

# TIME SYNCHRONIZATION ALGORITHM IN IEEE 802.11A COMMUNICATION SYSTEM

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## ABSTRACT

This paper proposes a novel approach for time synchronization in the IEEE 802.11a communication system. In addition to the conventional use of the 802.11a sequence preamble for synchronization, we exploit the SIGNAL field of the physical packet as a supplementary reference training sequence at the receiver for coarse time synchronization since this field consists of known and predictable parts. Fine time synchronization is then carried out jointly with minimum-mean-squared-error based channel estimation where the true channel is approximated according to a least-squares technique rather than using the power delay profile function. Simulations show that the proposed synchronization method improves the performance measured by the probability of synchronization failure as compared to existing methods.

**Index Terms**— IEEE 802.11a, OFDM, time synchronization, frequency synchronization, channel estimation, CSMA/CA, RTS/CTS, SIGNAL field.

## 1. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is used in most wireless communication systems. By carrying the data on orthogonal subcarrier frequencies, distortions caused by frequency selectivity and inter-symbol interference in multipath fading channels is reduced. However, in practical systems, symbol timing error and carrier frequency offset between the transmitter and the receiver can occur, causing undesirable effects such as inter-carrier interference and inter-symbol interference and, thus, degrading the system performance [1]. OFDM synchronization aims to find accurate symbol timing and the carrier frequency offset. It includes three stages: coarse time synchronization, then frequency synchronization, and finally fine time synchronization. This paper will however consider only coarse and fine time synchronization.

Generally, synchronization in OFDM systems often uses either a repeated training sequence or the Cyclic Prefix (CP) as the reference sequence at the receiver. In [2], a two-symbol training sequence is placed at the start of the transmitted frame and the receiver will search for the symbol whose first and second halves are identical. This is done based on the autocorrelation function (ACF) of the received symbols, and the symbol timing is the time at which the ACF attains its maximum. This method is fast and has a low overhead at the expense of low accuracy at low signal-to-noise-ratios (SNRs). In [3] and [4], the authors exploit the redundant information contained in the CP of data, and hence the time and frequency offsets are estimated from the maximum log-likelihood function.

Other methods have been developed specifically for the IEEE 802.11a wireless communication system. The training sequence is composed of a Short Training Field (STF) and a Long Training Field (LTF) which are specified in the standard. In [5], the STF is used for coarse synchronization based on the ACF, and the LTF is for fine synchronization relying on the cross-correlation (CCF) between the received sequence and the training sequence. In [6], the STF is used for both coarse and fine synchronization, based on the combination of the ACF and CCF.

To improve the performance of the previous methods, time synchronization is combined with channel estimation in [9, 10]. First, a set of possible Symbol Timing Offsets (STO) are obtained as results of coarse synchronization. Then, in fine synchronization, Least Square (LS)-based channel estimation is performed for each STO in order to select the correct STO. In [9], the LTF symbols are estimated according to the Mean Square Error (MSE) criterion and the selected STO is the one that minimizes the MSE. In [10], energies of the different Channel Impulse Responses (CIRs) over a given window (depending on the length of the channel) are compared and the selected STO is the one that corresponds to the CIR with the maximum energy. To improve the performance of channel estimation at low SNRs, the authors in [11] uses Minimum Mean Squared Error (MMSE) instead of LS.

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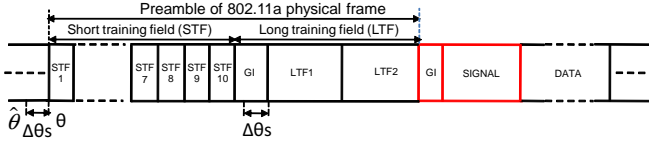


Fig. 1. Time offset.

This paper proposes a novel method to improve the performance of the time synchronization in the IEEE 802.11a wireless communication system. Specifically, apart from the conventional training sequence, we propose to also exploit the SIGNAL field as a supplementary reference sequence in coarse synchronization. This field is defined in the 802.11a physical packet when the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism is triggered. In addition, we observe that the MMSE-based estimation method proposed in [10] requires the knowledge of the power delay profile whose true values are difficult to obtain in general. Therefore, we will replace this with an LS approximation.

The rest of this paper is organized as follows. The IEEE 802.11a wireless communication system is briefly described in Section 2. The proposed time synchronization algorithm is then presented in Section 3. Simulation results are shown and discussed in Section 4. Conclusions are given in Section 5.

## 2. SYNCHRONIZATION IN IEEE 802.11A

In the IEEE 802.11a standard, the physical packet consists of three parts [12]: a preamble, a SIGNAL field and a DATA field. The preamble sequence is composed of the STF and the LTF fields, as shown in Fig. 1. The STF consists of ten known short repetitions (i.e., two OFDM symbols); each repetition is composed of 16 samples. The LTF contains a Guard Interval (GI) with a length of 32 samples and is followed by two known repetitions (i.e., two OFDM symbols); each repetition has a length of 64 samples. The SIGNAL field is represented by one OFDM symbol and contains 80 samples. The DATA field concerns the payload represented by a number of OFDM symbols.

The physical packet is transmitted according to the schematic diagram given in Fig. 2 via a multipath fading channel modeled as a finite impulse response filter of length  $L$ . The received signal in discrete form is modeled as

$$r_{\Delta}(n) = \sum_{i=0}^{L-1} h(i)x(n-i-\theta)e^{j2\pi\epsilon n} + g(n), \quad (1)$$

where  $h(n)$  denotes the slowly time-varying discrete time complex CIR with  $\sum_{i=0}^{L-1} E\{|h(i)|^2\} = 1$ ,  $\epsilon = \Delta F_c T_s$  is the normalized frequency offset where  $\Delta F_c$  is the frequency offset between the transmitter and the receiver and  $T_s$  is the

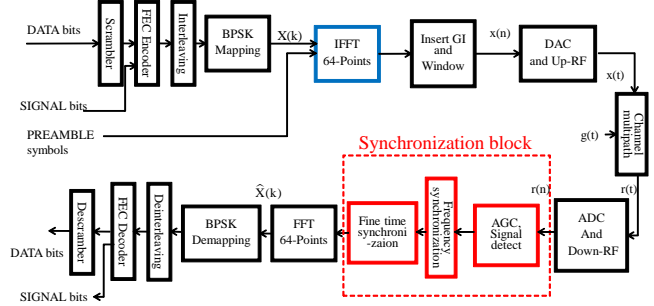


Fig. 2. Wireless communication system using OFDM.

sampling rate,  $g(n)$  is the complex additive white Gaussian noise, and  $x(n)$  is the transmitted signal. To recover the packet correctly, the symbol timing  $\theta$  and the frequency offset  $\epsilon$  have to be estimated. Since this paper only focuses on symbol timing estimation, we assume a perfect knowledge of  $\epsilon$ . Thus, having completely corrected the frequency offset<sup>1</sup>, the received signal in (1), in the noise-free case, can be effectively reduced to only include symbol timing information as follows:

$$r_{\Delta}(n) = \sum_{i=0}^{L-1} h(i)x(n-i-\theta). \quad (2)$$

This received signal is the input into the synchronization process that will be described in the next section.

## 3. PROPOSED METHOD FOR TIME SYNCHRONIZATION

We follow the approach of joint synchronization and channel estimation which have been developed in [10, 11]. These algorithms include two steps<sup>2</sup>: coarse and fine synchronization, as shown in Fig. 3(a). In this paper, we propose to incorporate in the coarse synchronization an additional synchronization step using the SIGNAL field, presented as block "SIGNAL" in Fig. 3(b). In addition, in the fine synchronization block "LS/MMSE", we will replace the estimation of the power delay profile, used in [11], by a LS approximation.

### 3.1. Coarse time synchronization

#### 3.1.1. Coarse synchronization using Short Training Field

Symbol timing is estimated using the cross-correlation between the received signal  $r_{\Delta}(n)$  and the known bitstream  $c(n)$  obtained from the first ten repetitions of the preamble

<sup>1</sup>Frequency synchronization can be done using the algorithm in [7].

<sup>2</sup>Note that, although frequency synchronization is performed in OFDM synchronization, we however have not presented in Fig. 3(a) for the sake of simplicity of presentation.

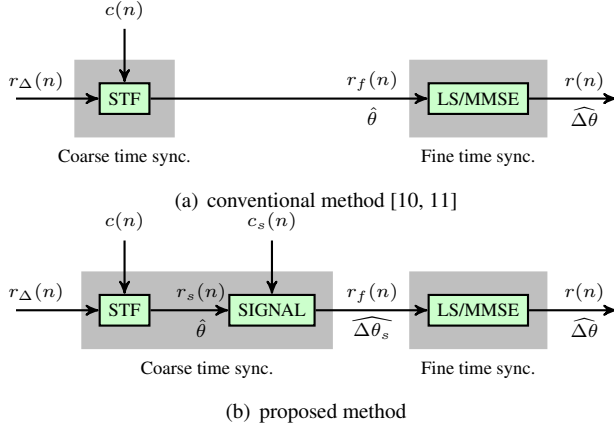


Fig. 3. Time synchronization methods.

STF. The CCF is given by:

$$Z(\theta) = \sum_{n=0}^{L_{\text{STF}}-1} c^*(n)r_{\Delta}(n+\theta), \quad (3)$$

where  $L_{\text{STF}}$  is the number of sample of  $c(n)$ . Then, the symbol timing is coarsely estimated by

$$\hat{\theta} = \arg \max_{\theta} |Z(\theta)|. \quad (4)$$

### 3.1.2. Coarse synchronization using SIGNAL field

To improve the above estimation of the symbol timing, we exploit the SIGNAL field specified in the 802.11a physical frame. This field is composed of two main bitstreams: RATE and LENGTH, as shown in Fig. 4. These subfields are formally used for informing the receiver about the transmission rate and the length of the physical packet, respectively, although they have also been used for robust transmission issues. The RATE bitstream is known while the LENGTH bitstream is predictable as it will be explained below.

Assumed that the CSMA/CA medium reservation procedure is triggered, the transmitter sends a Request To Send (RTS) control frame in order to ask the receiver if the communication is possible. If the receiver is not busy, then it will send another control frame called Clear To Send (CTS) to the transmitter, as well as all other stations in the same network to inform them of its unavailability for reception [13].

To predict the LENGTH field (in octets), the knowledge of the required time to transmit the physical frame,  $T_{\text{packet}}$ , is necessary since it is given by the following relationship:

$$\text{LENGTH} = \text{RATE} \times \frac{(T_{\text{packet}} - T_{\text{pre}} - T_{\text{SIGNAL}} - (T_{\text{symp}}/2)) - 22}{8}, \quad (5)$$

where  $T_{\text{pre}}$ ,  $T_{\text{SIGNAL}}$  and  $T_{\text{symp}}$  are the durations of the preamble, the SIGNAL field and the OFDM symbol, respectively.

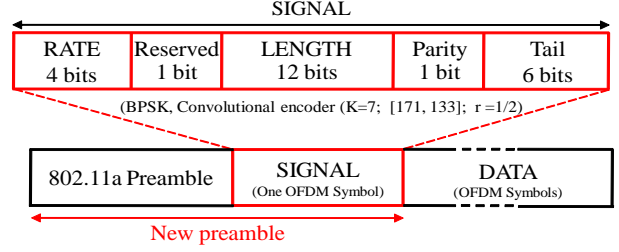


Fig. 4. Signal field.

These durations are known at the receiver [13]. The  $T_{\text{packet}}$  is deduced from the information provided by the RTS control frame namely the DURATION field (in micro-seconds) [13]:

$$\text{DURATION} = 3T_{\text{SIFS}} + T_{\text{CTS}} + T_{\text{ACK}} + T_{\text{packet}}, \quad (6)$$

where  $T_{\text{SIFS}}$  is the duration (in micro-seconds) of a Short Inter-Frame Space,  $T_{\text{CTS}}$  and  $T_{\text{ACK}}$  are the durations of the required time to transmit the frame CTS and frame ACK respectively. These are also known parameters. This strategy allows the receiver to deduce the SIGNAL field bitstream.

According to the standard, the SIGNAL field bitstream (composed of 24 bits) undergoes the following operations before being transmitted over the channel. It is first sent as an input to the specific convolutional encoder (with a constraint length equal to 7, a polynomial generator [171, 133], and a code rate equal to 1/2). Its outputs are interleaved (by a known interleaver) and then modulated by a BPSK modulator followed by the Inverse Fast Fourier Transform (IFFT) 64-points concatenated to a CP (16 samples). The resulting stream,  $c_s(n)$ , is thus composed of 80 samples. This stream is now used as an supplementary reference sequence to compensate the remaining time offset in coarse synchronization  $\Delta\theta_s$ , as shown in Fig. 3(b) and described next.

The received signal is expressed by

$$r_s(n) = \sum_{i=0}^{L-1} h(i)x(n-i-\Delta\theta_s), \quad (7)$$

where  $L$  is the number of channel taps, and  $\Delta\theta_s = \theta - \hat{\theta}$ . Define a set  $\Theta = \{\Delta\theta_s^{(k)} | k = -K, \dots, K\}$ , where  $K$  is a predefined number. Then, for a given  $\Delta\theta_s^{(k)}$ , we compute the cross-correlation between  $r_s(n)$  and  $c_s(n)$  as

$$Z(\Delta\theta_s^{(k)}) = \sum_{n=0}^{L_{\text{SIG}}-1} c_s^*(n)r_s(n+\Delta\theta_s^{(k)}), \quad (8)$$

where  $L_{\text{SIG}}$  is the combined length of the CP and the SIGNAL field. The remaining time is then estimated by

$$\widehat{\Delta\theta}_s = \arg \max_{\Delta\theta_s^{(k)}} |Z(\Delta\theta_s^{(k)})|. \quad (9)$$

### 3.2. Joint time synchronization and channel estimation

Fine time synchronization makes use of the LTF. The received signal is given by

$$r_f(n) = \sum_{i=0}^{L-1} h(i)x(n-i-\Delta\theta), \quad (10)$$

where  $\Delta\theta = \Delta\theta_s - \widehat{\Delta\theta}_s$  is the remaining time offset computed between the true symbol timing and its estimate. This time offset is estimated jointly with channel estimation using the MMSE criterion.

First, a finite set  $\mathbf{\Lambda}$  containing  $2M+1$  time offsets is defined as follows  $\mathbf{\Lambda} = \{\Delta\theta_m | m = -M, \dots, M\}$ . For a given value  $\Delta\theta_m$ , the CIR is then estimated in the frequency domain, based on MMSE, as follows [14]:

$$\widehat{\mathbf{H}}_{\Delta\theta_m} = \mathbf{R}_H(\mathbf{R}_H + \frac{\sigma_g^2}{\sigma_x^2}\mathbf{I})^{-1}\widetilde{\mathbf{H}}_{\Delta\theta_m}, \quad (11)$$

where the  $N \times 1$  vector  $\widetilde{\mathbf{H}}_{\Delta\theta_m}$  is the LS channel estimate,  $\sigma_x^2$  and  $\sigma_g^2$  are, respectively, the variance of the transmitted signal and the noise,  $\mathbf{R}_H$  is the frequency-domain correlation matrix of the true channel, and  $\mathbf{I}$  is the identity matrix. The LS estimates are given by

$$\widetilde{\mathbf{H}}_{\Delta\theta_m} = \mathbf{X}^{-1}\mathbf{Y}, \quad (12)$$

where  $\mathbf{Y}$  is received symbol vector in the frequency domain and  $\mathbf{X}$  is a diagonal matrix whose diagonal elements are samples of the known LTF symbol sequence. The frequency-domain channel correlation matrix  $\mathbf{R}_H$  in (10) is given by

$$\mathbf{R}_H = \mathbf{F}\mathbf{R}_h\mathbf{F}^H, \quad (13)$$

where  $\mathbf{F}$  is the  $N \times N$  FFT matrix,  $\mathbf{R}_h = E\{\mathbf{h}\mathbf{h}^H\}$  is correlation matrix of the time-domain true channel vector  $\mathbf{h}$ , and  $E$  is the expectation operator. Rather than using the power delay profile function, whose true values are difficult to obtain exactly, we propose to estimate  $\mathbf{h}$  using LS approximation as

$$E\{\mathbf{h}\mathbf{h}^H\} \approx E\{\widetilde{\mathbf{h}}_{\Delta\theta_m}\widetilde{\mathbf{h}}_{\Delta\theta_m}^H\}, \quad (14)$$

where  $\widetilde{\mathbf{h}}_{\Delta\theta_m}$  is the inverse Fourier transform of  $\widetilde{\mathbf{H}}_{\Delta\theta_m}$ .

Next, for each time offset  $\Delta\theta_m$  in  $\mathbf{\Lambda}$ , we obtain a time-domain estimate  $\widehat{\mathbf{h}}_{\Delta\theta_m}$  of the CIR. Among the  $M$  estimates, we consider only  $\Delta\theta_m$  that satisfy the following condition:

$$|\widehat{h}_{\Delta\theta_m}(0)| > \beta \max_{\Delta\theta_m} |\widehat{h}_{\Delta\theta_m}(0)|, \quad (15)$$

where  $\beta$  is a given threshold. Therefore, the set  $\mathbf{\Lambda}$  becomes  $\mathbf{\Gamma}$

$$\mathbf{\Gamma} = \{\omega_0, \dots, \omega_{M'}; M' \leq 2M\}. \quad (16)$$

Finally, the remaining time offset is estimated by

$$\widehat{\Delta\theta} = \arg \max_{\omega_{m'}} \{Z(\omega_{m'})\}, \quad (17)$$

**Table 1.** Simulation parameters

Parameters	Values
Bandwidth ( $B$ )	20 MHz
Sampling time ( $T_s$ )	50 ns
Number of subcarriers ( $N_c$ )	52
Number of points FFT/IFFT	64
Subcarrier spacing ( $\Delta F$ )	0.3125 MHz
Channel model	Rice with COST207-RA
Channel time delay	(0, 200, 400, 600) ns
Power of channel paths ( $P_c$ )	(0, -2, -10, -20) dB
Data rate	6 Mbps
Threshold ( $\beta$ )	0.7
$L_{STF}$	112
$L_{SIG}$	80
$M$	30
$K$	80

where  $Z(\omega_{m'})$  is the energy associated to the estimated CIR  $\widehat{\mathbf{h}}_{\omega_{m'}}$  and is given by

$$Z(\omega_{m'}) = \sum_{n=0}^{L-1} |\widehat{h}_{\omega_{m'}}(n)|^2. \quad (18)$$

## 4. SIMULATION RESULTS

This section provides the performance of the proposed time synchronization method using the SIGNAL field and compare this with the conventional method. In particular, we compare the following four algorithms:

i) **Algorithm 1 (LS)**: This algorithm uses STF for coarse synchronization and LS for channel estimation in fine time synchronization [10].

ii) **Algorithm 2 (MMSE)**: This algorithm is the same as Algorithm 1, but MMSE is used instead of LS for channel estimation [11].

iii) **Algorithm 3 (LS-SIGNAL)**: This algorithm additionally uses the SIGNAL field for coarse synchronization while fine synchronization is the same as in Algorithm 1.

iv) **Algorithm 4 (MMSE-SIGNAL)**: This algorithm is similar to Algorithm 3, but MMSE is used for channel estimation instead of LS.

The simulation parameters of the communication system based on Fig. 2 are summarized in Table 1 in accordance with the IEEE 802.11a standard [12]. The system uses one antenna both at the transmitter and the receiver ( $1 \times 1$ ). The channel follows the Rice model with a line-of-sight (LOS). The maximum delay of this channel is equal to 600 ns with a sampling time of  $T_s = 50$  ns. The number of taps is 13 and is suitable since the length of the CP is 16. Note that, in the simulation, we also implement FS using the approach developed in [7], for a frequency offset of  $0.32\Delta F$ , where  $\Delta F = 0.3125$  MHz is subcarrier spacing.

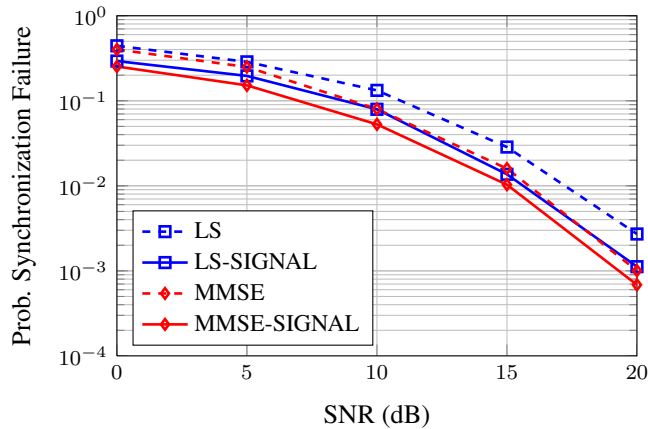


Fig. 5. Probability of synchronization failure performance.

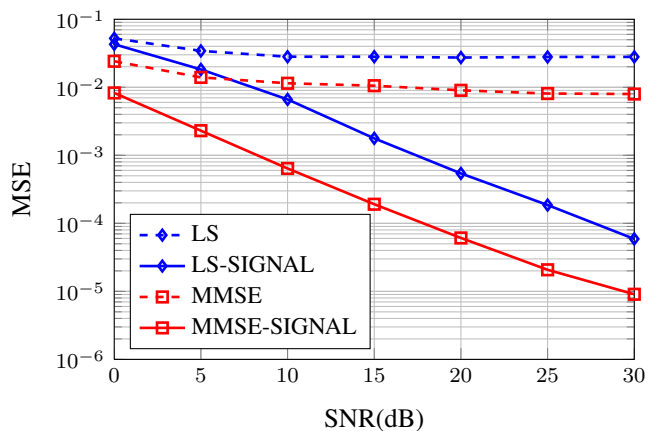


Fig. 6. MSE performance comparison.

The probability of failure synchronization versus the SNR is shown in Fig. 5. It is clear that the proposed Algorithm 4 (MMSE-SIGNAL) is the best. For a given  $SNR = 20$  dB and frequency tolerance of  $0.32\Delta F$ , the probabilities of failure synchronization for Algorithms 1, 2, 3 and 4 are respectively 0.0027, 0.001, 0.0011 and 0.00068.

Figs. 6 shows the MSE performance of the conventional and proposed algorithms. It can be seen that the proposed Algorithms 3 (LS-SIGNAL) and 4 (MMSE-SIGNAL) have significantly improved the MSE (between the true channel and estimated channel) as compared, respectively, to the conventional Algorithms 1 (LS) and 2 (MMSE). For example, for a given  $SNR = 20$  dB and frequency tolerance of  $0.32\Delta F$ , the MSE of channel estimate for Algorithm 1 (LS) and Algorithm 3 (LS-SIGNAL) are respectively 0.028 and  $5.90e-005$ .

## 5. CONCLUSION

This paper proposed a novel time synchronization method adapted to the wireless OFDM communication system based on the IEEE 802.11a standard. In addition to using con-

ventional Short Training Field sequence as the reference sequence specified by the standard, we also exploited the SIGNAL field in the standard and use it as a supplementary training sequence to enhance the coarse time synchronization. The SIGNAL field is given when the CSMA/CA medium reservation mechanism is triggered. The control frames RTS and CTS are then used for predicting the unknown part of the SIGNAL field and is exploited as the reference information by the receiver to improve the coarse time synchronization. Moreover, for the channel estimation, rather than using the power delay profile to define the true CIR, we proposed to use its approximation according to the LS criterion. The simulation results show that the probability of synchronization failure is lower than the conventional method.

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