PARALLEL INTERFERENCE CANCELLATION (PIC) IMPROVEMENTS FOR CDMA MULTIUSER RECEIVERS USING PARTIAL CANCELLATION OF MAI ESTIMATES

Peijun Shan and Theodore S. Rappaport
(pshan@vt.edu) (wireless@vt.edu)
The Bradley Department of Electrical and Computer Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061, USA

ABSTRACT

We study the improvement technique for multistage parallel interference cancellation (PIC) DS-CDMA multiuser receivers, which cancel only a fraction of the estimated multiple access interference (MAI) at each receiver stage. This technique takes into account the fact that the MAI estimate, especially in the earlier stages, contains substantial error, and a relatively conservative strategy of using the estimate may lead to better system performance (i.e., lower average bit error rate). We start with simulating the BER performance as a function of the fraction of cancellation, which shows that the fraction can make a significant difference and a “best” fraction can be far less than one. Then the PIC with partial cancellation and the standard PIC are compared under various near-far effects, channel SNR, and number of users. The simulations indicate how the partial cancellation technique can provide significant improvement over the standard PIC.

I. INTRODUCTION

The current direct sequence code-division multiple access (DS-CDMA) systems are based on the conventional matched filter receiver. This is called a single-user receiver as it takes all other user’s signals as noise and uses only the desired user’s spreading code to correlate with the received signal. With the MAI among users, the matched filter receiver is not optimal and suffers a substantial degradation in performance in the presence of the near-far effect and high traffic density.

A multiuser CDMA receiver makes use of all users’ information in the bit decision to achieve an optimal or sub-optimal performance. Since the optimal multiuser receiver proposed by Verdu [1] is too complex to be implemented for practical systems, many less complex sub-optimal multiuser receivers have been proposed and studied [2,3,4,5,6,7,8,9,11,12]. They can be classified into two main categories, the decorrelation receiver [2] and the subtractive interference cancellation receivers [3]. A decorrelation detector, or linear detector, attempts to remove the correlated MAI via linear operations on the decision statistics at the output of the conventional receiver. An interference cancellation receiver tries to first use the temporal decision to estimate the MAI, then the MAI estimate is subtracted from the received signal, and then another stage of decision is used on the new signal. Since the decorrelation technique still requires substantial computation, the interference cancellation receiver appears more promising for real systems [7].

MAI cancellation can be achieved in two different receiver structures: the successive interference cancellation (SIC) and the parallel interference cancellation (PIC) scheme [6]. A SIC receiver cancels the MAI, user by user, in each stage such that the remaining users see less and less MAI while a PIC scheme cancels the MAI for all the users simultaneously at each decision stage. A PIC receiver is much faster at the cost of more hardware complexity.

The standard PIC cancels the MAI with no weighting factor applied to the MAI estimated with the decision in the previous stage. At the earlier stages, a poor estimate of MAI due to the relatively high decision bit error rate may lead to a poor cancellation or even a higher BER at the following decision stage. Several approaches have been proposed to overcome this problem [6]. The examples include using: a) a decorrelation receiver as the initial stage [8], b) the multistage decision feedback detector which uses the detected bits in the current stage to help the decision on the remaining bits in the same stage [9], and c) the partial cancellation technique that we focus on in the following text.

The recently proposed improved PIC using partial cancellation at each stage [10,11,12] takes into account the fact that the tentative decision at the earlier stages is less reliable than the following stages, and lets the earlier cancellation be more conservative, which means that only part of the estimated MAI will be subtracted out. This idea was proposed by Divsalar and Simon [10], and dramatic capacity gain was reported in the case of uniform power distribution among the users [11]. Correal, Buehrer and Woerner [12] showed significant benefits of this technique by decision...
statistics bias analysis and simulations. In this paper, we further investigate this technique through simulations. The first problem we pose is to how much the fraction of cancellation can affect the performance and what could be a "good" value for the fraction at each stage. That is, we view the receiver performance as a function of the fraction of MAI cancellation. With some primary empirical knowledge of that, we then compare the improved PIC with the conventional brute force PIC in the aspects of near-far resistance, capacity, BER versus SNR and number of stages of cancellation. The results suggest a significant improvement of the studied technique over the standard PIC.

The rest of the paper is organized as follows. In section 2, we describe the improved PIC with partial cancellation at each stage. In section 3, the assumptions and simulation methods are described. In section 4, we simulate the system BER as a function of the fraction of cancellation employed at each stage. In section 5, we compare the studied technique with the standard PIC receiver under different near-far effects, channel SNR, and number of users for a single-cell situation.

II. PARTIAL CANCELLATION PIC

The only difference between the partial cancellation PIC and the standard PIC is that, at cancellation stage \( i \), the MAI estimate of each user is scaled by a fraction \( p_i \) (where \( i \geq 2 \) since stage 1 is an initial stage without cancellation) before being subtracted from the received signal. For the sake of decision, this is equivalent to the original received signal being multiplied by \( 1/p_i \) before subtracting the MAI estimate. A block diagram of the partial cancellation is given in Figure 1. The standard "brute force" PIC can be viewed as a special case when \( p_i = 1 \) for all \( i \). In Figure 1, the initial stage, referred to as stage 1, is a standard correlation CDMA detector implemented with a matched filter bank for all users. In the following stage, the first stage of partial cancellation, we first use the decision of the previous stage to estimate the amplitude of each user, then attempt to regenerate (respread) all of the users' received signals with the known spreading codes, the information bit decision obtained at the previous stage, and the estimated amplitudes. For each user, the MAI is then estimated as the sum of all of the other users signals. The original received signal \( r(t) \) is multiplied by \( 1/p_i \), subtracted by the corresponding MAI estimate for each user, and finally fed to the matched filter based detector for an improved decision for each user. Both the error of amplitude estimation and the error of previous decision will contribute to the MAI estimation error.

III. SIMULATION METHOD

Here we describe our assumptions and methods to the simulation study. We consider a synchronous code-on-pulse DS-CDMA system with BPSK modulation and processing gain \( N=15 \) chips/bit. To focus on the effect of the fraction of cancellation on BER performance, it is assumed that perfect phase and code synchronization exist, and that the channel is ideal (that is, multi-path effects are ignored). Such a system may exist in a high data rate wireless LAN in an indoor environment, for example, where propagation delays are small but not as small as a chip, or on a fiber optic cable system. We also assume that the additive channel noise is white Gaussian. The PN codes are random binary sequences of length \( N=15 \) with obviously non-zero cross-correlation, independently generated for each user. In all the simulation trials except the experiment on capacity in section 5.3 (BER versus number of users), we set the number of users to \( K=5 \), and used the same set of PN codes so that the results in different experiments are
comparable and consistent. In order to examine the MAI cancellation performance of the receivers, we need to choose PN codes with significant cross-correlation (and hence strong MAI) between users. We generated several sets of five length-15 random \{1, -1\} sequences and picked the set with cross-correlation up to ±7/15. The correlation matrix \( C \) of this set of PN codes is

\[
\begin{pmatrix}
15 & 3 & 7 & -7 & 3 \\
3 & 15 & 3 & 5 & -5 \\
7 & 3 & 15 & 1 & 7 \\
-7 & 5 & 1 & 15 & 1 \\
3 & -5 & 7 & 15 & 1
\end{pmatrix}
\]

In addition, the synchronous CDMA system considered here represents the worst case of an asynchronous system in the sense of MAI.

With the assumptions above, the system can be simulated in baseband. The following received signal model within a bit interval was derived (the derivation is quite straightforward and omitted here):

\[
R(n) = \sum_{k=1}^{K} \left( \frac{2}{N} \frac{E_b}{N_0} \right) b_k a_k(n) + G(n)
\]

where \( R(n) \) is the received CDMA signal in baseband at chip index \( n \) (integrated and sampled at the chip rate) within a bit interval (thus omitted the bit index), \( G(n) \) is the corresponding white Gaussian noise sequence in baseband with zero mean and unit variance, \( N \) is number of chips per bit (the processing gain), \( K \) is the number of users in the system, \( \left( \frac{E_b}{N_0} \right) \) represents the signal to noise ratio (SNR) for user \( k \), \( b_k \) is the information bit of user \( k \), and \( a_k(n) \) is the PN code for user \( k \). Hard decisions are used to estimate MAI at each stage of the receiver.

The simulation is carried out in data blocks (packets) of size 1000 bits. “Smooth” BER estimate curves and adequate confidence levels (>95%) are achieved by running 10 to 100 packets of 1000 bits for the BER ranging from \( 10^{-3} \) to \( 10^{-2} \).

IV. FRACTION OF CANCELLATION

Before comparing the partial cancellation PIC with the standard PIC, we first investigate how the BER performance of a PIC receiver is sensitive to the fractions of cancellation and what could be close to an optimal fraction of cancellation. Though, in general, there appears to be no common guidelines, it is insightful to look at a few examples.

Let us first consider a 2-stage receiver consisting of a stage of conventional single-user receiver followed by a stage of PIC with variable fraction of cancellation, as shown in Figure 1. We want to investigate the BER performance of the 2-stage receiver with respect to the fraction of the PIC stage.

**Example 1.** Ideal power control, \( N=15 \) chips per bit, \( K=5 \) users. Figure 2 depicts the simulated BER as a function of the fraction of cancellation. The fraction plays a significant role in the system performance, and the BER dips when the fraction is near 0.5 (for 15dB SNR) and 0.6 (for 8dB SNR). For the higher SNR, in which case the bit errors result mostly from MAI rather than channel noise, the influence of the fraction is more significant. Note that the user BER is reduced by nearly an order of magnitude at the optimal fraction when compared to a single-user receiver.

![Figure 2](image-url)

**Figure 2.** BER versus the fraction of cancellation, with ideal power control: (a) SNR=8dB, (b) SNR=15dB

**Example 2.** To consider near-far effects, the fifth user’s received power is set 10dB higher than users 1, 2, 3 and 4 (the normal users). Figure 3 shows the simulation results when the SNR for the four normal users are 8dB (a) and 15dB (b). Under the near-far situation, the partial cancellation exhibits comparable gain for the ideal power control cases, but the “best” fraction varies. Thus
fractional PICs may support the need for stringent power control in CDMA systems.

10°--------~--------~--~

N=15, K=5, SNR=8dB for users 1-4

Stage 1: Conventional
Stage 2: Partial PIC

Fraction of Cancellation at Stage 2
(a)

In Figures 2 and 3, the "best" fractions for the cancellation stage appear to be in the range of 0.5 to 0.8. Now we add a second stage of cancellation to the system. We simulate a 3-stage receiver, with the conventional matched filter-based decision as stage 1, followed by a stage of PIC with the "best" fraction of cancellation found above as the stage 2, and then followed by a PIC with variable fraction as stage 3.

Example 3. A 3-stage receiver with 2 stages of PIC, 5 users under ideal power control, N=15. Using the results in Example 1, the fraction of stage 2 is set to 0.6 for the case of SNR=8dB and 0.5 for the case of SNR=15dB. Figure 4 gives the BER at each stage against the fraction of the second cancellation. We can see that the fraction of the second cancellation is not as influential as that of the first cancellation from the observation that the bottom of the final (stage 3) BER curves is relatively flat, provided that the previous cancellation is well achieved.

Figure 3. BER versus the fraction of cancellation, under near-far effects (the 5th user is 10dB stronger): (a) SNR=8dB, (b) SNR=15dB

Figure 4. Varying the fraction at stage 3 with stage 2 tuned at the "best" fraction: (a) SNR=8dB, (b) SNR=15dB

Now we adjust the fraction of cancellation of both stage 2 and stage 3. Figure 5 shows 3 curves of the final BER at stage 3 when the fraction of cancellation at stage 2 is set to 0.5 (the "optimal" partial cancellation), 0.8 (an "arbitrary" partial cancellation), and 1 (the brute force cancellation) respectively. As we expected, using the fraction at stage 2 optimal for the 2-stage receiver also leads to the best performance for the 3-stage system. In other words, there is no need to adjust the fraction at the early stage when another stage is added after. The "arbitrary" fraction provided significant gain as well.
V. GAIN OVER STANDARD PIC

In this section we simulate the performance of the partial cancellation PIC receiver and compare it with the standard PIC receiver in terms of BER as functions of SNR, near-far effect and number of users.

5.1 BER versus SNR at Stages

We consider the 5-user ideal power control system with variable channel noise power density (varying $E_n/N_0$). A partial cancellation PIC receiver that uses 0.6, 0.7 and 0.8 as the fractions of cancellation at stages 2, 3, and 4, respectively, and a standard PIC receiver, both with an initial stage followed by 3 stages of PIC (with $p_i=1$), are compared. Here we “blindly” choose 0.6, 0.7 and 0.8 as $p_i$ rather than finding “optimal” $p_i$ for each stage since it may be impractical to track the time-varying optimal $p_i$ in real cases. As shown in Figure 6, a single stage of PIC with fraction 0.6 approximates the performance of 2 stages of standard PIC, and 2 stages of PIC with fractions 0.6 and 0.7 performs better (about 1.5dB improvement) than the 3 stages of standard PIC.

5.2 BER versus Near-Far Power Disparity

Consider a CDMA system consisting of 4 normal users, which have the same received power and SNR=8dB for each of the signals, and one “abnormal” (near or far) user, referred as user 5, with stronger (near) or weaker (far) received power. We simulate a 2-stage receiver with a stage of PIC following the initial stage of conventional decision. At the PIC stage, different fractions of cancellation: 0.6, 0.8, and 0.9 are compared in terms of BER performance as a function of the power disparity between the abnormal user and the normal ones, depicted in Figure 7. We can draw a few conclusions from Figure 7. First, the standard PIC can be significantly improved using partial cancellation. Second, the improvement margin disappears when the near-far effect is more severe. Third, the performance of a specific fraction of cancellation may not be consistent for different near-far conditions.

The partial cancellation PIC receiver examined in Section 5.1 is compared with the standard brute force PIC under conditions of near-far effect and 8dB SNR for the four normal users. The result is shown in Figure 8. The observations from Figure 7 are confirmed with the result in Figure 8.

5.3 BER versus the Number of Users

Unlike the previous cases where the fixed spreading codes were used, in this experiment we randomly generate spreading code for each data block so that the simulated BER will reflect the effect of the number of users in the system rather than the effect of which
specific user is dropped or added. Under 8dB SNR and ideal power control, we examine the BER performance of the partial cancellation PIC receiver as a function of the number of users K. As shown in Figure 9, the partial PIC with cancellation fraction 0.6, 0.7 and 0.8 successively, which consistently outperformed the brute force PIC with various SNR in Figures 6 and 8, also shows consistent superiority over the brute force PIC for the reasonable range of K (K<9 or K<60% of N). Here, again, one stage of partial cancellation PIC outperforms 2 stages of standard PIC consistently (for K<9).

![Figure 8. Partial cancellation against standard PIC: BER at stages versus near-far power ratio](image)

**Figure 8.** Partial cancellation against standard PIC: BER at stages versus near-far power ratio

![Figure 9. Partial cancellation against standard PIC: BER at stages versus capacity (number of users)](image)

**Figure 9.** Partial cancellation against standard PIC: BER at stages versus capacity (number of users)

### VI. CONCLUSION

Partial cancellation PIC can significantly improve the performance and/or reduce the complexity of a CDMA system. With partial cancellation, which just adds a single multiplication operation at each stage, we can use fewer number of stages of cancellation to achieve the performance of more stages of brute force PIC. That is, for a given performance goal, this improvement can reduce the system complexity and make PIC receivers more feasible and economical for real systems. With partial cancellation PIC receivers, we may be able to relax the requirement for power control to some degree.

### REFERENCES


