Selective Parallel Interference Cancellation for Uplink Cyclic-prefix CDMA

Kan Zheng, Wenbo Wang
Wireless Signal Processing Lab.
Beijing University of Posts & Telecomms
Beijing, China
Email: zkan@buptnet.edu.cn

Guillaume Decarreau
Wireless System Lab
France Telecom R&D center
Beijing, China
Email:guillaume.decarreau@francetelecom.com

Abstract—Code division multiplex access with cyclic prefix (CP-CDMA) is regarded as one of the best candidates for the broadband wireless communication systems in the uplink. This paper proposes a selective parallel interference cancellation (S-PIC) for uplink CP-CDMA. With less complexity and good resistance to near-far effect, the S-PIC can achieve better bit error rate (BER) performance than the conventional interference cancellation. Computer simulation demonstrates its effectiveness and conclusion is followed.

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) as a modulation technique is being applied extensively to high-speed wireless communication systems[1] due to its efficient usage of the available frequency bandwidth and robustness to frequency selective fading environments. However, recently much attention has been focused on another broadband technique, namely single-carrier (SC) transmission with frequency domain equalization (FDE). Similar to OFDM systems, Inter-block-Interference (IBI) in SC-FDE systems[2] can be eliminated completely using redundant cyclic prefix. The equalization is carried out in the frequency domain instead of in the time domain, which has less implementation complexity in the rich multipath environments. Furthermore, code division multiple access (CDMA), with higher capacity than other multiple access techniques, can be combined with SC-FDE not only to solve the difficult multipath environment problem but also to achieve good frequency efficiency[3]. This system, called as cyclic prefix (CP)-CDMA, also can tolerate some degree of asynchronous timing error. Moreover, CP-CDMA has reduced peak-to-average ratio (PAPR) requirements compared with OFDM thereby allowing the use of less costly power amplifiers, which is very attractive for the implementation of user terminal. Therefore, CP-CDMA with frequency domain equalization is a good choice for the uplink transmission in the broadband wireless communication systems.

In contrast to a synchronous downlink transmission where orthogonal spreading sequences suppress multi-user interference (MUI) efficiently, the orthogonality is destroyed seriously in an asynchronous uplink transmission. The conventional single-user detection technique is MUI-limited. It also requires strict power control in order to overcome the near-far problem, which is not easy to be implemented in practice. As a good solution to improve the system capacity, multiuser detection (MUD) approaches have been widely used in DS-CDMA systems. For the sake of practical implementation, interference cancellation schemes have been subjected to more attention. Compared with the successive interference cancellation (SIC) and parallel interference cancellation (PIC), the partial parallel interference cancellation (PPIC) can be applied to get better and faster convergence behavior[4]. Furthermore, the hybrid interference cancellation[5], which merges the SIC and PIC structures together, is the good tradeoff between the system performance and the processing delay. However, few MUD investigations have been carried out especially for CP-CDMA systems[6].

In this paper, we propose a novel selective parallel interference cancellation in CP-CDMA systems in the uplink. The cancellation is performed in the frequency domain while the user signal are despread and detected by hard-decision in the time domain. In order to alleviate the effects of the incorrect data estimates and reduce the computation complexity, the cancellation operation is selective and only the signals of the users with higher relative reliability will contribute to the necessary interference regeneration.

This paper is organized as follows. Section II gives the brief description of the CDMA systems with cyclic-prefix. The detector structure with selective parallel interference cancellation is described in Section III. Simulation results are presented and discussed in Section IV. Finally, Section V draws the conclusion.

II. SYSTEM MODEL

A single-cell system on the uplink is considered in this paper. It consists of $M$ user terminals transmitting quasi-synchronously (that is achieved by restricting the degree of synchronization to be less than the length of the cyclic prefix) with CP-CDMA symbols to a base station. After modulation (e.g. QPSK), the $p$th data symbol of the user $m$ within one burst of $P$ symbols with the sample rate of $1/T_d$ are arranged in the vector

$$a^{(m)} = [d_0^{(m)} d_1^{(m)} \ldots d_{P-1}^{(m)}]^T \in \mathbb{C}^{P \times 1}, \forall m \in \{1, 2, \ldots, M\}$$

(1)

Then, it is multiplied by the user-specific orthogonal spreading code $\{w_n^{(m)}\}, 1 \leq n \leq N$ with the chip duration $T_c = T_d/N$.
where $N$ is the spreading factor. The $NP \times P$ spreading matrix of the $m$th user can be expressed as

$$
c^{(m)} = \begin{bmatrix} w^{(m)}_1 & 0 & \cdots & 0 \\
0 & w^{(m)}_2 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & w^{(m)}_N \end{bmatrix} \in \mathbb{C}^{NP \times P} \tag{2}
$$

where $w^{(m)} = [w^{(m)}_1 \ w^{(m)}_2 \ \cdots \ w^{(m)}_N]^T \in \mathbb{C}^{N \times 1}$ is the user-specific orthogonal spreading vector for the $m$th user and the $N \times 1$ zero vector is $0_N = \{0\}_N$, $\forall n \in \{1, 2, \cdots, N\}$. The resulting signal vector with length of $N_c = NP$ for the $m$th user can be written as

$$s^{(m)} = c^{(m)}d^{(m)} \in \mathbb{C}^{N_c \times 1} \tag{3}
$$

Finally, a cyclic prefix with duration of $T_g$ is inserted to eliminate the inter-block interference (IBI).

The transmitted signal of each individual user passes through its $L$-path Rayleigh fading mobile channels, whose complex equivalent low-pass time-variant impulse response can be expressed as

$$h_l^{(m)}(\tau) = \sum_{i=0}^{L-1} \alpha_l^{(m)}(\tau - \tau_l^{(m)}) \tag{4}
$$

where $\alpha_l^{(m)}$ is the $l$th path gain of the $m$th user, which is independently complex Gaussian process with zero mean and variance $\sigma_{\alpha}^2$ for different $m$ and $l$; $\tau_l^{(m)}$ is the propagation delay for the $l$th path of the $m$th user. Here the time index is dropped due to the quasi-static character of the channel. The corresponding channel frequency response by $N_c$-point discrete Fourier transform (DFT) during one burst interval can be written as

$$H_k^{(m)} = \sum_{l=0}^{L-1} \alpha_l^{(m)} e^{-j2\pi \frac{\tau_l^{(m)}}{T_c} k/T_c} \tag{5}
$$

If the length of cyclic prefix is longer than the channel maximum delay spread, the convolution of channel impulse response and the transmitted signal becomes cyclic. At the receiver, the cyclic prefix is removed at first and the received signals are transformed to the frequency domain by Discrete Fourier Transform (DFT). Since a time-domain cyclic convolution is equivalent to a scalar frequency-domain multiplication, the received signal vector in frequency domain becomes

$$R = \sum_{m=1}^{M} H^{(m)}S^{(m)} + Z \tag{6}
$$

where $H^{(m)} = \text{diag}\{H_0^{(m)} H_1^{(m)} \cdots H_{N_c-1}^{(m)}\}$ is the $N_c \times N_c$ diagonal matrix formed by channel frequency response; $S^{(m)} = Fs^{(m)}$ is the signal in the frequency domain corresponding to the transmitted signal; and $Z = [Z_0 \ Z_1 \ \cdots \ Z_{N_c}]^T \in \mathbb{C}^{N_c \times 1}$ is additive white Gaussian noise (AWGN) with zero mean and variance $\sigma_0^2$. The $N_c \times N_c$ DFT matrix $F$ is defined by

$$\{F\}_{i,n} = e^{-j2\pi mi/N_c} \forall i, n \in \{0, 1, \cdots, N_c - 1\} \tag{7}
$$

### III. Detector Structure

The multi-stage detector consists of an MMSE equalizer and selective parallel interference cancellation. The stage of an MMSE equalizer produces initial data estimates of all the users, which will be used by the following stages to regenerate and cancel the interference in the frequency domain. Here the ideal channel estimation is assumed for simplification.

#### A. Initial MMSE equalizer

The initial (0th) stage is a linear filter bank in the frequency domain whose coefficients are determined by minimize mean square error (MMSE) criterion. By applying the MMSE criterion, the equalizer yields the output vector for the $m$th user as

$$Y^{(m)} = G_0^{(m)}R = [Y_0^{(m)} \ Y_1^{(m)} \ \cdots \ Y^{(m)}] \in \mathbb{C}^{N_c \times 1} \tag{8}
$$

where $G_0^{(m)} = \text{diag}\{G_{0,0}^{(m)} \ G_{0,1}^{(m)} \ \cdots \ G_{0,N_c-1}^{(m)}\} \in \mathbb{C}^{N_c \times N_c}$ is the MMSE weight matrix of the $m$th user with its elements of

$$G_{0,k}^{(m)} = \frac{H_k^{(m)*}}{\sum_{m=1}^{M} |H_k^{(m)}|^2 + \sigma_n^2}, \forall m \in \{1, 2, \cdots, M\} \tag{9}
$$

Then, the equalized signal vector is converted into the time-domain by Inverse DFT (IDFT). The initial (0th stage) tentative decision vector $\tilde{d}_0^{(m)} = [\tilde{d}_0^{(0,0)} \ \tilde{d}_0^{(0,1)} \ \cdots \ \tilde{d}_0^{(0,P-1)}] \in \mathbb{C}^{P \times 1}$ for the $m$th user is made by hard decision after despreading, which can be expressed as

$$\tilde{d}_0^{(m)} = \frac{1}{N_c}c^{(m)H}F^{-1}Y^{(m)} \tag{10}
$$

It consists of the desired signal vector $\beta_0^{(m)}$, multi-user interference (MUI) vector $\xi_0^{(m)}$ and noise vector $\eta_0^{(m)}$.

The data of all the $M$ users can be estimated similarly in the time domain. The orthogonality properties of spreading codes are destroyed when the transmitted signals of different users pass through different mobile channels on the uplink. In the system with high system load, each user undergoes the serious MUI that is proportional to the amount of active users. The detector using only initial MMSE equalizer leads to unacceptable performance degradation in term of BER. This presents the need for multi-user detection such as interference cancellation to improve the system performance.

#### B. Selective Parallel Interference Cancellation (S-PIC)

The computational complexity of the conventional interference cancellation methods in the time domain becomes extremely high when there are too many paths in the severe frequency selective fading channels. Considering the natural characters of CP-CDMA systems, it is better to perform the interference cancellation in the frequency domain while the data decision is still carried out in the time domain. Before
S-PIC stages, all the signals of the users are ranked according to the signal power of the desired part as follows:

$$\gamma^{(m)} = \frac{1}{N_c} \sum_{k=0}^{N_c-1} |H^{(m)}_k|^2, \forall m \in \{1, 2, \cdots, M\} \tag{11}$$

Without loss of generality we assume that the 1st user has the strongest received power, followed by the 2nd user,... (i.e. $\gamma^{(1)} > \gamma^{(2)} > \cdots > \gamma^{(M)}$). The S-PIC performs cancellation of interfering users from the whole received signal based on their relative reliability that is determined by the rank of $\gamma^{(m)}$.

In each IC stage, all the active users are divided into two groups: one is regarded as the reliable group including $K_i$ users that have stronger power and another is the unreliable group with $M-K_i$ users of weaker power. Here $i$ is the index of the IC stage and $i=0$ is reserved for the initial MMSE equalizer. Since the users in the reliable group have higher probability to be correctly demodulated, their BER performance will reach to be satisfied with fewer stages than those in the unreliable group. If the estimated data of the users (e.g. we assume that they are the first $K_i$, 1 $\leq K_i \leq L_i$, users for the sake of the description in the following part) within the reliable group keep no change at the last successive two stages, they can be regarded to be "correct". Then in the current stage it is unnecessary to perform interference cancellation to the signals of these users and the estimated data keep no change, \(d_i = d_{i-1}, 1 \leq m \leq K'_i\).

The estimated MUI due to those users is then subtracted from the received signal and the resulting residual signal is used for the detection of the left users in the reliable group, within which the parallel detection is performed to estimate the user's transmitted signal and MUI. Meanwhile, the estimated MAI due to the whole reliable group is also subtracted from the received signal and its residual signal is processed for the detection of the unreliable group. The signals in the unreliable group won't contribute to the cancellation part in the same stage due to its relative lower reliability.

For the users need to be estimated again, the cancellation part for the mth user at the ith stage can be expressed as

$$\xi^{(m)}_i = \begin{cases} \sum_{m'=1, m' \neq m}^{K_i} H^{(m')} F^{(m')} d_{i-1}^{(m')}, & K_i' < m \leq K_i \\ \sum_{m'=1}^{M} H^{(m')} F^{(m')} d_{i-1}^{(m')}, & K_i < m \leq M \end{cases} \tag{12}$$

The ith stage tentative decision data vector \(\hat{d}^{(m)}_i = [d^{(m)}_{i,0}, d^{(m)}_{i,1}, \cdots, d^{(m)}_{i,P-1}]^T \in \mathbb{C}^P \times 1\) is made by hard decision in the time domain after the interference cancellation and equalization in the frequency domain.

$$\hat{d}^{(m)}_i = \frac{1}{N} c^{(m)} H^{-1} G_i^{(m)} (R - \xi^{(m)}_i) \tag{14}$$

where \(G_i^{(m)} = \text{diag}\{G_{i,0}^{(m)} G_{i,1}^{(m)} \cdots G_{i,N_c-1}^{(m)}\} \in \mathbb{C}^{N_c \times N_c}\) is the weight matrix for the mth user in the ith, $i > 1$, stage and its elements can be written as

$$G_{i,k}^{(m)} = \begin{cases} \left| H_k^{(m)} \right|^2 + \sum_{m'=K_i+1}^{M} \left| H_k^{(m')} \right|^2 + \sigma_n^2, & K_i' < m \leq K_i \\ \sum_{m'=K_i+1}^{M} \left| H_k^{(m')} \right|^2 + \sigma_n^2, & K_i < m \leq M \end{cases} \tag{15}$$

where $k \in \{0, 1, \cdots, N_c-1\}$.

If $K_i = M, K_i' = 0, \forall i \in \{1, 2, \cdots\}$, S-PIC is equivalent to conventional PIC. On the other hand, it is as same as SIC with $K_i = 1, K_i' = 0, \forall i \in \{1, 2, \cdots\}$. The S-PIC combines the advantages of SIC and PIC together. Similar to PIC, its parallel process in each stage reduces the detection delay greatly compared with SIC. With the selective cancellation based on the power rank which is a key feature of the SIC, the "ping-pong" behavior of PIC may be overcome. The computational complexity and processing delay depend on the number of S-PIC stages, the size of the reliable group and the necessary cancellation operations at each stage. By changing the size of groups and stages in the detector, different levels of the detection delay and bit-error performance can be achieved. Finally, implementation complexity is taken into account. The numbers of computation required per stage with S-PIC (the main operations include interference re-generation, cancellation, equalization and despreading) become less compared to that with PIC if the size of reliable group is selected properly and only necessary cancellation is performed within the reliable group. Accordingly, the number of complex multiplex multiplications (CM), the number of complex additions (CA) and the number of DFT/IDFT used by these three steps in both IC detectors are listed in Table I. It can be seen that the amount of complexity reduction is dependent on the values of $K_i$ and $K_i'$ in each stage.

---

**Table I**

| Complexity Comparison Between PIC and S-PIC Per Stage |
| --- | --- | --- |
| PIC | CA | DFT/IDFT |
| $4N_cM$ | $(4N_c-1)M$ | $2M$ |
| $2N_c(M+K_i')$ | $N_c(M-1+2(K_i-K_i'))$ | $M$ |
| $2N_c(K_i-K_i')$ | $+(N_c-1)(M-K_i')$ | $+K_i-K_i'$ |

**Table II**

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel model</td>
</tr>
<tr>
<td>$\tau_{max}=1.15\mu s, \tau_{min}=0.29\mu s$</td>
</tr>
<tr>
<td>Mobile Speed</td>
</tr>
<tr>
<td>Carrier frequency@BW</td>
</tr>
<tr>
<td>Length of Burst</td>
</tr>
<tr>
<td>(1024+256 samples)</td>
</tr>
<tr>
<td>Guard interval</td>
</tr>
<tr>
<td>Number of data per burst($P$)</td>
</tr>
<tr>
<td>Length of Orthogonal Gold code</td>
</tr>
<tr>
<td>DFT size($N_c$)</td>
</tr>
<tr>
<td>Modulation</td>
</tr>
</tbody>
</table>
A. Ideal power control

It is assumed that ideal power control can combat slowly varying effects like lognormal fading or path loss. The simulation were initially run with all the active users having average equal power with variation in each user's power only caused by the channel fast fading. Each simulation was run for 20,000 bursts and the error produced by each detector counted. Fig. 1 shows the BER performance of the 1st stage with S-PIC versus the size of the reliable group in this stage (i.e. $K_1$), where the operating $E_b/N_0$ is assumed to be 15dB. As the size $K_1$ increases, the performance is improved significantly. However, after it becomes larger (e.g. $K_1 > 12$ if $M=16$), the system performance changes slightly. It indicates that with the size of stage increasing, the system performance can be improved due to parallel detection, but some of the estimated data in the reliable group are also more likely to become uncorrected with larger size. Therefore, there must exist an optimum size of the reliable group for each stage, depending on the channel environments and the number of active users. As shown in Fig.1, it is clear that $K_1=12$ or 14 is a good choice with 16 active users in the system. And according to the similar principle, $K_2$ is selected to be 14 and $K_3$ be 16. Therefore, the S-PIC with 3-stage ($K_1$=$K_2$=$K_3$: 12-14-16) in the system with 16 active users will be further investigated. In Fig. 2, the performance in term of BER applying different detector including only an MMSE, or plus 3-stage PIC, 3-stage S-PIC (12-14-16) detector versus average $E_b/N_0$ are compared. Besides being much better than that of an MMSE detector, the BER performance of 3-stage S-PIC is better that of 3-stage PIC.

B. Non-Ideal power control

Near-far effect is one of the most serious problems in all the CDMA systems. And power control only can deal with it and let it be less significant, not removing it perfectly. Fortunately, the S-PIC detector can also solve it well, not like PIC detector. The simulations are repeated with the user’s power levels spread over a uniformly distributed range between 0.1 and 1.9 times the averages power level, which build up a system model of non-ideal power control. Similarly, the optimum size of the reliable group in S-PIC detector is also investigated in the system with non-ideal power control. The optimum size of the 1st, the 2nd stage and 3rd stages can be selected to be 10, 14 and 16 respectively. Fig. 3 compares the performance in term of BER applying different detector including an MMSE, or plus 3-stage PIC, 3-stage S-PIC (10-14-16) detector under non-ideal power control with the same channel environment used as before. It is shown that the BER performance of S-PIC is much better than PIC because it also has the advantages as SIC to better solve the near-far problem.

C. Complexity Reduction

Fig. 4 shows the average numbers of the "correct" users ($K_i$) in the reliable group at the different stages in S-PIC detector under ideal/non-ideal power control environment. At the 2nd stage, there are few users that can be regarded as "correct" because the serious MUI at the 0th and 1st stage in the detector are dominant. But when the number of stage increases, the MUI becomes less and the data estimation
becomes more reliable so that less number of users needs to be estimated again after interference cancellation at the previous stages. Meanwhile, with higher $E_b/N_0$, more "correct" users will exist. Furthermore, it can be seen that larger number of the "correct" users in the system with non-ideal power control than that with ideal power control in the same environment because the users with larger received power have higher probabilities to be correctly detected with less stages. The computation complexity can be reduced by selective interference cancellation compared with traditional PIC although there are more sorting complexity in S-PIC than in PIC. Table III compares the average complexity caused by the operations of interference re-generation, cancellation and despreading when the operating $E_b/N_0$ is assumed to be 15dB. Less complexity is necessary at the later stage in a S-PIC detector. And the effect of complexity reduction by S-PIC becomes more obvious in case of non-ideal power control than in case of ideal power control.

V. CONCLUSION

In this paper, we propose a selective parallel interference cancellation algorithm for CP-CDMA systems on the uplink. This algorithm can improve the BER performance with the same processing delay compared with PIC especially in the systems with non-ideal power control. Furthermore, its computation complexity can be reduced by power ranking and selective interference cancellation. From simulation results, we can find that the CP-CDMA systems with the proposed S-PIC can achieve good performance on the uplink with reasonable complexity.

ACKNOWLEDGMENT

The authors would like to thank for the sponsored by France Telecom R&D center (Beijing).

REFERENCES


TABLE III
EXAMPLE OF AVERAGE COMPLEXITY COMPARISON BETWEEN PIC AND S-PIC

<table>
<thead>
<tr>
<th></th>
<th>PIC</th>
<th></th>
<th>S-PIC</th>
<th></th>
<th>Complexity Reduction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CM</td>
<td>CA</td>
<td>(IDFT)</td>
<td>CM</td>
<td>CA</td>
<td>(IDFT)</td>
</tr>
<tr>
<td>Ideal</td>
<td>2nd</td>
<td>65536</td>
<td>65520</td>
<td>32</td>
<td>54886</td>
<td>54461</td>
</tr>
<tr>
<td>Non-ideal</td>
<td>2nd</td>
<td>65536</td>
<td>65520</td>
<td>32</td>
<td>42189</td>
<td>46991</td>
</tr>
</tbody>
</table>

![Fig. 3. BER comparison with different detectors (Non-ideal PC)](image)

![Fig. 4. Average number of the "correct" users at different stages in S-PIC](image)