Performance of a novel carrier frequency offset estimation algorithm for OFDM-based WLANs*

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Abstract: This paper presents a novel carrier frequency offset estimation (CFO) algorithm for orthogonal frequency division multiplexing (OFDM)-based Wireless Local Area Networks (WLANs). Compared with previous approaches, this paper extends the whole frequency offset acquisition range by embedding a synthetic algorithm according to the preamble structure of WLANs symbols. The numerical results presented support the effectiveness of this algorithm by which the estimation error of the whole carrier frequency offset in the WLANs is effectively decreased.

Key words: Carrier frequency, OFDM, WLANs, Preamble structure, Acquisition

INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has been treated as the key transmission method in Wireless Local Area Networks (WLANs) based on IEEE802.11a protocol (IEEE Standard 802.11a-1999). However, the sensitivity of the scheme to the frequency offset limits its development. Moose (1994) proposed maximum likelihood estimation for the carrier frequency offset by using two different received symbols, but the limitation of this method is that the acquisition range is only ±1/2 of the sub-carrier frequency spacing. Schmidl and Cox (1997) presented an algorithm to extend the frequency acquisition range by limiting the training symbols, but this algorithm could not be directly adopted by IEEE802.11a-based WLANs groups because it was performed by using a special preamble structure. Li et al. (2001) presented a nonlinear least squares (NLS) scheme to estimate the offset, but this proposition is only used when the frequency offset is less than the sub-carrier frequency spacing. Therefore, the objective of this paper is to estimate the entire frequency offset range with OFDM data symbols via a high performance novel estimation algorithm.

PROBLEM FORMATION

The transmitted frame structure specified by IEEE802.11a is described in Fig.1. Each frame consists of a packet preamble, signal section and data blocks. The packet preamble consists of ten identical short OFDM training symbols (each containing 16 data samples) and two long OFDM training symbols (each containing 64 data samples). Between the short training symbols and long training symbols, there is a guard interval (GI2) which constitutes the cyclic prefix of the long training symbols to reduce the ISI. We consider a multi-path and frequency selective fading
channel and let $M_S (M_L)$ denotes the number of short (long) training symbols and $N_S (N_L)$ denotes the samples of short (long) symbols (subscripts ‘S’ and ‘L’ represent short symbols and long symbols). According to IEEE802.11 standardization (IEEE Standard 802.11a-1999), $M_S=10$, $M_L=2$, $N_S=16$, $N_L=64$. Since the short and long training series in the preamble are only used for the signal detection, timing synchronization and frequency offset estimation, we only focus on the relationship between frequency offset and the data symbols mapped onto sub-carriers. We let $x(m,n)$ denote the $n$th sample of the $m$th noise-free OFDM symbols prior to taking $N$-point IFFT, and let $s(m,n)$ denote the $n$th sample of the $m$th noise-free OFDM symbols after taking $N$-point IFFT:

$$s(m,n) = \sum_{k=-N/2}^{N/2-1} x(m,k) e^{j2\pi kn/N},$$

$$m=1,2; \quad k=1,2,\ldots,N; \quad n=1,2,\ldots,N_{\text{sym}},$$

(1)

where $N_{\text{sym}}$ is the number of samples for every data block of symbols and $N_{\text{sym}}=N+N_g=80$. $N_g$ denotes the number of samples of the guard interval (GI). Meanwhile, let $h_i$ and $\tau_i$ denote respectively the component of the channel impulse response and the component of the time delay, and also let $r(m,n)$ denote the $n$th sample of the $m$th received OFDM symbols at the receiver, then $r(m,n)$ is given by

$$r(m,n) = e^{j2\pi nT} \left( \sum_i h_i (nT) x(m,nT-\tau_i) + w(nT) \right),$$

$$n=1,2,\ldots,N_{\text{sym}},$$

(2)

where $T$ is the sample period and $w(nT)$ is the sample value of the zero mean additive white Gaussian noise (AWGN). Note that data block after taking the IFFT is only mapped onto an individual sub-carrier rather than sub-carrier pairs, the sample frequency $1/T$ is equal to sub-carrier frequency spacing $1/T_o$. The received $n$th sample of the $m$th OFDM symbol after removing the cyclic prefix and demodulated by FFT is given by

$$Z(m,k) = \sum_{n=-N_g+1}^{N_g} r(m,n) e^{-j2\pi (n-N_g) k/N}$$

$$= \left( e^{j\Phi} e^{j2\pi (N_{\text{sym}}+N_g) k/N} \text{sinc}(\pi \Phi) X_{\text{sym}} H_k + \sum_{k',k' \neq k} \left( e^{j\Phi} e^{j2\pi (N_{\text{sym}}+N_g) k'/N} \text{sinc}(\pi \Phi) X_{\text{sym}} H_{k,k'} + N_{\text{sym}} \right) \right)$$

$$\quad (k=1,2,\ldots,N; \quad n=N_g+1, N_g+2, \ldots, N_{\text{sym}}),$$

(3)

where $\Phi$ denotes the phase offset from frequency offset $\Delta f$ and $H_k$ is the channel frequency response and $\text{sinc}(x)=\sin(x)/x$ is the sample function. In Eq.(3), the first section is an available value with frequency offset, the second section is inter-carrier interference (ICI), the third is AWGN. According to (Narayanan, 2001), the maximal sub-carrier frequency offset may be given by

$$\left( \frac{\Delta f}{T_o} \right) < \frac{\sqrt{3}}{\pi} \left( 1 - \frac{1}{\Delta\gamma_{\text{max}}} \right) \frac{1}{\gamma},$$

(4)

where $\gamma$ is the Signal Noise Rate (SNR) and $\Delta\gamma_{\text{max}}$ is the maximal and allowable SNR loss because of the ICI. Apparently, $\Delta\gamma_{\text{max}}$ is up to 1 dB and maximal frequency offset $(\Delta f)_{\text{max}}$ must be less than 1% when the SNR is 30 dB. This algorithm has two disadvantages: One is that the precision of the frequency offset estimation will be greatly influenced when considering other factors like timing offset and phase shift; The other is that the range of the acquisition process is limited because of not considering the different offset variable. Li et al.(2001) presented a nonlinear least squares (NLS) scheme to estimate the offset, but this algorithm can be utilized only if the frequency offset is less than the sub-carrier frequency spacing.

Our problem of interest herein is to estimate the entire frequency offset $\Delta f$ that not only includes the integral times of sub-carrier spacing, but contains the fraction part less than the sub-carrier frequency spacing.

ALGORITHM

According to the requirement of the frequency offset estimation specified by IEEE802.11 stan-