Partial PIC for Multi-Carrier DS-CDMA

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Abstract. This paper explores a multi-user detection scheme of multi-carrier direct-sequence code division multi-access (MC DS CDMA). By the combination of weighted interference cancellation with frequency diversity, we propose a modified interference cancellation algorithm, namely, partial parallel interference cancellation (MC-PPIC). For the proposed algorithm, the negative effect due to inaccurate multi-access interference estimation can be effectively alleviated, and therefore can dominantly improve the system performance. With the choices of simulation parameters, we perform the computer simulations over the proposed MC-PPIC, and the numerical analysis is also made in detail. On basis of numerical analysis, the main conclusions are finally drawn as follows: 1) whether for AWGN channel or for Rayleigh fading channel, the performance improvement can be acquired with the increase in the IC stage number and whatever IC stage number is taken, MC-PPIC always greatly outperforms MF receiver in performance; 2) MC-PPIC can enhance the system performance dominantly with the small number of IC stages, but only slightly with the large number of IC stages, and 3) compared to PIC, MC-PPIC exhibits the superior capability of suppressing multi-access interference with the same number of IC stages taken.

Introduction

CDMA, which is based on spectrum spreading theory, is a promising multiple access technology. Unlike FDMA and TDMA, CDMA systems distinguish each user’s signals by the assigned spreading sequences or signature codes, which are required to be strictly orthogonal to each other. If ideal orthogonality between users’ signature codes is satisfied, the detection of users’ signals with no interference can well be implemented. However, it is hardly possible to assign completely orthogonal signature codes to each user. On the other hand, even if such ideal codes exist, the orthogonality will be probably destroyed by the channel multi-path effect. Therefore, the ideal orthogonality is actually difficult to achieve, and thus leads to multi-access interference (MAI) among active users, which is one of the main obstacles against the performance improvement of CDMA systems.

In order to overcome the negative effects of MAI on the performance of CDMA systems, some scholars proposed multi-user detection (MUD) schemes creatively, in which MAI among active users are suppressed or cancelled [1-5]. It is shown that multiuser detection can effectively combat MAI and improve the system performance. However, high complexity faced by multi-user detection has become a problem to restrict its practical application.

Multi-carrier modulation (MCM) is a parallel transmission technology, which firstly converts a successive data transmission to multiple parallel streams, each of which is then modulated by a sub-carrier frequency. Generally, the frequency spectrum of each sub-carrier does not overlap to avoid the inter-carrier interference (ICI). In fact, however, if each sub-carrier is kept orthogonal to each other in frequency, then ICI from sub-carriers can be also avoided. The kind of MCM is generally called orthogonal frequency division multiplexity (OFDM). Apparently, OFDM dominantly improves the spectrum efficiency.

By the combination of MCM with CDMA, a mixed technology, known as multi-carrier CDMA, was proposed and explored theoretically and numerically[6]. Multi-carrier CDMA has two types, depending on whether time domain spreading or frequency domain spreading is adopted [7]. The type based on time domain spreading is called multi-carrier DS CDMA or MC DS CDMA, while the other
one is called MC CDMA. It has been proved that both types of multi-carrier CDMA systems show a
strong capability of combating interference and fading.

Like single-carrier CDMA, multi-carrier CDMA will suffer from MAI if the orthogonality among
active users’ signature codes can’t be guaranteed. The performance degradation resulting from MAI
will be inevitable. As a key method of overcoming the influence of MAI, multi-user detection can be
applied to multi-carrier CDMA. A lot of work has been done in this aspect [8]. For example, in [9], L.
Fang et al applied successive interference cancellation (SIC) to multi-carrier DS CDMA, and
corresponding theoretical exploration and numerical analysis are made in detail, which shows that SIC
can dominantly improve the performance of MC DS CDMA.

In this paper, we explore multi-user detection of multi-carrier DS CDMA, and propose a scheme of
multi-stage parallel interference cancellation. In the proposed scheme, the estimated MAI is weighted
before interference cancellation is performed, and frequency diversity combining is used at each
interference cancellation stage. We make theoretical analysis and numerical simulation over the
proposed scheme, respectively. We call the proposed scheme MC-PPIC in the following.

Analysis of the proposed scheme

For a synchronous transmission, the effective base-band signal for the k-th user is expressed as
$$S_k(t) = \sqrt{E_s} \sum_{j=0}^{M-1} b_j(k) c_i(t-jT_s) \sum_{n=1}^{N_c} \cos(\omega_n t + \theta_{k,m})$$
where $E_s$ and $b_i(k)$ are, respectively, the chip energy and binary transmitted symbol of the
k-th user, the $\{\omega_n\}$ are a set of sub-carrier frequencies with the sub-carrier number $M$, the $\{\theta_{k,m}\}$ are random
variables with a uniform distribution of $[0,2\pi)$, the $c_i(t)$, which is the spreading code of user $k$, can be
expressed as $c_i(t) = \sum_{n=0}^{N_c-1} c_i^n(t-nT_s)$, where $h(t)$ denotes the impulse response of the chip wave shaping
filter, the $\{c_i^n\}$ are the code chips with the spreading gain $N$. $T_s$ and $T_c$ are, respectively, the symbol
duration and chip duration.

The channel complex transfer impulse response for Rayleigh fading channel is modeled as
$$r(t) = \sum_{i=1}^{L} \sqrt{E_s} \sum_{j=0}^{M-1} b_j(k) c_i(t-jT_s) \sum_{n=1}^{N_c} \cos(\omega_n t + \theta_{k,m}) + n(t)$$
where $\theta_{k,m} = \theta_{i,k} + \beta_{i,m}$, the $n(t)$ is AWGN and has two-sided power spectral density of $\eta_s/2$.

Figure 1 describes the structure of the proposed MC-PPIC. The whole MC-PPIC receiver block
consists of a number of partial parallel interference cancellation (PPIC) stages, as shown in Figure 2.

MC-PPIC with Q PPIC stages is considered for theoretical analysis. Here, we describe how to
detect the $i$-th symbol for user $k$ by MC-PPIC scheme in detail. After band-pass filtering (BPF),
coherent demodulation and low-pass filtering (LPF) over the $r(t)$ in (2), we get the result as follows:
$$y^n_{i,k}(t) = \sqrt{E_s} \sum_{i=1}^{L} \sum_{j=0}^{M-1} \alpha_i \beta_j(k) c_i^j(t-jT_s) \sum_{n=1}^{N_c} c_i^n(t-nT_s) \cos(\omega_n t + \theta_{k,m}) + n(t)$$
where $n_{i,k}(t)$ is the LPF output of the $n_i(t)$ after being multiplied by $\cos(\omega_n t + \theta_{k,m})$, and $x(t)$ is an
inverse Fourier transform of $|H(f)|^2$, where $H(f)$ is a Fourier transform of $h(t)$.

The $y^n_{i,k}(t)$ is then despaced by the k-th user’s signature code to get the expression form as
$$Z^n_{i,k}(t) = \frac{1}{N} \sum_{i=1}^{L} \sum_{j=0}^{M-1} \sum_{n=1}^{N_c} \cos(\omega_n t + \theta_{k,m}) b_j(k) c_i^j(t-nT_s) + n_{i,k}(t)$$
where $l_{i,m}(t) = \sum_{i=1}^{L} \sqrt{E_s} \cos(\omega_n t + \theta_{i,m}) b_j(k) c_i^j(t-nT_s)$ is the multi-access interference (MAI) imposed on the user $k$
in the sub-carrier channel, which is closely related to cross correlation coefficient $\rho_{k,i}$, and
$n_{i,k}(t) = \frac{1}{N} \sum_{i=1}^{L} \sum_{n=1}^{N_c} c_i^n(t-nT_s)$, which variance is $\eta_s/2N$. 

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For each sub-carrier, and we have

\[ \hat{b}_q(i) = \text{sgn}(Z_{k,i}^{(q)}(i)) \]  

Furthermore, we define

\[ \hat{a}_{k,i}^{(q)}(i) = Z_{k,i}^{(q)}(i) \]  

The \( \{ \hat{a}_{k,i}^{(q)}(i) \} \) and \( \{ \hat{b}_q(i) \} \), which are used as initial values in the following iteration loops, are subsequently sent to multi-stage MC-PPIC for the estimation and cancellation of MAI.

A) The \( q \)-th MC-PPIC stage

For the \( q \)-th MC-PPIC stage illustrated as in Figure 2, MAI of each sub-carrier effective base-band signal is firstly estimated, and then subtracted from \( y_{k,i}^{(0)}(t) \) in (3) to obtain the interference-cancelled signal \( \tilde{y}_{k,i}^{(q)}(t) \). Finally, we make the despreading over the \( \tilde{y}_{k,i}^{(q)}(t) \), which leads to such a result as

\[ Z_{k,i}^{(q)}(i) = \sqrt{E} \alpha_{k,i} b_i(i) + \Delta I_{k,i}^{(q)}(i) + n_{k,i}(i) \]  

where \( \Delta I_{k,i}^{(q)} \) is the difference between the estimated value and real value of MAI, i.e., \( \Delta I_{k,i}^{(q)} = I_{k,i}(i) - \hat{I}_{k,i}^{(q)}(i) \).

Similarly to (6), we define

\[ \hat{a}_{k,i}^{(q)}(i) = p^{(q)} Z_{k,i}^{(q)}(i) + (1-p^{(q)}) \hat{a}_{k,i}^{(q-1)}(i) \]  

where \( p^{(q)} \) is a parameter, and \( 0 \leq p^{(q)} \leq 1 \) and \( p^{(q)} > p^{(q-1)} \). After frequency diversity combining of \( \hat{a}_{k,i}^{(q)}(i) \), we obtain \( Z_{k,i}^{(q)}(i) = \sum_{m} g_{k,i,m}^{(q)} \hat{a}_{k,i}^{(q)}(i) \), where \( \{ g_{k,i,m}^{(q)} \} \) are a set of combining coefficients. Finally, decisions are performed over the \( \{ Z_{k,i}^{(q)}(i) \} \), and we acquire the tentative value of \( b_i(i) \) as

\[ \hat{b}_i(i) = \text{sgn}(Z_{k,i}^{(q)}(i)) \]  

The \( \hat{a}_{k,i}^{(q)}(i) \) from (8) and \( \hat{b}_i(i) \) from (9) are used as the inputs of the next MC-PPIC stage.

B) The last MC-PPIC stage

For the last MC-PPIC stage, hard decisions are performed over \( Z_{k,i}^{(q)}(i) \), and we obtain the decision value of the \( i \)-th symbol of user \( k \) as \( \hat{b}_i(i) = \text{sgn}(Z_{k,i}^{(q)}(i)) \), where \( Z_{k,i}^{(q)}(i) = \sum_{m} g_{k,i,m}^{(q)} \hat{a}_{k,i}^{(q)}(i) \).
Simulation results

In the following, we will make the numerical simulations over the proposed MC-PPIC in different conditions. The simulation parameters are set as: (1) the user number \( K = 11 \); (2) spreading sequences assigned to each user are randomly generated, and code length \( N = 15 \); (3) subcarrier number \( M = 3 \); and (4) the weighted coefficients are taken as 0.6, 0.8, 0.95 and 1 for continuous four IC stages.

Figure 3 and Figure 4 show the bit error rate (BER) performance of the MC-PPIC with one, two, three and four IC stages in case of AWGN channel and Rayleigh fading channel, respectively. As comparison, the performance curves of match-filtered (MF) receiver are also plotted in both figures. It is clear from both figures that whether for AWGN channel or Rayleigh fading channel, the performance improvement can be acquired with the increase in the IC stage number, and with the small number of IC stages, such as one and two IC stages, MC-PPIC can bring the dominant performance enhancement. Instead, the large number of IC stages, such as three or four, can improve the system performance only slightly. A numerical analysis over the performance of signal to noise ratio (SNR) of 14 dB is made to illustrate the above-mentioned results. In Figure 4, at the given SNR value of 14 dB, the BER for one, two, three and four IC stages are \( 1.2 \times 10^{-3}, 3 \times 10^{-4}, 1.5 \times 10^{-4} \) and \( 1 \times 10^{-4} \), respectively, while in Figure 3, the BERs are \( 6 \times 10^{-3}, 2 \times 10^{-3}, 1 \times 10^{-3} \) and \( 9 \times 10^{-4} \).

It is also seen from Figure 3 and Fig.4 that at the low SNR values, MC-PPICs with different numbers of IC stages, are close to each other in performance, while when the SNRs increase, the performance advantage from MC-PPIC with the larger number of IC stages becomes apparent. For example, in Fig.3, at the SNR of 2 dB, a typical low SNR value, MC-PPICs with one, two, three and four IC stages have nearly the same BER performance, which is between \( 3.5 \times 10^{-2} \) and \( 7 \times 10^{-2} \), while at the SNR of 10 dB, which is a typical large SNR value larger than 2 dB, MC-PPICs with different number of IC stages exhibit their distinct performance, and BER values are about \( 5.7 \times 10^{-3} \), \( 2 \times 10^{-3} \), \( 1.2 \times 10^{-3} \), and \( 8.6 \times 10^{-4} \) for one, two, three and four IC stages, respectively. Meanwhile, it should be noticed that with interference cancellation strategy taken, MC-PPIC always outperform MF receiver of multicarrier DS CDMA in performance. At the same SNR of 14 dB, the BER of MF receiver is about \( 1 \times 10^{-2} \), which is far below that of MF receiver.

With different IC stage number considered, Figure 5 and Figure 6 compare the BER performance of MC-PPIC with that of PIC of multi-carrier DS-CDMA over Rayleigh fading channel. Both figures give the comparison results of MC-PPIC and PIC with two IC stages and three IC stages. In Figure 5, at the BER of 12 dB, the BERs of MC-PPIC and PIC with two IC stages are about \( 6 \times 10^{-3} \), and \( 3 \times 10^{-2} \), respectively, while In Fig.6, the BERs of MC-PPIC and PIC with three IC stages are about \( 3 \times 10^{-3} \), and \( 2 \times 10^{-2} \), respectively. All the numerical results suggest that at the same number of IC stages, MC-PPIC always exhibit superior performance advantage, compared to PIC. It is also shown in both Figure 5 and Figure 6 that MC-PPIC and PIC outperform MF receiver in performance at the same SNRs. For example, at the SNR value of 10 dB, in Figure 5, the BER of MF receiver is about \( 2 \times 10^{-1} \), which is far higher than the BER values of MC-PPIC and PIC.
Conclusions

In this paper, we propose a scheme of weighted interference estimation and cancellation (MC-PPIC) for multi-carrier DS-CDMA systems. The dominant advantage over conventional PIC is that MC-PPIC can effectively alleviate the negative effect due to inaccurate multi-access interference estimation. The overall numerical analysis in terms of the proposed MC-PPIC is performed with different IC stages and for different channel choices. By the computer simulation, we obtain the corresponding results, which show that (1) whether for AWGN channel or for Rayleigh fading channel, the performance improvement can be acquired with the increase in the IC stage number and whatever IC stage number is taken, MC-PPIC always greatly outperforms MF receiver in performance; (2) MC-PPIC can enhance the system performance dominantly with the small number of IC stages, but only slightly with the large number of IC stages, and (3) compared to PIC, MC-PPIC exhibits the superior capability of suppressing multi-access interference.

References