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Maximum likelihood carrier frequency offset estimation algorithm with adjustable frequency acquisition region

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Abstract

This study presents a simple yet effective carrier frequency offset (CFO) estimation algorithm for orthogonal frequency division multiplexing (OFDM) systems. At the transmitter, the proposed algorithm uses null subcarriers to render the OFDM signal periodic in the time domain. At the receiver, these periodic time samples become CFO-bearing signals, which can be adopted to develop the maximum likelihood (ML) CFO estimation algorithm accordingly. In addition to providing reliable and efficient CFO estimation, the proposed algorithm has an adjustable acquisition region linearly proportional to the order of the null subcarrier insertion scheme.

1. Introduction

Frequency discrepancies between transmitters and receivers destroy the orthogonality among subcarriers in orthogonal frequency division multiplexing (OFDM) systems, and thus induce intercarrier interference (ICI) [1]. Although several ICI self-cancellation (ICI-SC) schemes have been proposed to combat ICI [1–3], these methods can only handle ICI caused by small-valued frequency errors. As frequency error values increase, frequency synchro-

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nization is inevitable in OFDM systems for ensuring reliable transmission. Many algorithms have been proposed to estimate the carrier frequency offset (CFO) [4–10]. For example, Hui and Tureli [4] proposed a subspace-based algorithm that uses null subcarriers in an OFDM symbol to estimate the CFO. Yang et al. [5] proposed a null-subspace-based vector coding scheme that enables a receiver to estimate the CFO by using a set of predetermined filters. However, the methods in [4,5] have limited estimation accuracy. In response, Gao and Nallanathan [6] modified the cost function in [4] to estimate the CFO through a polynomial rooting method. Although the method in [6] is more accurate than its precedent algorithm [4], it is also computationally intensive due to its high-order polynomial rooting process. Hao [7] proposed a decision-feedback (DF) algorithm that estimates the CFO using the intrinsic property of the signal generated by the ICI-SC scheme in [1]. The DF algorithm is computationally efficient, but it suffers from the noise-enhancing problem caused by the associated equalization process. Elsewhere, Wang [8] used a sample selection scheme to mitigate the noise-enhancing problem in [7], and then proposed a subspace-based algorithm to estimate the CFO. The maximum likelihood (ML) method was proposed by Chin [10] to estimate the CFO using the distinct correlation property of an OFDM signal. Despite its theoretical optimality, the ML algorithm in [10] has a frequency acquisition region (FAR) that is smaller than a single subcarrier spacing. Because frequency synchronization is crucial to OFDM, a computationally efficient CFO estimation algorithm with a large FAR warrants exploration.

In most wireless communication standards that use OFDM as the modulation scheme [11], subcarriers are classified into pilot subcarriers, null subcarriers (also called virtual carriers in [4]) and data subcarriers. Null subcarriers are zero-padded subcarriers that generally serve for band guarding, and sometimes facilitate peak-to-average power ratio (PAPR) reduction [12] or CFO estimation [4,6]. This study used null subcarriers to generate an OFDM signal with a CFO-dependent Vandermonde structure in the time domain. This Vandermonde structure was then accordingly used to develop the ML CFO estimate. The proposed algorithm has two distinctive features: (1) it has an adjustable FAR linearly proportional to the order of the NSI, which is significantly larger than that of conventional ML algorithms (e.g., [9,10]); and (2) unlike conventional ML algorithms using multiple OFDM symbols to estimate the CFO, the proposed approach employs only a single OFDM symbol for the estimation, rendering it more appropriate for burst mode communication.

2. System model

Consider an OFDM system with CFO ε_0. The received signal at time n can be expressed through the inverse fast Fourier transform (IFFT) as

$$y_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k H_k e^{j\frac{2\pi}{N}(k+\varepsilon_0)n} + z_n = (x_n * h_n) e^{j\frac{2\pi}{N}\varepsilon_0 n} + z_n, \tag{1}$$

where X_k denotes the modulated signal of subcarrier k; H_k is the channel frequency response of subcarrier k, which is the kth element of the fast Fourier transform (FFT) of a K-tap FIR channel modeled by coefficients $\{h_n, n = 0, \ldots, K-1\}$; N is the total number of subcarriers in an OFDM symbol; $x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j\frac{2\pi}{N}kn}$ is the transmit signal at time n; the operator * denotes the circular convolution; and z_n is the additive white Gaussian noise (AWGN), which is circularly symmetric with zero mean and variance $\frac{N_0}{2}$. Moreover, the CFO ε_0 is normalized to subcarrier spacing.