Preamble-based Symbol Timing Estimation for Wireless OFDM Systems

Manik Gadhiok and Joseph R. Cavallaro
Rice University, 6100 Main Street MS-380
Houston, Texas, 77005
E-mail:{gadhiok,cavallar@rice.edu}

Abstract[1]**—We propose a timing estimation scheme that reduces computational complexity while achieving performance comparable to the autocorrelation method commonly employed at the wireless receiver. The proposed method is based on the average magnitude difference function (AMDF). We present performance results for the proposed method for AWGN and Raleigh-fading channels in the context of IEEE 802.11a short preamble sequence. We also propose a preamble sequence based on Golomb sequence and compare its timing estimation performance with the IEEE 802.11a short-sequence. Simulation results show significant performance improvements for AWGN as well as Raleigh-fading channels.**

Index Terms**— Symbol timing estimation, Synchronization, OFDM, WLAN, IEEE802.11a, Autocorrelation, AMDF, Golomb sequence, preamble sequence**

I. INTRODUCTION

ORTHOGONAL Frequency Division Multiplexing (OFDM) has proved to be an enabling technology for high data rate wireless communication networks. Wireless LAN (WLAN) standards such as IEEE 802.11a/g/n [1] as well as broadband wireless access systems such as IEEE 802.16 use OFDM modulation. Because of the bursty nature of data transmission and fast acquisition times needed, these systems use preamble-based methods to acquire symbol timing and carrier frequency synchronization at the wireless reciever. The sensitivity of OFDM receiver performance to symbol timing estimation and carrier frequency offset (CFO) estimation errors is well known [1,2].

A timing estimation method proposed by Schmidl and Cox [2] estimates symbol timing offset using received signal correlation based on knowledge of the transmitted preamble signal. Minn, Bhargava et. al. [3] and Park et. al. [4] have proposed modified preamble schemes that try to reduce the variance of this correlation based estimator. Most of these methods use autocorrelation properties of the received signal to detect the periodicity of the preamble signal. By exploiting the apriori knowledge of the preamble sequence, the methods try to maximize the similarity between samples contained in the two sliding windows [2,3,4]. In [5], the authors present a different approach for cyclic-prefix based timing estimation where they minimize the anti-correlation or dissimilarity between the sliding windows. Also known as average magnitude difference function (AMDF), this method has been studied for pitch detection of voice signals [6-8]. This method has a significantly lower computational complexity compared to the autocorrelation-based estimation scheme. In this work, we investigate the AMDF-based metric in the context of preamble-based symbol timing synchronization. Unlike cyclic-prefix based timing estimation methods, the preamble-based estimation method does not require averaging over multiple OFDM symbols and therefore is able to meet the stringent acquisition time requirements for bursty wireless OFDM transmission systems. The proposed has comparable performance to the autocorrelation-based method under AWGN and Raleigh-fading channel conditions. Furthermore, the estimation algorithm does not require any modifications to the preamble signal . As a related contribution, we propose a new repetition preamble based on Golomb sequence [9], a sequence with low auto-correlation properties, and compare its performance in the context of IEEE 802.11a preamble signal [1] (also used by the newer IEEE 802.11n standard). Simulation results show that significant performance gains are achieved by exploiting the proposed preamble signal.

This paper is organized as follows: Section II gives an overview of the OFDM system and traditional symbol timing estimation method. In Section III, we present the proposed estimation method along with the modified preamble signal and performance/complexity analysis. Finally, we conclude the paper in Section IV.

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II. OFDM SYSTEM DESCRIPTION

A. OFDM System Overview

We consider a packet-based wireless OFDM transmission system. The n^{th} sample of the m^{th} OFDM symbol can be represented as the inverse Discrete Fourier Transform (IDFT) of the complex data vector $d_{m,0} .. d_{m,N-1}$ as

$$x_m(n) = \sum_{k=0}^{N-1} d_{m,k} \exp(j2\pi kn/N) \qquad 0 \le n \le N-1 \quad (1)$$

Here N represents the number of sub-carriers or equivalently the length of the DFT. A cyclic prefix of length N_g is appended to give the m^{th} transmitted OFDM symbol $\underline{x}_m = [x_{m,N-Ng}, \ldots, x_{m,N-1}, x_{m,0}, \ldots, x_{m,N-1}]^T$. Next, a preamble sequence is inserted at the beginning of each frame of data before transmission. We assume that the transmitted signal passes through a quasi-static wireless multipath-channel, constant over one OFDM symbol, and additive white Gaussian noise (AWGN) is added at the receiver. In the absence of any synchronization errors, the receiver can perform a Discrete Fourier Transform (DFT) in order to recover the original data vector,

$$z_m(n) = \sum_{k=0}^{N-1} r_{m,k} \exp(-j2\pi kn/N) \qquad 0 \le n \le N-1 \quad (2)$$

In practice, the DFT and IDFT operations are implemented using the Fast Fourier Transform (FFT) algorithm. For our simulations, the system parameters are based on the IEEE 802.11a standard [1] and are shown in Table I.

Table I. System Parameters

Parameter	Value
OFDM symbol duration	4.0 μs
Guard interval duration	0.8 μs
FFT size	64
# of data-carrying sub-carriers	52
Modulation scheme	QPSK

B. Overview of Symbol Timing Estimation

Let $\underline{s} = [s_0, s_1, \ldots s_L]$ represent a known sequence, where s_i are complex numbers representing the time-domain samples. The sequence is desired to have perfect autocorrelation and very low aperiodic autocorrelation [9], facilitating detection at the receiver. Here we focus on coarse symbol timing estimation in the context of IEEE 802.11a WLAN using what are known as short symbols or the short preamble sequence. Figure 1 shows the structure of the transmitted OFDM frame for IEEE 802.11a WLAN, each short symbol being 16 samples long. The symbols are repeated 10 times (160 samples) to generate the short preamble sequence.

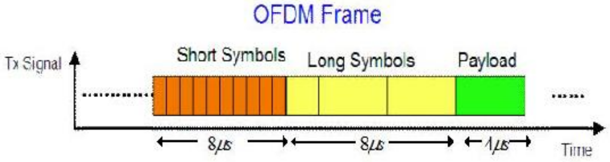

Fig.1. IEEE 802.11a: OFDM frame structure

At the receiver, the task of the symbol timing estimation block is to estimate the beginning of the Fast Fourier transform (FFT) window. The traditional receiver computes autocorrelation over the received samples, r, to find the timing estimate. In [2], the authors define the metric, *M(d)* and maximize it w.r.t. *d,* the sampled index in the buffer of received samples, to generate the estimate of the timing offset. M(d) is computed as [2]:

$$M(d) = \frac{|P(d)|^2}{(R(d))^2} \quad (3)$$

where,

$$P(d) = \sum_{m=0}^{L-1} r^*(d+m) r(d+m+L) \quad (4)$$

$$R(d) = \sum_{m=0}^{L-1} |r_{d+m+L}|^2 \quad (5)$$

Here |r| and r* represent the norm and complex conjugate of r respectively. Here, L is the length of one short symbol. In [3], the authors have shown that averaging the signal power over a larger window improves performance significantly, i.e. defining a new metric $M_1(d)$ by replacing *R(d)* in eq. (3) above, with $R_f(d)$ [3]

$$R_f(d) = \frac{1}{2} \sum_{m=0}^{L} |r_{d+m+L}|^2 \quad (6)$$

We will use this modified metric in order to evaluate the performance of the proposed symbol timing estimation method.

III. PROPOSED ALGORITHM

A. Algorithm

We define the average magnitude difference function (AMDF) as [5-8] :

$$M'_2(d) = \sum_{m=0}^{L-1} \left| r(d+m) - r(d+L+m) \right| \quad (7)$$

We define the modified AMDF function as follows where the square root operation inherent to the norm computation has been eliminated:

$$M_2(d) = \sum_{m=0}^{L-1} \left| r(d+m) - r(d+L+m) \right|^2 \quad (8)$$

The symbol timing offset estimate is the sample index (d) that minimizes the above metric, i.e. $\arg\min_{d} M_2(d)$.

The metric $M_2(d)$, as defined above, is a measure of the dissimilarity between the two windows of received samples. We discuss the estimation performance of the modified-AMDF method in the performance results section.

B. Computational Complexity

The complexity of the wireless receiver is a key ingredient of system design. Table II shows a computational complexity comparison between the proposed AMDF-based timing estimation method and the traditional autocorrelation-based method. The proposed method exhibits a lower complexity and facilitates an implementation with fewer hardware resources.

Table II. Complexity order comparison between autocorrelation and AMDF-based timing estimation

Method	**MUL**	**ADD/SUB**
Autocorrelation function (ACF)	8L	6L
Modified Average magnitude difference function (AMDF)	2L	4L

We note that the complexity of the ACF method can be reduced by using *R(d)* instead of $R_f(d)$, i.e. by computing the signal energy over a smaller number of samples. However, as indicated in [3], this lower complexity comes at the cost of significant performance degradation.

C. Preamble sequence

We now address the transmitted preamble signal that is utilized at the receiver for achieving synchronization and propose a short preamble based on Golomb sequence, a sequence with low auto-correlation properties [9]. A Golomb sequence comprises of L^{th} roots of unity and is defined as α_k where [9]:

$$\alpha_k = \alpha^{(k-1)k/2} \qquad 1 < k < L \qquad (9)$$

and $$\alpha = e^{2\pi i/L} \qquad (10)$$

A Golomb sequence of length 16 is generated and its amplitude scaled to match the signal power of the IEEE 802.11a short symbol. Fig. 2 shows the time-domain representation of one OFDM symbol (without cyclic-prefix) generated by repetition of the IEEE 802.11a short symbol and Golomb sequence respectively. We note that the proposed preamble has a constant envelope, thus resulting in excellent peak-to-average power ratio (PAPR) properties.

The time-domain sample autocorrelation function for both the preamble sequences is shown in Fig. 3. We note that the mean value of autocorrelation function is much lower at non-zero lags for the Golomb sequence when compared with the IEEE 802.11a short sequence.

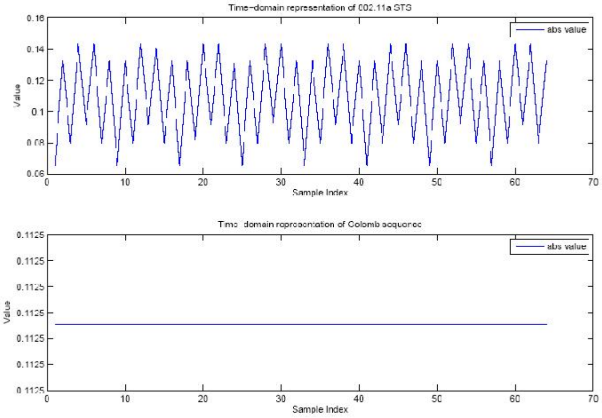

Fig. 2. Preamble sequence repetition based on IEEE 802.11a STS (top) and Golomb sequence (bottom)

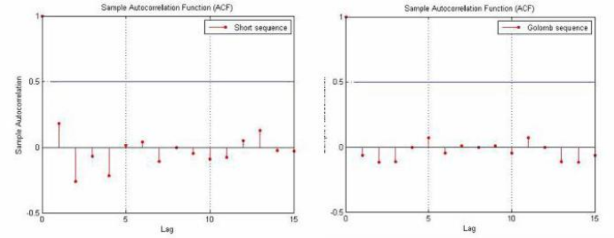

Fig. 3. Sample autocorrelation function: IEEE 802.11a STS (left) and Golomb sequence (right)

C. Performance Results

In this section, we discuss the performance results of the proposed algorithm for symbol timing estimation and compare it with the autocorrelation algorithm employed in [2], arguable the most commonly used method. The results are based on Monte Carlo simulations over 1000 runs, with a known fixed offset applied to the OFDM frame. The short training symbol (STS) is taken from IEEE 802.11a standard and was repeated twice. The performance comparisons are presented for four configurations:

1. ACF1: Autocorrelation function (ACF)-based estimation with IEEE 802.11a STS.
2. ACF2: ACF-based estimation with preamble signal generated using Golomb sequence
3. AMDF1: Average magnitude difference function (AMDF)-based estimation with IEEE 802.11a STS.
4. AMDF2: AMDF-based estimation with preamble symbol generated using Golomb sequence.

a. AWGN Channel

Fig. 4. shows the probability that the generated timing estimate matches the actual timing offset – in other words, the FFT window is aligned perfectly. The AMDF-based methods match the performance of the ACF-based methods very closely. Furthermore, there is a signification performance improvement achieved by using the Golomb sequence based preamble signal as compared to IEEE 802.11a based preamble signal.

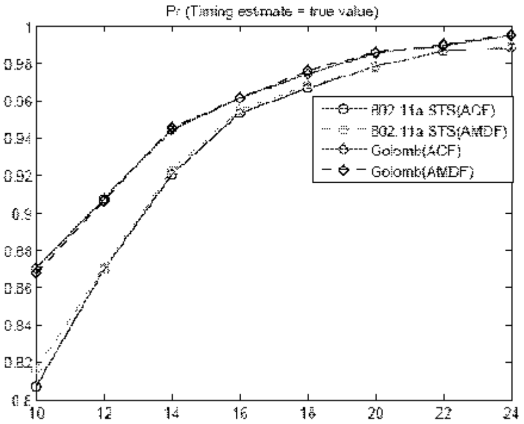

Fig. 4. : Probability of correct detection versus SNR for AWGN channel

b. Multipath Channel

The multipath channel model used is based on IEEE 802.11n and represents a typical residential environment (LOS conditions) with a rms delay spread of 15 ns and 10 dB Ricean K-factor at first delay. From Fig. 5, we see that the AMDF-based methods induce a small performance loss for this channel environment. Compared with the AWGN case, the Golomb sequence based preamble methods (ACF2, AMDF2) provide a greater performance improvement over the IEEE 802.11a STS-based methods. Fig. 6 shows the mean error of the symbol timing estimate.

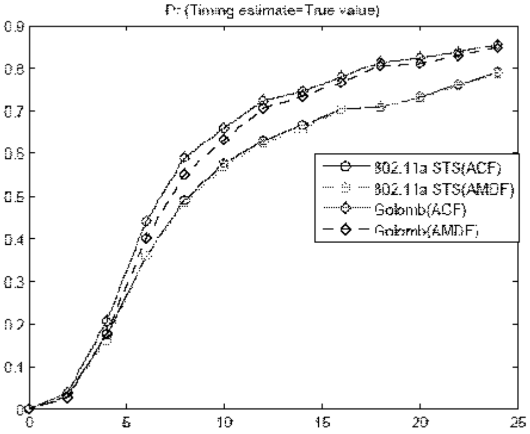

Fig. 5. : Probability of correct detection for multipath channel

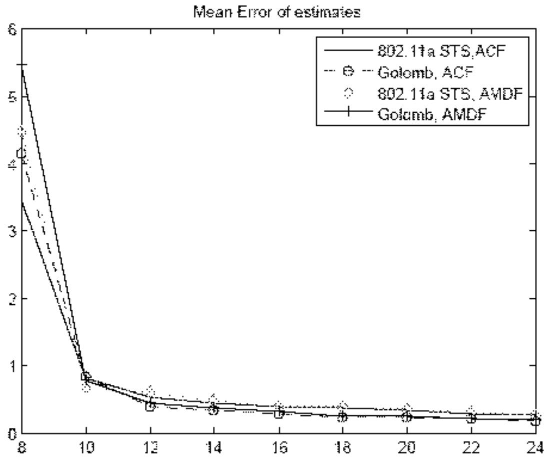

Fig. 6. : Mean error of estimates (measured in samples) versus SNR for Raleigh-fading multipath channel

IV. CONCLUSIONS AND FUTURE WORK

We present a reduced-complexity preamble-based timing estimation method that can achieve performance similar to the autocorrelation-based method. The proposed method does not require any modifications to the preamble signal and can be applied to the general class of repetition preamble sequences. We propose a short preamble signal based on Golomb sequence - a sequence with low auto-correlation properties - that enables more accurate symbol timing estimation.

As future work, it is worth investigating how the proposed preamble sequence will impact characteristics of a WLAN standard specification such as IEEE 802.11a in terms of spectral mask, PAPR etc.

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