Timing Synchronization and Channel Estimation of a Constant Pilot Padding OFDM System

Chi-Min Li, Hui-Che Chen, Po-Jen Wang, Jia-Chyi Wu and I-Tseng Tang

***Abstract*— In this paper, we propose a Constant Pilot Padding Method (CPPM) that can perform both the timing synchronization and channel estimation in the Orthogonal Frequency Division Multiplexing (OFDM) systems. The CPPM method exploits the repetitive structure of the preamble generated by inserting the constant pilots in the frequency domain to execute the timing synchronization. In addition, the CPPM method has the ability of channel estimation with these padding pilots. Compared with the conventional synchronization methods, such as the S&C method and the Park's method, the preamble of the CPPM provides not only timing synchronization but also data transmission. Simulation results show that the proposed method is more precise and robust than the S&C method and the Park's method.**

***Index Terms*—Timing Synchronization, Channel Estimation, OFDM**

I. INTRODUCTION

ORTHOGONAL Frequency Division Multiplexing (OFDM) has been widely adopted in the current wireless communication systems, such as IEEE802.11a/g, Digital Video Broadcasting for Handheld (DVB-H), and IEEE802.16 Wireless MAN, due to its high bandwidth efficiency and the ability of overcoming frequency selective fading channel. To accomplish the frequency synchronization and the symbol detection, an OFDM system has to establish the timing synchronization [1]-[11] firstly. Two types of timing synchronization methods can be classified: one is the data-aided schemes [1]-[5] that design a preamble structure suitable for timing synchronization. For example, the S&C method [1] and the Park's method [2] use the repetitive preamble to estimate the timing offset. These methods use the PN (pseudo-noise) sequence in the frequency domain to generate preamble with a specific repetitive form. The second type of the timing synchronization is the non-data-aided schemes [6]-[11]. [6] exploits the cyclic prefix (CP) structure of OFDM symbol and performs the Maximum Likelihood Estimation (MLE) for the timing offset. [7] uses a BPSK modulated signal to carry out a blind timing synchronization. However, the estimation performance of the non-data-aided schemes are generally poor than the data-aided methods.

In this paper, we propose a Constant Pilot Padding Method (CPPM) that has both the timing synchronization and the channel estimation abilities. Compared with the S&C method and the Park's method, the repetitive structure of the preamble is generated by inserting constant pilots in the frequency domain rather than the PN sequences. Besides, the generated preamble can also carry the modulated information symbols to improve the disadvantage of inefficiency bandwidth usage of the conventional data-aided methods.

This paper is organized as follows. In Section II, the proposed CPPM method and the corresponding repetitive preamble structure will be described in detail. Besides, the linear interpolated channel estimation via using the padding pilots will also be illustrated. Simulation results of the proposed CPPM method, the S&C method and the Park's method are investigated in Section III. Some conclusions for this paper are given in Section IV.

II. METHOD DESCRIPTION

The proposed OFDM system that exploits Constant Pilot Padding Method (CPPM) with data padding interval I=2 is shown in Fig.1. Before the Inverse Fast Fourier Transform (IFFT), the padding pilots P along with the modulated data Xk are arranged as

$$X_k^P = \begin{cases} X_k, & k = 0 : I : (N - I) \\ P\ , & otherwise \end{cases} \tag{1}$$

where X_k are the modulated symbols inserted on the subcarriers with interval I, I is defined as data padding interval, N is the total number of subcarriers, k is the subcarrier index and P is the pilot value.

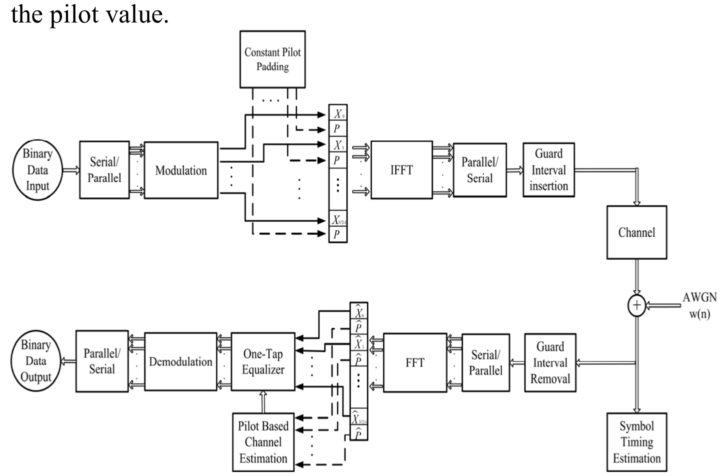

Fig.1 Block Diagram of the Proposed CPPM OFDM System

The generation of the CPPM method can be illustrated in

Fig.2. Assume there are N/I modulated symbols X_k (Fig.2(a)), Fig.2(b) illustrates the arrangement of CPPM method in the frequency domain. The modulated symbol X_k and the constant padding pilot P are inserted into the subcarriers specified in Eq.(1). After the IFFT operation, the generated preamble will have a repetitive time domain waveform in Fig.2(c). The number of repetitive waveform is determined by the padding interval I. Besides, the padding pilot P can perform the channel estimation as in Fig.2(d). Compared with the S&C's and the Park's preamble, the generated preambles of the CPPM method for timing synchronization can transmit the modulated symbols to increase the bandwidth efficiency.

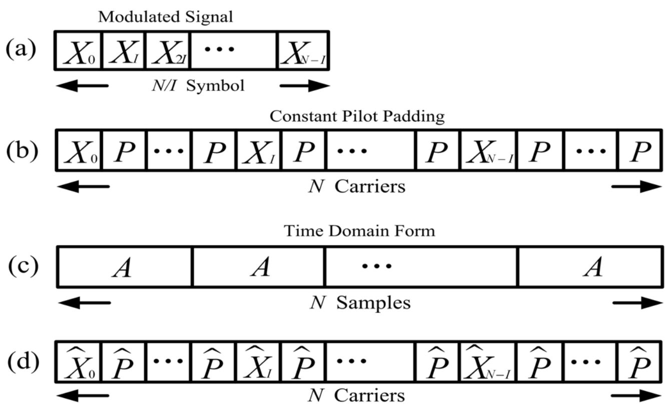

Fig.2 The CPPM Method Structure

Besides, the repetitive structure of the preamble depends on the modulation of the inserted symbols X_k. Two examples are given below:

(a). Repetitive Waveform of Inserting BPSK Modulated Symbols

In the proposed CPPM, if the X_k are BPSK-modulated, let the padding pilot P =1, the carrier number N=256 and the padding interval I=1, after the IFFT operation, the real part and the imaginary part of the generated time domain waveform of the preamble X can be depicted in Fig.3.

An interesting property can be observed that the CPPM preamble X has the following property.

$$[x(1),x(2),\dots,x(127)] = symmetry\{[x(129),x(130),\dots,x(255)]^*\} \quad (2)$$

Except the two points on $x(0)$ and $x(128)$, the preamble $x=[B \quad B_S^*]_{1*N}$ contains two repetitive conjugate symmetric segments, $B=[x(1),x(2),...,x(127)]$, $B_s=[x(129),x(130),...,x(255)]$, $(\bullet)^*$ denotes the complex conjugate.

If the padding interval I=2, except the four points on x(0), x(N/4), x(N/2), x(3N/4), the preamble X contains four repetitive conjugate symmetric segments depicted in Fig.4.

Similar results can be observed if different padding interval I is adopted. Table-1 lists the time domain repetitive waveform of the preamble for different padding interval I. Generally, the preamble composes of 2I segments of time domain waveform with the conjugate symmetric property. Besides, each segments contains (N/I)-1 samples.

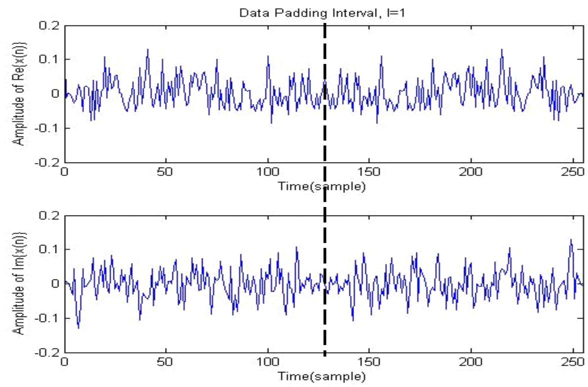

Fig.3 Time Domain Waveform of the Preamble with BPSK Modulated Symbols

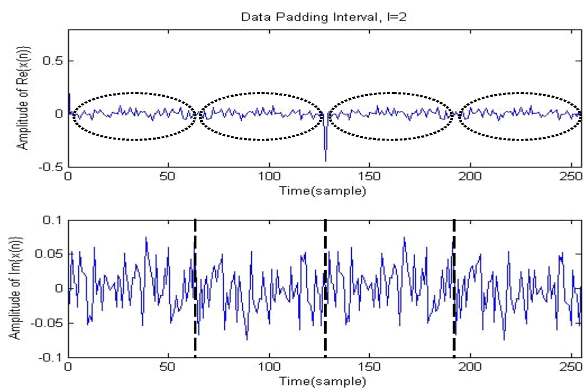

Fig. 4 Time domain waveform of BPSK with I=2, P=1

TABLE-1 TIME DOMAIN WAVEFORM OF THE PREAMBLE WITH BPSK MODULATED SYMBOLS

I	Time Domain Form
I=1	[B Bs*]
I=2	[D Ds* D Ds*]
I=4	[G Gs* G Gs* G Gs* G Gs*]
I=8	[T Ts* T Ts* T Ts* T Ts* T Ts* T Ts* T Ts* T Ts*]

(b). Repetitive Waveform of Inserting QPSK/QAM Modulated Symbols

If the X_k are QPSK or QAM modulated symbols, let the padding pilot P =1, the carrier number N=256 and the padding interval I=2. After the IFFT operation, the real part and the imaginary part of the generated time domain waveform of the preamble has the following properties. Its waveform can be depicted in Fig.5.

$$\text{Real}\{[x(1),x(2),...,x(127)]\} = \text{Real}\{[x(129),x(130),...,x(255)]\}$$

$$\text{Imag}\{[x(0),x(1),...,x(127)]\} = \text{Imag}\{[x(128),x(129),...,x(255)]\}$$

Except for the two points on $x(0)$ and $x(N/2)$, the preamble X

contains two repeated segments.

Similar results can be observed if different padding interval I is adopted. Table-2 lists the time domain repetitive waveform of the preamble for different padding interval I of the QPSK/QAM modulations.

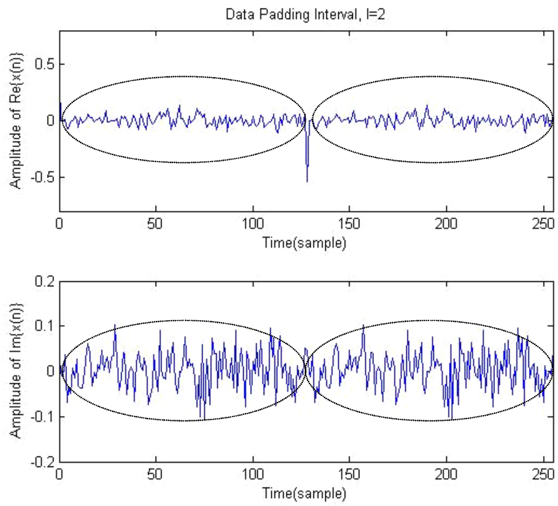

Fig.5 Time domain waveform of QPSK with I=2, P=1

TABLE-2 TIME DOMAIN WAVEFORM OF THE PREAMBLE WITH QPSK MODULATED SYMBOLS

I	Time Domain Form
I=1	[Random]
I=2	[A A]
I=4	[Z Z Z Z]
I=8	[H H H H H H H H]

(c). Channel Estimation of the Proposed CPPM Method

Let the received preamble signal of the OFDM system be $y(n)$, after removing the CP and applying the FFT operation to the $y(n)$, the frequency domain signal Y_k is

$$\begin{aligned} Y_k &= FFT\{y(n)\} \\ &= \sum_{n=0}^{N-1} y(n) e^{-j2\pi kn/N}, \quad k = 0,1,\ldots,N-1 \\ &= X_k H_k + W_k \end{aligned} \tag{4}$$

where H_k is k-th channel response, W is the AWGN in the frequency domain. Because Y_k is composed of the estimated modulated symbol $\widehat{X}_k$ and the estimated padding pilots $\widehat{P}$ (Eq.(5)). The channel estimation can be carried out via the Eq.(6) on the subcarriers with the padding pilots. Once these pilot channels have been estimated, the data channels can be predicted by using the simple linear interpolation in Eq.(7).

$$Y_k = \begin{cases} \widehat{X}_k, & k = 0 : I : (N-I) \\ \widehat{P}, & otherwise \end{cases} \tag{5}$$

$$\widehat{H}_k = \frac{Y_k}{X_k} \quad ,k \neq 0 : I : (N-I) \tag{6}$$

$$\widehat{H}_k = \begin{cases} \dfrac{\widehat{H}_{k-1} + \widehat{H}_{k+1}}{2} & ,k = I : I : (N-I) \\ \widehat{H}_{k+1} & ,k = 0 \end{cases} \tag{7}$$

III. SIMULATION RESULTS

In this section, we compare the proposed CPPM method with the Park's and the S&C methods for the BPSK and QPSK modulations respectively. The number of subcarrier is 256, the length of the inserted CP is 64 samples and the channel delay time is 256 samples.

A. Performance of Timing Offset Estimation

Fig.6 is the simulation result if we compare the CPPM method with the Park's method under the AWGN channel with SNR=20dB. The timing metric M is defined directly from the Park method as

$$M_{\text{BPSK}}(d) = \frac{|P_{BPSK}(d)|^2}{(R_{BPSK}(d))^2} \tag{8}$$

$$P_{BPSK}(d) = \sum_{m=0}^{N/2} y(d-m) \cdot y(d+m) \tag{9}$$

$$R_{BPSK}(d) = \sum_{m=0}^{N/2} |y(d+m)|^2 \tag{10}$$

where d denotes the timing index corresponding to the first sample of a window with N samples. The estimated timing offset is the timing index with the maximum metric value in Eq.(11).

$$\hat{\tau}_{\text{BPSK},I} = \arg\max_d \{M_{\text{BPSK}}(d)\} \tag{11}$$

Note that for the Park's method, the peak of the metric will occur at the middle of the preamble. Fig.6 shows that both methods can estimate the timing offset 447 (=256+64+128-1) correctly.

Compared with the Park's method, the proposed CPPM method can insert the modulated information symbols on the even subcarriers instead of the the real-valued PN sequences.

If we compare the CPPM with the S&C method and use the S&C timing metric defined in Eq.(12)~(14). For the S&C method, the peak of the timing metric occurs at the beginning of the generated preamble. Fig.7 illustrates the simulation result under the AWGN channel with SNR=20dB.

$$M_{QPSK}(d) = \frac{|P_{QPSK}(d)|^2}{(R_{QPSK}(d))^2} \tag{12}$$

$$P_{QPSK}(d) = \sum_{m=0}^{N/2-1} y^*(d+m) \cdot y(d+m+N/2) \tag{13}$$

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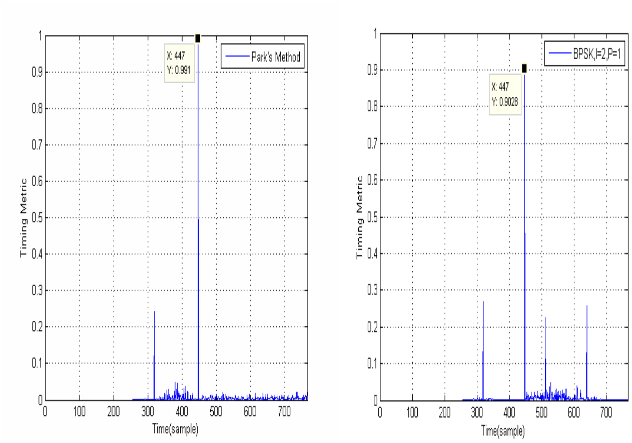

(a) Park's method (b) CPPM, I=2, P=1

Fig.6 The calculated timing metric of the Park's and CPPM methods

$$R_{QPSK}(d)=\sum_{m=0}^{N/2-1}\left|y(d+m+N/2)\right|^2 \tag{14}$$

$$\hat{\tau}_{\mathrm{QPSK},I}=\arg\max_{d}\left\{\mathrm{M}_{\mathrm{S\&C}}(d)\right\} \quad ,P>0. \tag{15}$$

The correct timing offset should be 320(256+64) in the Fig.7. Due to the CP insertion, the S&C method contains a plateau in the calculated timing metric. On the contrary, the proposed CPPM method can predict the timing index 321(correct timing offset+1) precisely. It reveals that the CPPM method has more accurate timing offset estimation than the S&C method.

The statistical performance of timing synchronization in a five-paths Rayleigh fading channel can be illustrated in Fig.8. That CPPM method has almost similar performance compared with the Park's method. However, the CPPM method has a smaller variance of timing estimation than the Park's method. Besides, results also show that the timing offset estimation of the CPPM method is more accurate than the S&C method.

B. Performance of Channel Estimation

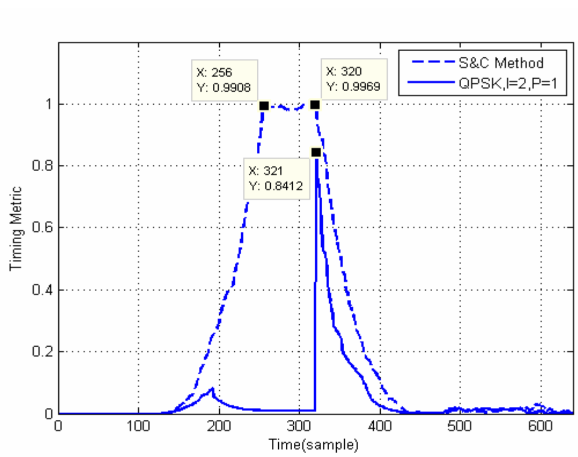

Fig.7. The calculated timing metric of the S&C and the CPPM methods.

In addition to the timing offset estimation, the proposed CPPM method has the ability of channel estimation. Define the mean square error (MSE) of the channel estimation as

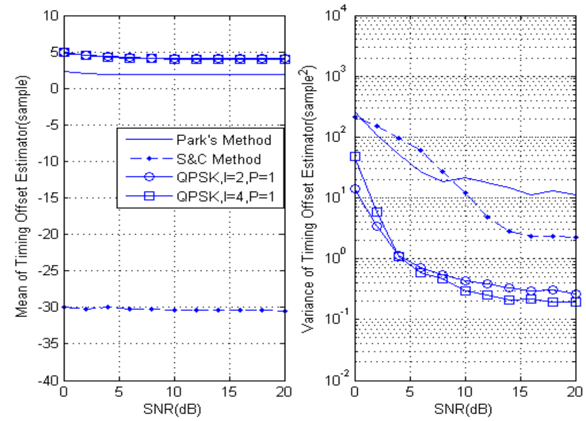

Fig.8 Mean and Variance of the Timing Offset Estimation.

$$MSE_{Ch}=E\left[\frac{1}{N_d}\sum_{k}\left|H_k-\widehat{H}_k\right|^2\right] \qquad ,k=0:I:N-I \tag{16}$$

where I is data padding interval, N is subcarriers number, N_d is number of the data subcarriers. Fig.9 shows the MSE of the CPPM method for the different padding interval I under a five-paths Rayleigh fading channel. Because we use the linear interpolation in this simulation, the MSE is independent of the padding interval I.

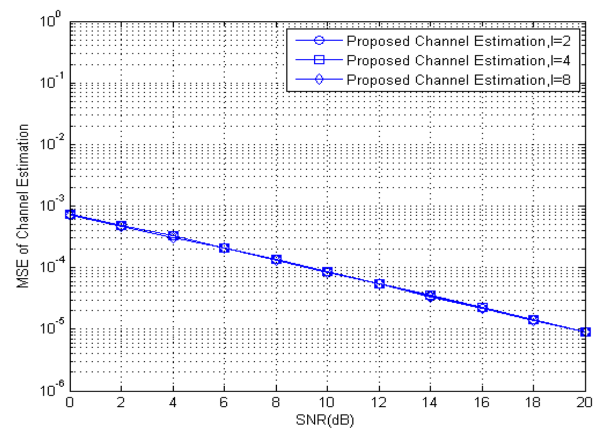

Fig.9 MSE of the CPPM Channel Estimation

The BER performance of the CPPM method can be illustrated in Fig.10. The simulated OFDM system contains 256 subcarriers, the length of the CP is 64 samples, a five-paths Rayleigh fading channel is considered. From the simulation result, the proposed method will have 3dB BER degradation compared with the perfect channel estimation.

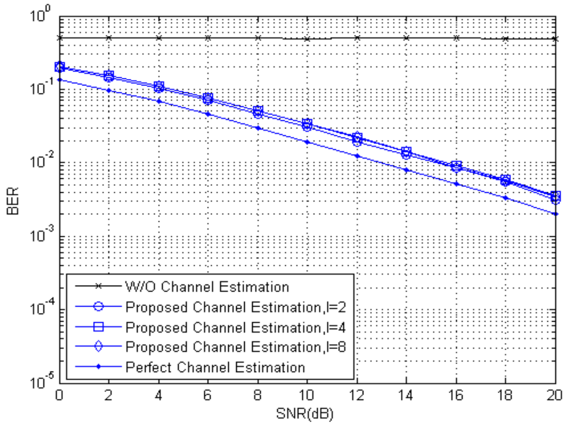

Fig.10 BER Performance of the CPPM Method

IV. CONCLUSIONS

In this paper, we propose a CPPM method that can perform both the timing synchronization and channel estimation in the Orthogonal Frequency Division Multiplexing (OFDM) systems. According to simulations, the CPPM method has more accurate timing estimation than the S&C method and has similar performance compared with the Park's method. However, the CPPM method is more robust than the Park's method. Besides, the CPPM method can also transmit the modulated information symbols in the preamble to improve the disadvantage of inefficiency bandwidth usage of the conventional data-aided timing synchronization methods.

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