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A novel CFO estimator with joint bisection-searching and complexity-reduction technique for uplink MC-CDMA systems

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ABSTRACT

This paper presents a simple scheme, which speeds the estimation of carrier frequency offset (CFO) as well as reducing the estimation complexity for multicarrier code-division multiple-access (MC-CDMA) uplink. Based on the concept of bisection method, the CFO is efficiently estimated by way of locating the peak value in the output power spectrum of the minimum output energy (MOE) detector. Complexity reduction results from the proposed data vector partition associated with an innovative data processing technique for the MOE detector. Simulation results show that the expected advantage of the proposed scheme can be achieved at the expense of a reasonable performance loss even in the presence of a large CFO.

1. Introduction

The direct sequence code-division multiple-access (CDMA) air interface, which possesses the advantages of soft multiple access characteristics, robustness against fading and anti-interference capability, has been suggested to be a candidate for providing multimedia services in wireless mobile communications, e.g., the fourth generation (4G) wireless standard. Among the CDMA techniques, the multicarrier CDMA (MC-CDMA) is developed by exploiting the combination of orthogonal frequency-division multiplexing (OFDM) and CDMA. Owing to possessing both the advantages of OFDM and CDMA, MC-CDMA has been widely used in high data rate services (Chien, Hwang, & Kuo, 2006; Hara & Prasad, 1997; Seo & Kim, 2009). In an MC-CDMA system, the spread sequence is serial-to-parallel converted, and then each chip modulates a different carrier frequency. Since the data sequence is spread in the frequency domain, MC-CDMA achieves both of frequency diversity and robustness to frequency-selective fading. However, MC-CDMA systems suffer from certain undesirable effects such as multiple access interference (MAI) (Rappaport, 2002) and carrier frequency offset (CFO) (Han, Seo, & Kim, 2001; Shin, Kim, Lee, & Kang, 2007). An appreciable CFO destroys the orthogonality of subcarriers, and thus induces inter-carrier interference (ICI) which results in considerable performance degradation (Han et al., 2001; Lin, 2008; Rappaport, 2002; Shin et al., 2007).

In wireless communication systems, carrier frequency error inevitably exists due to the mismatch between the local oscillators and/or Doppler shifts, and the error is often out of an acceptable range. For example, in satellite digital video broadcasting applications (Han et al., 2001), CFO may range from several hundred kHz to a few thousand kHz owing to the frequency uncertainty of the RF oscillators. In addition, a 2.4 GHz Zigbee application may have a maximum CFO of ±192 kHz (Shin et al., 2007), which induces a value of 0.192 for the normalized CFO with respect to the signal bandwidth of 2 MHz. The normalized CFO less than the threshold value of 0.01 is suggested to ensure that an MC-CDMA system provides an acceptable bit error rate (BER) (Wei & Schlegel, 1995). Since 0.192 is far more than 0.01, CFO compensation is an imperious demand before data decoding.

In the past, a number of effective algorithms regarding CFO estimation for uplink OFDM systems have been proposed (Armstrong, 1999; Bolcskei, 2001; Moose, 1994). All of these schemes gain remarkable estimation performance, but they cannot be directly applied to MC-CDMA systems due to the presence of MAI. So far there is not much work, which concerns the CFO estimation, can be found while considering the presence of MAI. In Ma and Tafazolli (2007), a training-based CFO estimation method for the MC-CDMA uplink was proposed where the desired subspace is determined by using the singular-value decomposition (SVD) to find the CFO estimate. This approach requires training sequence transmission, and thus reduces the spectral efficiency. Based on the subspace concept, a blind estimator has been proposed in Thiagarajan, Attallah, Abed-Meraim, Liang, and Fu (2008) where the CFO is estimated by minimizing the determinant in response to the matrix composed of the noise subspaces. Following (Thiagarajan et al., 2008) and exploiting the polynomial root-find

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algorithm, another blind technique for both CFO and channel estimation in a single carrier CDMA system was presented in Li and Liu (1999). In Deng and Lee (2003), Deng proposed an iterative MC-CDMA receiver by using the technique of generalized sidelobe cancellation where the CFO estimate was determined by way of an exhaustive search.

With regards to the MAI suppression, constrained linear minimum output energy (MOE) for a multiuser receiver (Honig, Madhow, & Verdu, 1995) has been proposed and considered to be an effective scheme for suppressing MAI. The MOE receiver is aimed at minimization of the total output power subject to the constraints that guarantee the constant output power of the user-of-interest at the receiver. Generally speaking, the MOE receiver is capable of providing effective suppression of strong MAI. Nevertheless, a weakness for the MOE receiver is that it is very sensitive to CFO. In order to reduce the sensitivity to CFO, the MOE-based min/max scheme (Seo & Kim, 2002) has been presented where CFO estimation is realized by a frequency search for a peak value on the output spectrum with a given step size. The computation of this algorithm turns into quite time-consuming while a fine step size is adopted for reaching an accurate estimate of CFO. In practical applications, the estimation time is necessarily requested to be as short as possible so as to compensate the time-varying CFO in time. As a result, the issue about speeding the CFO estimation seems to be particularly essential.

In this paper, we propose a simple scheme for reducing the complexity of the CFO estimator in the uplink transmission of an MC-CDMA system. It is known that the CFO can be accurately estimated by searching the frequency at which the output power spectrum of the MOE receiver has the maximum value. Thus, the design conception of the proposed scheme originated from two basic ideas. The first one is the reduction of the times for computing the values of the output power during the search for CFO. We introduce the bisection technique to assist the partition of the frequency interval that is used to determine the candidates of CFO at each update of a search interval. It can be shown that the bisection method can effectively decrease the total number of computations for the output power values than the conventional approach in an exhaustive CFO search. The second idea is to simplify the computation of the output power value since the computation involves a sequence of complicated matrix operations. Here, the way of computation reduction is suggested to partition the data vector into a number of data subvectors such that the dimensions of the corresponding matrices can be diminished. This paper starts with the deviation of the output power spectrum of the MOE detector with the proposed estimator, which is used to determine the survival subinterval of frequency. Two algorithms of CFO estimation have been considered for complexity reduction. We term the first one the *bisection-based* (BS-based) CFO estimation which is associated with the first idea. BS-based CFO estimation is shown to provide a more efficient search than the conventional one at the expense of a little performance loss. The other one is termed the *complexity-reduced* (CR) CFO estimation, which exploits the partition of data vectors and thus enjoys the advantage of further complexity reduction. Simulations and complexity analysis have been conducted to verify the expected merits for the proposed schemes.

The rest of this paper is organized as follows. Section 2 depicts the received data model of the considered MC-CDMA system where the MOE-based scheme is used for CFO estimation. In Section 3, we introduce the proposed BS-based and CR CFO estimators. For comparison, the computational complexities of all concerned schemes are also provided here. In Section 4, we present the simulation results to verify the advantages of the proposed scheme. Finally, Section 5 concludes the paper.

The notations in this paper are defined as follows: Vectors (matrices) are typed with boldface small (capital) letters. $\mathbf{I}_n$ and $\mathbf{O}_{m\times n}$ represent an $n\times n$ identity matrix and an $m\times n$ all-zero matrix respectively. $diag\{\mathbf{a}\}$ is a diagonal matrix with the diagonal entries taking from the vector $\mathbf{a}$. $\lfloor a\rfloor$ is the largest integer not greater than a. $(\cdot)^*$, $(\cdot)^T$, and $(\cdot)^H$ are the complex conjugate, transpose, and Hermitian transpose operations of a matrix respectively. In addition, $Im\{\cdot\}, E\{\cdot\}$, and $|\cdot|$ denote the imaginary part of a complex number, taking ensemble average, and an absolute operator respectively.

2. Data model and MOE-based CFO estimation

Consider a baseband digital MC-CDMA system (Chien et al., 2006) with N subcarriers and K active users. For user k, in the frequency domain each data symbol is spread by the user's spreading code $\mathbf{c}_k$ of length N, and then the spread chips are fed into the serial-to-parallel (S/P) converter. Apply inverse discrete Fourier transform (IDFT) to these N parallels chips, and the IDFT operator outputs the time domain samples in parallel form. After being converted by the parallel-to-serial (P/S) block, the time domain samples are low-pass-filtered, and the data sample corresponding to the ith symbol of user k is given by

$$\mathbf{b}_k(i) = \sigma_k \mathbf{F}\mathbf{c}_k b_k(i), \tag{1}$$

where the data symbol $b_k(i)$ is assumed to be a sequence of independent and identically distributed (i.i.d.) random variables with zero-mean and unit variance, σ_k^2 represents the average transmission power, $k = 1,2,\ldots,K$, and $\mathbf{F}\in C^{N\times N}$ denotes the IDFT matrix with $e^{j2\pi(m-1)(n-1)/N}/\sqrt{N}$ being the (m,n) entry. For user k, the channel is assumed to be an L-resolved multipath fading with the impulse response being the $L\times 1$ vector $\mathbf{h}_k$. A guard period of length N_g is inserted to avoid the intersymbol interference (ISI) where N_g is larger than the maximum path delay L. At the receiver, the guard periods are removed, and discrete Fourier transform (DFT) is applied to the received signal in the presence of CFO. The ith received symbol is written as

$$\begin{aligned}\mathbf{y}(i) &= \sum_{k=1}^{K}\sigma_k\psi_k^{(i-1)(N+N_g)}\mathbf{F}^H\mathbf{E}(\epsilon_k)\mathbf{F}\mathbf{H}_k\mathbf{c}_k b_k(i) + \mathbf{n}(i)\\ &= \sum_{k=1}^{K}\sigma_k\psi_k^{(i-1)(N+N_g)}\mathbf{S}(\epsilon_k)\mathbf{d}_k b_k(i) + \mathbf{n}(i),\end{aligned} \tag{2}$$

where $\mathbf{S}(\epsilon_k)\triangleq\mathbf{F}^H\mathbf{E}(\epsilon_k)\mathbf{F}, \mathbf{H}_k\triangleq diag\{\mathbf{F}^H\left[\mathbf{h}_k^T;\mathbf{O}_{1\times(N-L)}\right]^T\}$ is the channel matrix, $\mathbf{d}_k\triangleq\mathbf{H}_k\mathbf{c}_k$ represents the effective signature vector of user k, and $\psi_k\triangleq e^{j2\pi\epsilon_k/N}$ is the phase shift between two successive data samples with ϵ_k being the related frequency offset normalized to subcarrier spacing for user k. The CFO effect in (2) is modeled by the diagonal matrix (Chien et al., 2006)

$$\mathbf{E}(\epsilon_k) = diag\{1,\psi_k,\ldots,\psi_k^{N-1}\},\quad k=1,2,\ldots,K. \tag{3}$$

The noise $\mathbf{n}(i)$ is an $N\times 1$ complex Gaussian random vector with zero mean and variance $\sigma_n^2\mathbf{I}_N$. Here the transmitted symbols and noise samples are assumed to be mutually independent. Without loss of generality, suppose that user 1 is the desired user and the others are the MAIs for user 1.

In case of frequency mismatch between local oscillators and/or Doppler shifts, the resultant CFO effect will destroy the orthogonality between each pair of sub-carriers. This results in the ICI, which is exhibited on the off-diagonal terms of $\mathbf{S}(\epsilon_1)$, and leads to a substantial performance degradation. Consequently, the development of a low-complexity scheme for CFO estimation is essential. In the past, MOE detectors are known to be effective in MAI suppression for CDMA/MC-CDMA systems since the detector is designed to output specifically the desired signal-to-noise ratio as large as possible. According to the characteristic of MAI suppression, the min/max approach for the MOE detector is naturally associated with