2017 International Symposium on Nonlinear Theory and Its Applications,
NOLTA2017, Cancun, Mexico, December 4-7, 2017

Preamble-less Synchronization by Short Block Autocorrelation for OFDM Systems over Multipath Fading Channels

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Abstract—This paper proposes a novel symbol timing synchronization scheme for preamble-less OFDM systems. In the next generation wireless communication system we have to deal with signals from huge sensors set up everywhere such as wearable devices, cars and production facilities in the factory. These applications require low latency for quick response or feedback. Preamble-less packet transmission is one of the effective means to reduce overhead and has been widely investigated. However, multipath fading channel causes inter symbol interference (ISI) which worsens synchronization accuracy and leads to a negative impact on the overall system performance. The basic idea of the proposed scheme is to utilize correlation block shorter than cyclic prefix, so as to avoid the multipath effect. Computer simulations demonstrate the proposed scheme achieves improved synchronization performance and reduced computation complexity compared with the existing schemes.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is implemented to the great majority of modern wireless communication systems such as long term evolution (LTE), worldwode interoperability for microwave access (WiMAX) and wireless local area network (WLAN), due to its robustness against the multipath fading channel. Thanks to a cyclic prefix (CP) inserted to the OFDM symbol, the received multipath components can be treated as circular convolution and it allows application of fast Fourier transform (FFT). It also alleviates the timing synchronization exactness. Multicarrier structure of OFDM is quite effective in flexible time frequency resource utilization. With orthogonal frequency division multiple access (OFDMA), time or frequency resources are allocated to user equipments (UEs) wherein good channel condition; multiuser diversity can be obtained.

This flexibility has been extended to Internet of things (IoT) application. Narrow band IoT (NB-IoT) [1], Wi-Fi HaLow [2], etc. have been specified as the low power wide area network (LPWAN) systems. Each of them uses reduced frequency resources whereas power density is increased. Transmission rate is low but its coverage can be significantly expanded. Meanwhile, some IoT applications require lower latency. Wearable devices [3] should deliver rich contents to the users depending on their demands. Connected car [4] indicates in-vehicle infotainment (IVI) via network and safe automotive enabled by vehicle to everything (V2X) communication. Emergency signals should be transmitted instantaneously.

On the premise of OFDM systems, preamble less transmission is expected to reduce latency [5]-[7]. Generally, timing synchronization to extract FFT window is performed using preamble whose length is more than two OFDM symbols [8]. It is regarded as the overhead, thus omitting this can realize low latency. Preamble less synchronization exploits the CP inserted in the OFDM symbols. Receiver detects the peak points of the correlation output between the CP and its corresponding period at the end of symbol. Although this approach works well in single path channels, it often miscaptures the exact timing position in multipath fading channels.

Upon the above drawback, this paper proposes a novel timing synchronization scheme that exploits smaller correlation block than CP length. Its improved timing synchronization performance is presented through computer simulations. The rest of the paper is organized as follows. Sect. 2 describes the system model and existing preamble less synchronization scheme, respectively. Sect. 3 presents the proposed scheme. Sect. 4 shows computer simulation results and Sect. 5 then concludes this paper.

2. Preamble-less Synchronization

2.1. System model

Let $x(n)$ denote the n-th $(0 < n < N_{CP} + N_{FFT})$ sample of the transmission OFDM symbol inserted CP where N_{FFT} and N_{CP} indicate the number of FFT point and CP samples, respectively. The n-th sample of reception signal, $y(n)$, is then expressed as,

$$y(n) = \sum_{l=0}^{L-1} h(l)x(n-l-\eta) + \omega(n), \qquad (1)$$

where $h(l)$ and $\omega(n)$ represent the l-th $(0 < l < L-1)$ tap of impulse response and additive white Gaussian noise (AWGN), respectively. L is the maximum path length. η stands for the timing offset to be detected at the receiver.

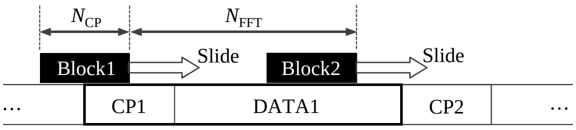

Figure 1: Principle of preamble-less synchronization

Preamble-less synchronization exploits similarity between the CP and the end of the symbol. Two blocks separated by N_{FFT} samples are compared with sliding their position and the start point of the OFDM symbol is then detected. Each of then generally has CP length. Here describes representative synchronization schemes.

2.2. Minimum Difference (DF)

DF [5] scheme extracts the symbol timing where difference between two blocks is minimized. Metric function is expressed as,

$$\delta_{DF} = \arg\min_{\delta} \left(\sum_{i=\delta}^{N_{CP}-1+\delta} |y(n+i)-y(n+N_{FFT}+i)| \right). \quad (2)$$

Although it can be calculated in reasonable complexity, detection accuracy is degraded in multipath fading environment.

2.3. Maximum Correlation (MC)

MC [6] scheme calculates auto-correlation between two blocks and seeks synchronization point.

$$\delta_{MC} = \arg\max_{\delta} \left(\sum_{i=\delta}^{N_{CP}-1+\delta} |y(n+i)y^*(n+N_{FFT}+i)| \right). \quad (3)$$

Detection accuracy of MC is also limited since multiple peaks are observed due to the multipath and it results in miscapture.

2.4. Maximum Likelihood (ML)

ML [7] scheme exhibits the better synchronization performance than DF and MC whereas it require the enlarged complexity.

$$\delta_{ML} = \arg\max_{\delta} \left(\left| \sum_{i=\delta}^{N_{CP}-1+\delta} y(n+i)y^*(n+N_{FFT}+i) \right| - \frac{\rho}{2} \sum_{i=\delta}^{N_{CP}-1+\delta} \left[|y(n+i)|^2 + |y^*(n+N_{FFT}+i)|^2 \right] \right), \quad (4)$$

where

$$\rho = \frac{E\left[|y(n)|^2\right] - E\left[|\omega(n)|^2\right]}{E\left[|y(n)|^2\right]} \approx \frac{\sigma_m^2}{\sigma_m^2 + \sigma_n^2}. \quad (5)$$

Here we used the fact that

$$\begin{aligned} E\left[|y(n)|^2\right] &= E\left[\left| \sum_{l=0}^{L-1} h(l)x(n-l-\eta) + \omega(n) \right|^2 \right] \\ &\approx \sum_{l=0}^{L-1} |h(l)|^2 \sigma_x^2 + \sigma_n^2 \\ &= \sigma_m^2 + \sigma_n^2. \end{aligned} \quad (6)$$

As shown in (4), metric function is normalized by the second term and thus the detection accuracy can be improved compared to MC.

3. Proposed Scheme: Short Block based ML (SBML)

Block length for preamble-less synchronization has been thought to be same as CP. Although long block length is preferable to obtain the strong peak, inter-symbol interference (ISI) causes inaccurate synchronization instead. Proposed scheme shorten the block length to avoid ISI and it also contributes to reduce the computation complexity. Let $N_p (< N_{CP})$ denote the block length, metric function of the proposed SBML is defined as,

$$\begin{aligned} \phi(n) &= \left| \sum_{i=0}^{N_p-1} E\left[y(n+i)y^*(n+N_{FFT}+i)\right] \right| \\ &\quad - \frac{\rho}{2} \sum_{i=0}^{N_p-1} \left[E\,|y(n+i)|^2 + E\,|y^*(n+N_{FFT}+i)|^2 \right]. \end{aligned} \quad (7)$$

From (5) and (6), the second term of (7) can be deformed;

$$\phi(n) = \left| \sum_{i=0}^{N_p-1} E\left[y(n+i)y^*(n+N_{FFT}+i)\right] \right| - N_p \sigma_m^2. \quad (8)$$

In order to analyze the principle of the proposed scheme, we observe autocorrelation in (8) at the n-th sample point;

$$E\left[|y(n)y^*(n+N_{FFT})|\right] = E\left[|P_1(n) + P_2(n)|\right]. \quad (9)$$

From (1), respective part $P_1(n)$ and $P_2(n)$ can be derived as follows.

$$\begin{aligned} P_1(n) &= \left(\sum_{l=0}^{L-1} h(l)x(n-l-\eta) \right) \\ &\quad \times \left(\sum_{l=0}^{L-1} h^*(l)x^*(n+N_{FFT}-l-\eta) \right), \end{aligned} \quad (10)$$

$$\begin{aligned} P_2(n) &= \left(\sum_{l=0}^{L-1} h(l)x(n-l-\eta) \right) \omega^*(n+N_{FFT}) \\ &\quad + \left(\sum_{l=0}^{L-1} h^*(l)x^*(n+N_{FFT}-l-\eta) \right) \omega(n) \\ &\quad + \omega(n)\omega^*(n+N_{FFT}). \end{aligned} \quad (11)$$

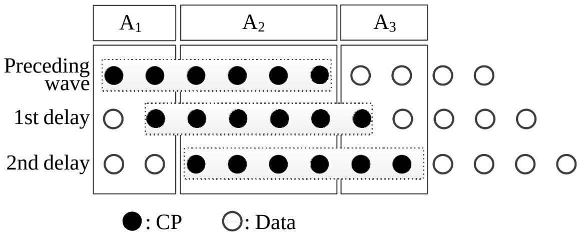

Figure 2: Incoming symbol offset due to the multipath

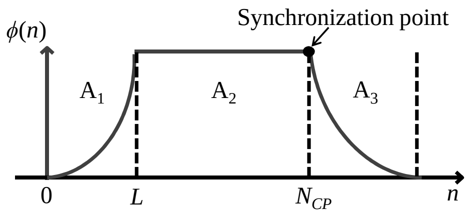

Figure 3: Correlation value versus sample point

Since AWGN term $\omega(n)$ is independent and identically distributed (i.i.d), expectation of $P_2(n)$ goes to zero. Hence,

$$\begin{aligned} &E\left[|y(n)y^*(n+N_{FFT})|\right] \\ &= \sum_{l=0}^{L-1}\left|h(l)^2\right| E\left[x(n-l-\eta)x^*(n+N_{FFT}-l-\eta)\right] \\ &\approx \begin{cases} Q_1(n) & n \in A_1 \\ \sigma_m^2 & n \in A_2 \\ Q_2(n) & n \in A_3 \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad (12)$$

where

$$\begin{cases} A_1 = [\eta, \eta+1, ..., \eta+L-1] \\ A_2 = [\eta+L, \eta+L+1, ..., \eta+N_{CP}-1] \\ A_3 = [\eta+N_{CP}, ..., \eta+N_{CP}+L-1] \end{cases} \quad (13)$$

As shown in (12), behavior of the autocorrelation value can be classified into three regions as indicated in Fig. 2. A_1 and A_3 indicate the mixed regions including head of CP and tail of the previous symbol, i.e. ISI region. A_2 consists of only own symbol in CP. Expected value of $Q_1(n)$ and $Q_2(n)$ in (12) can be formulated as follows.

$$\begin{aligned} Q_1(n) &\approx \sum_{l=0}^{n} |h(l)|^2\sigma_x^2 < \sigma_m^2, \\ Q_2(n) &\approx \sum_{l=n}^{L-1} |h(l)|^2\sigma_x^2 < \sigma_m^2, \end{aligned} \quad (14)$$

where $\sigma_x^2 = E[|x(n)|^2]$, $n = 0$ or N_{FFT}. As expressed in (14), value of $Q_1(n)$ and $Q_2(n)$ are smaller than σ_m^2 whereas σ_m^2 is independent of n. This characteristics can be visualized in Fig. 3. Meanwhile, larger block length will raise the value of $Q_2(n)$ and it may worsen the detection accuracy of synchronization point.

Table 1: Simulation parameters.

Parameter	Value
Transmission scheme	OFDM
Number of FFT point, N_{FFT}	128
CP length, N_{CP}	32
Number of symbol	20
Modulation	QPSK
Channel model	16 path Rayleigh fading with 1 dB decay
Doppler frequency	10 Hz

4. Computer Simulation

4.1. Simulation Parameters

Monte Carlo simulations have been conducted to evaluate the synchronization performance of the proposed SBML. Simulation parameters are listed in Table 1. We consider an OFDM system with 128 subcarriers (N_{FFT} = 128) and CP length of 32. Assuming a Rayleigh fading channel, the multipath component is modeled as 16 path with 1 dB attenuation for each tap as per. The expectation was calculated over 20 OFDM symbols.

4.2. Simulation Results: Optimal Block Length

First evaluation is to determine the optimal block length for autocorrelation. Synchronization error rate with respect to the block length, N_p, is shown in Fig. 4. $N_P = 4$ always achieve the lowest error rate for various SNR condition of 10, 20 and 30 dB. It is because that $N_P = 4$ provides the best isolation between σ_m^2 (A_2) and $Q_2(n)$ (A_3). Following evaluation utilizes $N_P = 4$.

4.3. Simulation Results: Synchronization Error Rate

Here compares error rate performance of the proposed SBML scheme with DF, MC and ML schemes. Synchronization error rate versus SNR is plotted in Fig. 5. SBML outperforms the other schemes for SNR > 10 dB. Due to shortened the block length, autocorrelation output becomes sensitive to additive noise. It causes dispersion of timing detection in lower SNR region. When SNR = 20 dB, SBML can achieve reduced synchronization error by 45.45%, 41.29% and 24.46% compared to DF, MC and ML, respectively.

4.4. Complexity Analysis

Computation complexity required for metric calculation is summarized in Table 2. It is obtained as the number of multiplications and their exemplified values are also shown. DF is the simplest approach without any multiplications but synchronization performance is quite low.

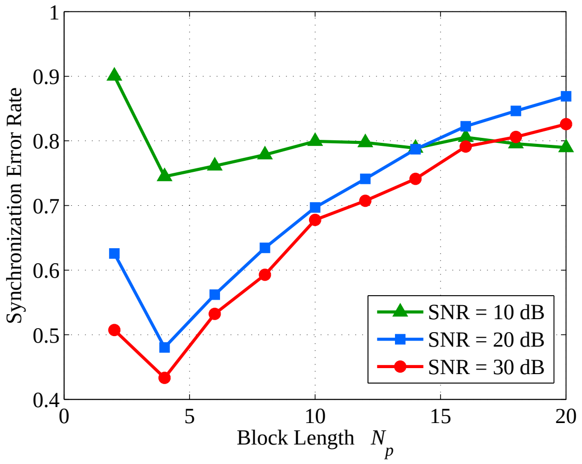

Figure 4: Synchronization Error Rate versus Block length.

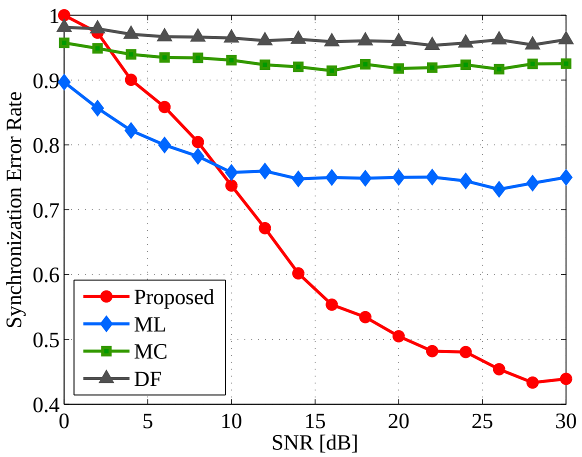

Figure 5: Synchronization Error Rate versus SNR.

The proposed SBML scheme has the least complexity next. MC and ML follow it and resultant complexity reduction is 62.5% and 87.5%, respectively. This result emphasizes the effectiveness of the proposed SBML that aims low latency OFDM transmission. Improving synchronization accuracy in lower SNR region should be further investigated.

5. Conclusion

This paper proposed a novel preamble-less synchronization scheme for OFDM systems over the multipath fading channel. Its basic idea is shortening the correlation block length than that of CP. It can effectively avoid ISI due to the multipath effect and stably extract the symbol timing for accurate FFT windowing. Computer simulations clarified improved timing synchronization performance as well as reduced computation complexity. Our proposed scheme can contribute to the real-time requirements in wireless IoT applications.

Table 2: Computation complexity.

Scheme	Complexity	Value
DF	0	0
MC	$N_{CP}(N_{FFT}+N_{CP})$	5120
ML	$3N_{CP}(N_{FFT}+N_{CP})$	15360
Proposed	$3N_p(N_{FFT}+N_{CP})$	1920

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