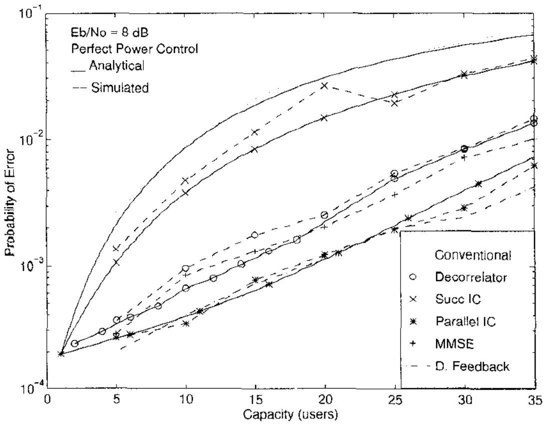

Figure 1: Multiuser Receiver Probability of Error vs. Number of Users K in AWGN (Eb/No = 10dB, and N = 31). Two Stages of Cancellation (S=3) used in the Multistage Partial Parallel Interference Cancellation Approach.

This paper is organized as follows: Section 2 presents a system model for multistage parallel interference cancellation. In section 3, the parallel partial interference cancellation approach is introduced and a low complexity approach for computing the decision statistics is derived. Section 4 describes the real-time implementation and section 5 describes the experimental results obtained with the real-time system. Conclusions are presented in section 6.

2 System Model

The model for the DS-CDMA multiuser system used in this paper is similar to that in [4]. The received baseband signal from user k is defined as a binary phase modulated waveform:

$$s_k(t) = \sqrt{P_k} a_k(t) b_k(t) e^{j\theta_k} \tag{1}$$

where P_k is the kth user's received signal power, $a_k(t)$ and $b_k(t)$ are the spreading and data waveforms respectively, and θ_k is the received phase of the kth user relative to some reference phase. Due to the asynchronous nature of the system

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*This work has been funded by DARPA's Global Mobile Information Systems (GloMo) program, the Office of Naval Research and the MPRG Industrial Affiliates Program.

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uplink, the received signal is

$$r(t) = \sum_{k} s_k(t - \tau_k) + n(t) \tag{2}$$

where τ_k is the time delay of the kth user relative to a reference time, and we assume a single noise source from a common front end.
The set of sufficient statistics can be shown to be a set of matched filter outputs Z where the filters are matched to each user's spreading code. The decision metrics $Z^{(s+1)}_{I_{k,i}}$ and $Z^{(s+1)}_{Q_{k,i}}$for the ith bit of the kth user after s stages of cancellation for an S-stage parallel cancellation scheme can be expressed as:

$$Z^{(s+1)}_{I_{k,i}} = \frac{1}{T}\int_{(i-1)T+\tau_k}^{iT+\tau_k} \hat{r}^{(s)}_{I_k}(t) a_k(t - \tau_k) dt \tag{3}$$

$$Z^{(s+1)}_{Q_{k,i}} = \frac{1}{T}\int_{(i-1)T+\tau_k}^{iT+\tau_k} \hat{r}^{(s)}_{Q_k}(t) a_k(t - \tau_k) dt, \tag{4}$$

Where the received baseband signal at stage s for user k is generated by subtracting from the received signal the estimated MAI:

$$\hat{r}^{(s)}_{I_k}(t) = r_I(t) - \sum_{j\neq k} \hat{s}^{(s)}_{I} a_j(t - \tau_j)\cos(\theta_j) \tag{5}$$

$$\hat{r}^{(s)}_{Q_k}(t) = r_Q(t) - \sum_{j\neq k} \hat{s}^{(s)}_{Q} a_j(t - \tau_j)\sin(\theta_j), \tag{6}$$

and the signal $\hat{s}^{(s)}$ corresponds to the estimated reconstructed signal for user j at stage s:

$$\hat{s}^{(s)}_{I_j}(t) = \frac{1}{T} a_j(t)\cos(\phi_j) \sum_{i=-\infty}^{\infty} C^{(s)}_{K} Z^{(s)}_{j,i} p_T(t - iT). \tag{7}$$

$$\hat{s}^{(s)}_{Q_j}(t) = \frac{1}{T} a_j(t)\sin(\phi_j) \sum_{i=-\infty}^{\infty} C^{(s)}_{K} Z^{(s)}_{j,i} p_T(t - iT). \tag{8}$$

where $C^{(s)}_K$ is the partial-cancellation multiplicative factor used for bias mitigation, and its value is selected according to the number of users K in the system.

For the complete cancellation scheme $C^{(s)}_K = 1$.
In terms of the complex envelope, the decision statistics are given by:

$$Z^{(s)}_{k,i} = Z^{(s)}_{I_{k,i}}\cos(\theta_k) + Z^{(s)}_{Q_{k,i}}\sin(\theta_k) \tag{9}$$

3 An Improved Strategy for Multi-stage Parallel Interference Cancellation

In a direct implementation of parallel interference cancellation, each user's received signal is computed in parallel by *completely* subtracting out from the received signal the estimated MAI from all other users. Improved estimates are then obtained from each user's cleaner signal. This process can be repeated iteratively.

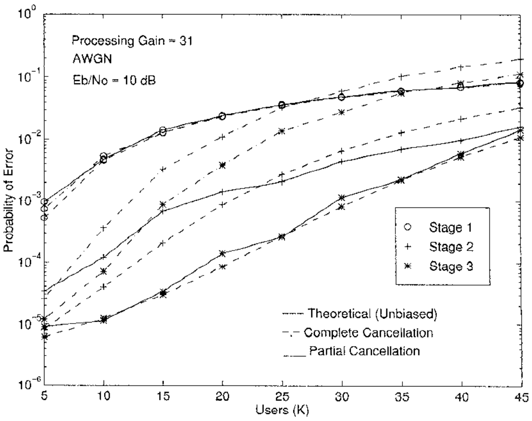

Figure 2: Simulated Probability of Error vs. Number of Users K for the Complete Parallel Cancellation, and the Partial Parallel Interference Cancellation Approach Used in the DSP Implementation.(Eb/No = 10dB, and $N = 31$, with $C^{(2)}_K = 0.5$ and $C^{(3)}_K = 1$).

In order to lessen the computational complexity of the receiver, at each stage a bank of matched filters is generally used for estimation of the transmitted bits and received signal energies. A drawback of this approach however, is that it gives rise to biased decision statistics that cause reduced performance. It was shown in [6] that after one stage of interference cancellation, the expected value of the decision statistic conditioned on the transmitted bit and normalized for $T_c = 1$ is given by:

$$E\{Z^{(2)}_{1,i}|b^{(1)}_i\} = \sqrt{\frac{P_1}{2}} b^{(1)}_i \left[1 - \frac{(K-1)}{3N}\right]. \tag{10}$$

The bias is produced because the estimates of the interfering signals are correlated with the desired user's received signal due to imperfect MAI reconstruction and cancellation. The bias increases with system loading and is inversely proportional to the processing gain N.

The technique used in the implementation for parallel interference cancellation is based on multiplying the channel gain estimates during signal reconstruction by a partial-cancellation factor $C^{(s)}_K$ as indicated in Equations 7 and 8. The value of the partial-cancellation factor varies with the stage of cancellation s, and the system loading K. A more complete study of the proposed parallel partial interference cancellation technique and the bias in the decision statistics can be found [6]. Figure 2 shows capacity curves for the proposed partial cancellation approach, direct cancellation and the analytical results that would result from unbiased estimation. In this figure we can see the significant enhancements in performance provided by the proposed technique over direct cancellation.

The computational complexity of an advanced algorithm is of key importance for its real-time implementation. In parallel interference cancellation, use of the approach described by Equations 5 and 6 makes the underlying concept of interference cancellation easy to understand. However, it also has a computational complexity of $O(K^2)$ since for each one of the K users, re-creation of the MAI affecting its signal is accomplished by adding the estimated signals of the other $K - 1$ users. As the number of users increases, the

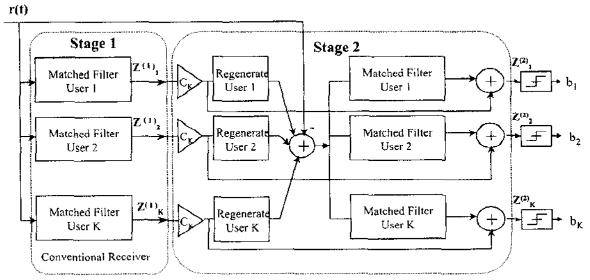

Figure 3: Block Diagram of the Parallel Partial Interference Cancellation Receiver

complexity of this approach grows rapidly. In our implementation, an alternate approach that is theoretically equivalent but reduces the complexity of the re-estimation scheme to $O(K)$ was used. A block diagram of this approach is shown in Figure 3.

The reduced complexity approach used in the DSP implementation can be summarized as follows: First, a residual signal $\tilde{r}(t)$ is created by subtracting from the received signal the sum of the estimated signals of *all* users:

$$\tilde{r}^{(2)}_{I_k}(t) = r_I(t) - \sum_{j=1}^{K} \hat{s}^{(2)}_I a_j(t-\tau_j)\cos(\theta_j) \tag{11}$$

$$\tilde{r}^{(2)}_{Q_k}(t) = r_Q(t) - \sum_{j=1}^{K} \hat{s}^{(2)}_Q a_j(t-\tau_j)\sin(\theta_j), \tag{12}$$

With these definitions, it is easy to see that $\hat{r}^{(2)}_{I_k}(t)$ and $\hat{r}^{(2)}_{Q_k}(t)$ respectively can be expressed as:

$$\hat{r}^{(2)}_{I_k}(t) = \hat{s}^{(2)}_I a_k(t-\tau_k)\cos(\theta_k) + \tilde{r}^{(2)}_{I_k}(t) \tag{13}$$

$$\hat{r}^{(2)}_{Q_k}(t) = \hat{s}^{(2)}_Q a_k(t-\tau_k)\sin(\theta_k) + \tilde{r}^{(2)}_{Q_k}(t), \tag{14}$$

Substituting these expressions into Equations 3 and 4, and using the definitions of Equations 7 and 8 for the reconstructed signal of user k, the decision statistics for stage 2 reduce to:

$$Z^{(2)}_{I_{k,i}} = C^{(2)}_K Z^{(1)}_{I_{k,i}} + \frac{1}{T}\int_{(i-1)T+\tau_k}^{iT+\tau_k} \tilde{r}^{(2)}_{I_k}(t)a_k(t-\tau_k)dt \tag{15}$$

and

$$Z^{(2)}_{Q_{k,i}} = C^{(2)}_K Z^{(1)}_{Q_{k,i}} + \frac{1}{T}\int_{(i-1)T+\tau_k}^{iT+\tau_k} \tilde{r}^{(2)}_{Q_k}(t)a_k(t-\tau_k)dt, \tag{16}$$

The new decision statistics are computed from the decision statistics obtained in the the previous stage and a correction factor computed from the residual signal $\tilde{r}(t)$. The dramatic reduction in computational complexity over the straightforward approach stems from the fact the residual signal is common to all users and thus it is only generated once per stage.

The computational complexity per bit of the algorithm can be expressed in terms of the number of users K, the spreading factor N, and the number of samples per chip N_s as follows: Data acquisition and storage is an $O(NN_s)$ task, matched filter bank demodulation is $O(KNN_s)$, normalization of the decision statistics by NN_s and storage is an $O(K)$ operation. Respreading the estimated user signals has a complexity that is $O(KNN_s)$, creation of the residual signal by partially subtracting every reconstructed signal from the received signal is an $O(KNN_s)$ task, and computation of the correction term from the residual signal via correlation and re-estimation of the decision statistics is $O(KNN_s)$. From the previous estimates, it is straightforward to see that the overall computational complexity of this approach is linear in the number of users, the processing gain and the number of samples per bit. This result can be extended to a more complex multistage implementation with S stages and L finger rake receivers. In this case the overall complexity will be $O(LSKNN_s)$.

4 System Description

An asynchronous real-time two-stage multiuser CDMA receiver that employs the proposed parallel partial interference cancellation technique has been implemented. The system is based on an ADSP21020 EZLAB board. The direct sequence BPSK system supports an aggregate rate of 20 Kbps, and has a processing gain $N = 15$. The input to each receiver is the complex-baseband multiple access signal stream. Data acquisition is interrupt-driven. Four samples per chip are used in order to keep timing errors below $T_c/8$. The effects of timing errors on the performance of multistage parallel interference cancellation receivers has been studied in [5]. Analytical and simulation results indicate that multistage parallel interference cancellation receivers are fairly robust, and show moderate reductions in performance due to timing errors on the order of $T_c/5$. Therefore a rate of 4 samples per chip was selected as a compromise between minimizing the negative effects of synchronization errors and timing misalignment at the receiver, and increasing the overall computational complexity of the implementation.

The system operates on the complex-baseband signal as it arrives, which avoids unnecessary processing delays and storage requirements associated with block processing. In this system we use an early-late approach for synchronizing with user 1, which is the first user to start transmitting. For the tests presented in this paper, the delays of the remaining users are maintained fixed with respect to user 1. An approach that takes advantage of the multistage architecture by using the residual signal $\tilde{r}(t)$ for improved acquisition and tracking has been studied in [7]. Since the residual signal has reduced levels of MAI, the probability of false alarm and mean acquisition time of the system are reduced. This technique will be incorporated in the receiver in the near future.

After synchronization, the conventional receiver soft-outputs are computed for all users. For each user, a decision statistic is computed via correlation with the corresponding signature sequence. Each decision statistic provides an estimate of the transmitted symbol and the received energy. Due to the asynchronous nature of the multiple access channel, in general two consecutive bit intervals of the received signal need to be considered to compute the decision statistics for all users.

In our system, the conventional receiver soft outputs

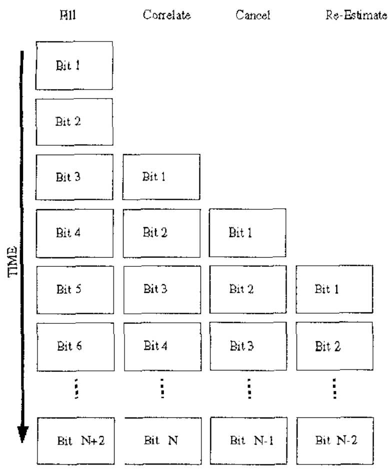

Figure 4: Timing Diagram Describing the Processing Chain for the real-time implementation

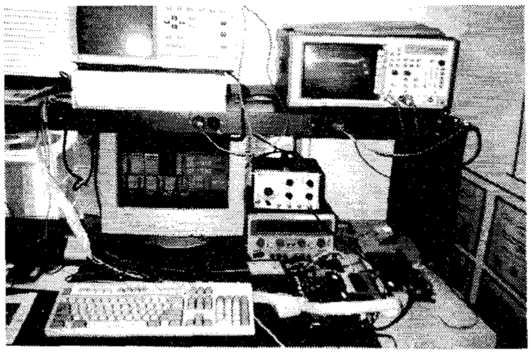

Figure 5: Laboratory Setup for the Real-time DSP Parallel Partial Interference Cancellation Multiuser Receiver .

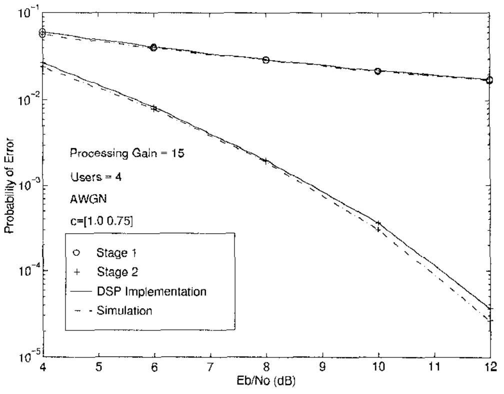

Figure 6: Probability of Error vs. Eb/N_o Experimental and Simulation results for a single trial of the DSP Implementation ($N = 15$, with $C_K^{(2)} = 0.75$).

are computed for every user via correlation between the segment of the received signal corresponding to bit n of each user and the user's signature sequence. The soft outputs are then multiplied by the partial-cancellation factor and stored in memory. The residual signal, defined in Equations 11 and 12, is then computed for bit $n-1$ by first estimating and regenerating every user's spread signal (see Equations 7 and 8), and then subtracting the regenerated signals from the received signal. An improved decision statistic is then created for bit $n-2$ by adding the modified original decision statistic of bit $n-2$ to the correction factor obtained from the residual signal, as summarized in Equations 15 and 16. Since data acquisition is interrupt driven and the system operates in real-time, all this processing occurs while the processor is collecting samples corresponding to bit $n+2$. A timing diagram is presented in Figure 4

5 System Verification and Experimental Results

In order to test the real-time DSP implementation of the parallel interference cancellation receiver, a real-time multiple access channel emulator was developed using a second ADSP21020 EZLAB board. The channel emulator takes the information that the different users wish to convey to the multiuser receiver, and creates an asynchronous complex-baseband multiuser signal stream. The system allows stipulation of the desired E_b/N_o, and the relative delays and phases among users. The delays and phases once selected, remained constant for the duration of the test. Figure 5 shows the real-time multiuser system in the laboratory.

A bit-error-rate tester was developed based on the multiple access channel emulator. At the transmitter, a pseudorandom data stream is internally generated and bits are assigned to the different users, the composite multiple access signal is created and AWGN is added. At the receiver, the received stream is decoded and the estimated data is compared against an internally generated reference pseudorandom signal. The number of mismatches were measured in real-time and compared with those predicted by simulations. Figure 6 shows a comparison between the experimental BER results obtained with the real-time system and those predicted via simulation for a four user case. The match between both sets of results are almost perfect. In this case, the delays and the phases remained constant throughout the experiment. Results for other tests show a good fit between experimental and simulation results resembling those in Figure 6.

Figure 7 shows a plot of BER results obtained for several trials with different delays and phases for the 4 user case. From this figure we can verify that the real-time DSP implementation of the parallel partial interference cancellation receiver provides significant gains in performance compared to the conventional receiver for DS-CDMA. We also see that the analytical results based on the assumption of unbiased estimation [8] give optimistic results. In all these tests perfect knowledge of the relative phases and delays between between users was made available to the receiver. It has been shown analytically and via simulation that this structure is robust to phase estimation and synchronization errors [5]. In this paper the effects of imperfect phase and timing estimation are not addressed.

Another version of the system has been successfully used to transmit JPEG files in AWGN channels. In order to bring to light the improved performance provided by the DSP implementation of the multiuser receiver, a JPEG file

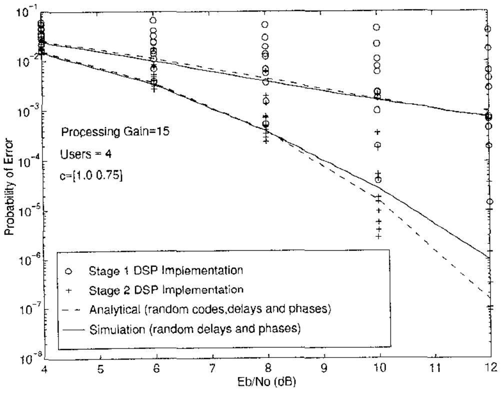

Figure 7: Probability of Error vs.Eb/N_o From Real-time BER Measurement Results, Simulated Curves for Random Delays and Phases, and Analytical Curves Assuming Unbiased Estimation ($N = 15$, with $C_K^{(1)} = 1.0$ and $C_K^{(2)} = 0.75$).

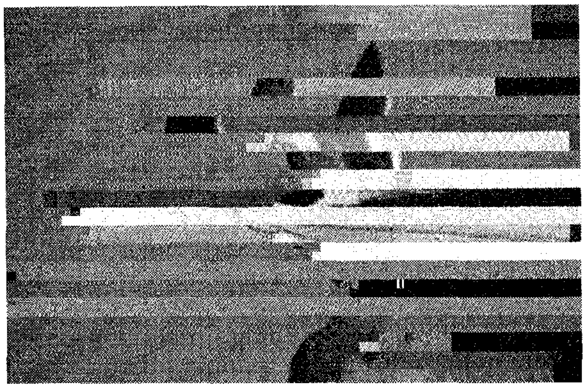

Figure 8: Reconstructed JPEG file from data estimated by the conventional CDMA receiver ($Eb/No = 10$dB, $N = 15$).

was jointly transmitted by 4 users. Each one of the users was given one bit of the JPEG file in a round-robin fassion for transmission. At the receiver, after estimation and decoding, the file was reassembled. The goal of this strategy is to have the reconstructed JPEG file give a feeling for the average performance of the system across all users. Figure 8 shows the reconstructed signal obtained from data estimated using the conventional receiver for a 4 user system operating at an $E_b/N_o = 10$ dB. Figure 9 shows the JPEG file reconstructed from the estimates obtained in real-time for the parallel partial interference cancellation approach.

6 Conclusions

A real-time DSP implementation of a parallel partial interference cancellation receiver has been successfully implemented and its performance has been experimentally tested in AWGN channels. This implementation provides significant performance gains over the conventional DS-CDMA detector. The excellent tradeoff between complexity and performance offered by the parallel partial interference cancellation technique makes it a very attractive approach for practical implementation of systems employing multiuser detection.

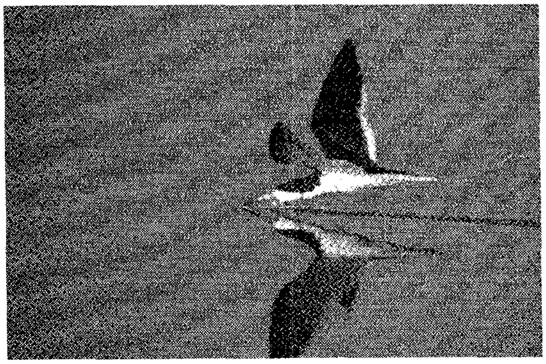

Figure 9: Reconstructed JPEG file from data estimated by the partial parallel interference cancellation receiver ($Eb/No =$ 10dB, $N = 15$, with $C_K^{(1)} = 1.0$ and $C_K^{(2)} = 0.75$).

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