On the Use of Pilot Signals in OFDM Based WLANs *

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Abstract

Pilot signals are used in the OFDM (orthogonal frequency-division multiplexing) based WLAN (wireless local area network) standard adopted by the IEEE 802.11 standardization group in July 1998. We present a simple method of effectively using these pilot signals to significantly reduce the bit error rate (BER) of data symbol detection.

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1 Introduction

In July 1998, the IEEE 802.11 standardization group selected Orthogonal Frequency Division Multiplexing (OFDM) as the basis for the new 5 GHz physical layer wireless local area network (WLAN) standard for data rates as high as 54 Mbps [1]. The OFDM training structure is contained in each packet preamble of this packet based communication scheme. The packet preamble specified by the IEEE standard (see Figure 1) consists of 10 identical short OFDM symbols ($\mathrm{t}_i,\ i = 1, 2, \ldots, 10$) each of length 16 (with a fundamental sampling rate of 20 MHz for the IEEE 802.11 standard) 2 identical long OFDM symbols ($\mathrm{T}_i,\ i = 1, 2$) each of length 64. Between the short and long OFDM symbols there is a guard interval (GI2) of length 32 that is the cyclic prefix of the long OFDM symbols. Each short OFDM symbol is generated via IFFT (inverse fast Fourier transform) from 12 known QPSK symbols and 4 nulls. Each long OFDM symbol is generated via IFFT from 52 known BPSK symbols and 12 nulls. The preamble is used for packet detection, OFDM symbol timing determination, carrier frequency offset correction, and channel estimation. The signal and data OFDM symbols follow the preamble. To generate a data OFDM symbol, the input binary serial data sequence is mapped to data symbols drawn, for example, from 16QAM constellation points. (Please note the difference between a data OFDM symbol and a data symbol.) Each data OFDM symbol has 64 subcarriers with 48 data symbols transmitted over 48 subcarriers, 4 known pilot symbols on 4 subcarriers, along with 12 null subcarriers and is also generated via IFFT. Each data OFDM symbol is augmented by a CP or guard interval (GI) of length 16, which is used to combat intersymbol interference.

In this paper, we present a simple method of effectively using the known pilot symbols to significantly reduce the bit error rate (BER) of data symbol detection after a brief discussion on OFDM symbol timing determination, carrier frequency offset correction, and channel estimation.

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2 OFDM Symbol Timing, Carrier Frequency Offset, and Channel

We assume that the OFDM symbol timing is known or can be determined by using a correlation approach similar to the one in [2]. The timing will be determined to be within an ambiguity range allowed by the GI and the the channel FIR (finite impulse response) filter length [2].

For carrier frequency offset correction, the simplest approach, where a closed-form solution exists, is to determine a coarse carrier frequency offset from two of the short OFDM symbols in the packet preamble by taking the argument of the correlation between them (see, for example, [2, 3, 4]). This step is needed to obtain a large unambiguous range of the carrier frequency offset. It is followed by the fine carrier frequency offset estimation from the 2 long OFDM symbols in the preamble with a similar correlation approach. If the automatic gain control (AGC) effects at the beginning of the packet preamble can be neglected, however, the last 9 short OFDM symbols can be used alone or with the 2 long OFDM symbols in the preamble to obtain better carrier frequency offset estimates. These estimates are 2.7 dB and 4.6 dB, respectively, better than using the 2 long OFDM symbols [4]. Yet more complicated estimation algorithms will be needed to achieve these improvements [4]. Further, the most important issue, of course, is not the best carrier frequency offset estimation, but the lowest BER of data symbol detection, which we will address in this paper.

Once we have corrected the carrier frequency offset and obtained the OFDM symbol timing, we can use the 2 long OFDM symbols to determine the channel FIR filter response with a linear least squares approach. Let $\mathbf{z}$ denote the average of the 64-point FFTs of the 2 long OFDM symbols in the packet preamble after the carrier frequency offset correction. Then we discard the 12 nulls from $\mathbf{z}$. Let $\mathbf{S}_L$ denote the 52×52 diagonal matrix containing the 52 BPSK known symbols. Let $\mathbf{W}_L$ denote the $52 \times L$ FFT matrix without the 12 rows corresponding to the 12 nulls and with only the first L_f columns, where L_f is the channel FIR filter length. Then the channel impulse response $\mathbf{h}$ can be estimated by minimizing $\|\mathbf{z} - \mathbf{S}_L \mathbf{W}_L \mathbf{h}\|^2$, which gives

$$\hat{\mathbf{h}} = \left(\mathbf{W}_L^H \mathbf{W}_L\right)^{-1} \mathbf{W}_L^H \mathbf{S}_L \mathbf{z}, \tag{1}$$

where $(\cdot)^H$ denotes the conjugate transpose and $\left(\mathbf{W}_L^H \mathbf{W}_L\right)^{-1} \mathbf{W}_L^H \mathbf{S}_L$ can be pre-calculated. The least squares cost function can be used to estimate the channel FIR filter length L_f with the generalized Akaike information criterion (GAIC) (see [5] and the references therein). Since the OFDM timing determined with a correlation method similar to the one in [2] is somewhere within the ambiguity range, the estimate of L_f is usually larger than the true L_f.

If the AGC distortion can be ignored, the channel response can be determined similarly from only the 9 short OFDM symbols as well as from both the 9 short and 2 long OFDM symbols in the preamble. We can also consider joint carrier frequency offset correction and channel estimation. However, the joint approaches can be complicated and are really not needed as far as the data BER is concerned if we use the pilot symbols effectively, as shown later with numerical examples.

3 Pilot Symbols for Phase Correction

Once we have obtained the OFDM symbol timing, corrected the carrier frequency offset, and calculated the channel response, we can detect the data symbols contained in the data OFDM symbols following the preamble. We have found that when the number of data OFDM symbols is small in a packet, all of the aforementioned approaches, obtained by using only the 2 long (following using only 2 short), only the 9 short, and both the 9 short and 2 long OFDM symbols in the packet preamble, yield similar BERs for data symbol detection when the pilot symbols in the data OFDM symbols are not used. When the number of data OFDM symbols is large in a packet but with the total packet length still less than the maximum of around 3 ms, different carrier frequency offset and channel estimates yield different BERs with the more accurate estimates resulting in lower BERs, as shown in Figure 2. To obtain the curves in this figure, we assume that each packet contains 100 data OFDM symbols and the data symbols (without using a convolutional encoder) are drawn from a 16QAM constellation. The carrier frequency offset is assumed to be 0.005 Hz and the channel FIR filter has $\mathbf{h} = [e^{j1.38} \; 0.5e^{j0.30} \; 0.3e^{-j2.02}]^T$, where $(\cdot)^T$ denotes the transpose. The BER is obtained from 400 Monte Carlo trials. The signal-to-noise ratio (SNR) is defined as the ratio of the average power per sample to the variance of the additive white Gaussian noise. We considered estimating the carrier frequency offset and the channel response by using 2 short, 9 short, 2 long (following using 2 short), and both 9 short and 2 long OFDM symbols in the preamble in Figure 2(a) by assuming that the OFDM symbol timing is perfect and the channel FIR filter length is 3. Note that using both the 9 short and 2 long OFDM symbols yields the lowest BER if the pilot symbols are not used.

Yet the only difference between larger and smaller numbers of data OFDM symbols in a packet is the phase change, or additional channel phase error accumulated over time, due to the unknown residue carrier frequency offset. Hence we invoke the parsimonious principle [5] and use the 4 pilot symbols in each data OFDM symbol to estimate only one unknown, the channel phase error for each data OFDM symbol, with a simple linear least squares method as follows.

Let $\mathbf{d}_k$ denote the length 64 vector containing the FFT of the kth data OFDM symbol (after discarding the GI) in a packet. The channel equalization can be done easily by dividing each element of $\mathbf{d}_k$ by the corresponding element of the FFT of $\hat{\mathbf{h}}$ after zero-padding it to 64. Let $\mathbf{q}_k$ denote the length 64 channel equalization output vector. Let $\mathbf{g}_k$ denote the length 4 vector containing the 4 elements of $\mathbf{q}_k$ corresponding to the 4 subcarriers occupied by the 4 pilot symbols. Let $\mathbf{p}_k$ denote the vector of the 4 known pilot symbols. Then we obtain the channel phase error ϕ_k by minimizing the following cost function:

$$\hat{\phi}_k = \arg\min_{\phi_k} \left\| \mathbf{g}_k - \mathbf{p}_k e^{j\phi_k} \right\|^2, \tag{2}$$

the closed-form solution of which is:

$$\hat{\phi}_k = \arg\left(\mathbf{p}_k^H \mathbf{g}_k\right). \tag{3}$$

Then the data symbol detection is performed on $\mathbf{q}_k \exp(-j\hat{\phi}_k)$, which compensates out the estimated channel phase error $\hat{\phi}_k$.

We note from Figure 2(a) that when the pilot symbols are used to correct the channel phase error, using the different carrier frequency offset and channel estimates (except for using only 2 short OFDM symbols in the preamble) yields nearly identical BERs that are almost the same as when the channel response is perfectly known and the carrier frequency offset is zero. Moreover, the BER difference with and without the simple use of the pilot symbols is rather significant!

If the OFDM symbol timing is not exact but somewhere within the ambiguity range, a longer channel FIR filter length will result. Figure 2(b) shows the BERs of data symbol detection as a function of SNR when the channel length is assumed to be 3, 10, and 16. The carrier frequency offset and channel response are obtained by using the 2 long OFDM symbols (after the coarse carrier frequency offset correction by using 2 short OFDM symbols) in the preamble and the pilot symbols are used for channel phase error correction. We note that the channel FIR filter length we assume can slightly affect the BER of data symbol detection and hence should be determined as accurately as possible, which also requires a more precise OFDM symbol timing determination approach than the one similar to [2]. This topic is currently a subject of our investigation.

We conclude that this simple method of effectively using the pilot symbols makes the simplest approach of using 2 short and 2 long OFDM symbols in the packet preamble for carrier frequency offset and channel estimation the best since more complicated approaches are not needed as far as the BER of data symbol detection is concerned.

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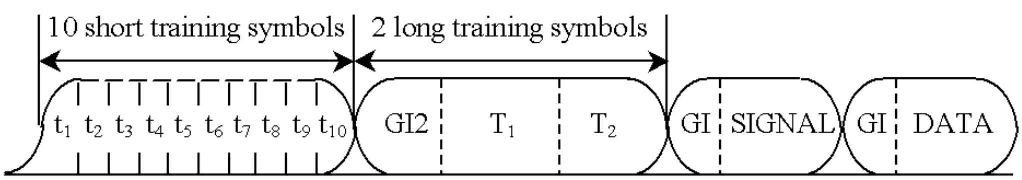
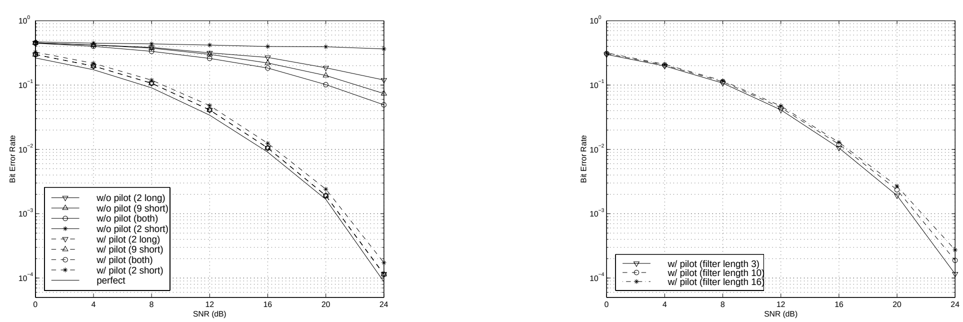


Figure 1: OFDM preamble structure adopted by the IEEE 802.11 standardization group.



(a) (b)

Figure 2: BER of data symbol detection vs. SNR with and without using the pilot signals for 16QAM data symbols. (a) Channel FIR filter length assumed 3. (b) Various channel FIR filter lengths assumed when 2 long OFDM symbols (after coarse carrier frequency offset correction with 2 short OFDM symbols) in the preamble are used for carrier frequency offset and channel estimation.