A Novel Timing Synchronization Method for MIMO OFDM Systems

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***Abstract*—This paper presents a timing synchronization method with shift-orthogonal Constant Amplitude Zero Auto Correlation (CAZAC) sequences for the multiple-input multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM) systems. Utilizing the unique properties of CAZAC sequences, at the receivers, unit pulses can be obtained by the symmetrical correlation to detect time offsets and differentiate inter-transmitter delays (ITDs). The performance of the proposed method is compared with traditional methods at different values of ITDs. Simulations demonstrate that the proposed CAZAC sequence-based method provides high accuracy in detecting the different time offsets caused by the distributed transmitters of the MIMO OFDM systems.**

***Index Terms*—CAZAC, MIMO, OFDM, timing synchronization**

I. INTRODUCTION

SYNCHRONIZATION has been a major research topic in orthogonal frequency division multiplexing (OFDM) systems due to the sensitivity to symbol timing offset and carrier frequency offset. Numerous techniques have been suggested in the literatures for OFDM time and frequency synchronization [1]-[3]. However, none of the synchronization methods used in OFDM systems can be applied to multiple-input multiple-output (MIMO) OFDM systems without major modifications.

Utilizing the spatial multiplexing technique, the capacity of the MIMO OFDM system can be increased linearly with respect to the minimum number of antennas. MIMO OFDM systems can be categorized into the centralized and the distributed systems. For the centralized system, the antennas at the transmitters and receivers are placed closely. Therefore the signals from different transmitters arrive at the receivers simultaneously, i.e. no inter-transmitter delay (ITD). By contrast with the centralized system, the transmitters and receivers in a distributed system are sparsely placed, and ITD has to be taken into account since the signals from different transmitters will be delayed and summed at the receivers.

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A lot of research has been devoted to solving the timing synchronization problem of the MIMO OFDM systems, but most of them are based on the assumption that the systems are centralized [4]-[7]. In these approaches, the synchronization sequence (SS) is constructed by several repetitions of a synchronization pattern (SP). Since SP for various transmitters has equal period, the approaches are referred here as the Equal Period Synchronization Pattern (EPSP) method. This method can give available estimation in the centralized systems, but in distributed systems it is unable to find the ITDs and distinguish the signals from different transmitters. In [7], a method utilizing Unequal Period Synchronization Pattern (UPSP) is introduced. When the delays are larger than several decades of samples, the UPSP method can find the delays successfully. However, in practical MIMO OFDM systems, the ITDs are much smaller, and later simulations show that the UPSP method can not afford correct estimation any more in this situation.

In this contribution, a method using shift-orthogonal Constant Amplitude Zero Auto Correlation (CAZAC) sequences [8]-[10] is proposed to estimate the time offsets and detect the ITDs for MIMO OFDM systems. In the method, the synchronization sequences for various transmitters are constructed by weighted phase-shift CAZAC sequences, and the proposed method will be represented as WPS. The ITDs can be easily found by the symmetrical correlation estimator in the receivers. As shown in the Section IV, the method is efficient in distinguishing the different time offsets between the transmitters and receivers.

The contribution is structured as follows. In section II the MIMO OFDM signal model is briefly defined. In section III the existing timing synchronization method will be overviewed, and the preamble design and timing synchronization algorithm of the proposed method will be described. The simulations are discussed in Section IV. Finally, conclusions are drawn in Section V.

II. MIMO OFDM SYSTEM MODEL

A general MIMO OFDM system with N_t transmitters and

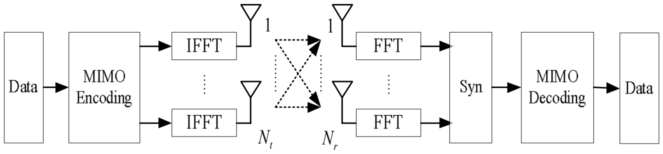

Fig. 1. $N_t \times N_r$ MIMO OFDM system

N_r receivers is depicted as Fig.1. The complex baseband samples of an OFDM symbol transmitted by the ith transmission antenna are expressed as

$$x_i(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_i(k) e^{j2\pi kn/N} \quad -N_g \le n \le N-1, \qquad (1)$$

where $X_i(k)$ is the data in the frequency domain before inverse fast Fourier transform (IFFT), N is the number of IFFT points, and N_g is the length of the cyclic prefix (CP) to eliminate the inter-symbol interference (ISI).

The complex baseband samples received at the jth receiving antenna is given by

$$r_j(n) = \sum_{i=1}^{N_t} \sum_{k=0}^{N-1} X_i(k) H_{ij}(k) e^{j2\pi k(n-\tau_{ij})/N} + w_j(n) \quad -N_g \le n \le N-1, \qquad (2)$$

where $H_{ij}(k)$ and τ_{ij} respectively represent the complex transfer function at the kth sub-carrier and the integer-valued time offset of the channel between the ith transmitter to the jth receiver. $w_j(n)$ is the time domain complex Gaussian noise.

III. TIMING SYNCHRONIZATION METHOD FOR MIMO OFDM SYSTEM

A. Review of Timing Synchronization Methods

In this section, the timing synchronization methods mentioned in [5] and [7] will be briefly introduced, which are named as EPSP and UPSP. For simplicity, a two-transmitter one-receiver system ($N_t = 2$ and $N_r = 1$) will be considered in this contribution. However, the generalization to the system invoking higher number of receivers is straightforward.

In the two methods, the preamble at the beginning of the frame is constituted with a zero power sequence with length L_0 and a synchronization sequence with length L_{SS}. Additionally, the synchronization sequence is composed of several repetitions of a shorter synchronization pattern with length L_{SP}.

1) EPSP Method

For the EPSP method, the synchronization sequences of different transmitters are designed using the same synchronization pattern. As a result, just one estimator is needed at the receiver, and the timing synchronization can be operated by correlating the received samples that are at a distance of L_{SP} from each other over a window of length $L_{SS} - L_{SP}$. The metric to estimate $\hat{\tau}_{ij}$ can be given by [5]

$$\hat{\tau}_{ij} = \arg\max_d \left(M(d)\right), \qquad (3)$$

where

$$M(d) = \left| \sum_{n=0}^{L_{SS}-L_{SP}} r_j(n+d) r_j^*(n+d+L_{SP}) \right|^2. \qquad (4)$$

For the centralized MIMO OFDM scenario, the data sent by different transmitters are perfectly aligned when they arrive at the receiver. Therefore, the time offset τ_i has the same value for various transmitters. However, when the transmitter antennas are placed apart when considering the distributed systems, the data from different transmitters will be no longer perfectly aligned as that in the centralized systems, which means τ_i is depended on ith $(i = 1, 2, \cdots, N_t)$ transmitters. The difference will be demonstrated in Section IV.

2) UPSP Method

For the sake of obtaining the individual time offset associated with different transmitters, UPSP using unequal period synchronization patterns to construct synchronization sequences for different transmitters. More explicitly, a unique L_{SP} value is assigned for each individual transmitter when forming the synchronization sequence. Hence $L_{SP,i}$ is denoted as the length of the synchronization pattern assigned to the ith transmitter. Therefore, at the receiver, N_t estimators are needed to find the time offsets of each individual transmitter, and, to carry out the calculation, the Equation (3) and (4) are modified as [7]

$$\hat{\tau}_{ij} = \arg\max_d \left(M_i(d)\right), \qquad (5)$$

and

$$M_i(d) = \left| \sum_{n=0}^{L_{SS}-L_{SP,i}} r_j(n+d) r_j^*(n+d+L_{SP,i}) \right|^2. \qquad (6)$$

As shown in (6), $M_i(d)$ implements the correlation process using $L_{SP,i}$, only the synchronization sequence sent by the ith transmitter will contribute to the correlation peak, and individual time offsets for the transmitters can be detected. However, the performance of UPSP is degraded when ITD is smaller than several decades of samples, due to the interference between the different synchronization sequences.

B. Proposed Timing Synchronization Method

In the proposed WPS method, the preamble for the ith transmitter is defined as

$$x_{i,k} = w_i c_{\mathrm{mod}(k+D_i)_N} \qquad k = 0, 1, 2, \ldots, N-1, \qquad (7)$$

where w_i is an orthogonal weighted factor, and $c_{\mathrm{mod}(k+D_i)_N}$ is the CAZAC sequence which is cyclically shifted with D_i samples. D_i is a unique number for the individual transmitter.

In order to achieve accurate estimation and distinguish ITD efficiently, the synchronization sequences for different transmitters should be unique, and, at the jth receiver, correlation results of the synchronization sequences from the transmitter should satisfy a pulse function [5]

$$M_i(d) = \begin{cases} C & d = \tau_{ij} \\ 0 & d \neq \tau_{ij} \end{cases}, \tag{6}$$

where C is a real number. The optimal auto-correlation property [8] [9] of CAZAC sequences can guarantee the correlation results of the synchronization sequences satisfy (6).

At the jth receiver, only one estimator is needed to find the time offsets of the data from different transmitters. For the different cyclic-shift number D_i, the time offsets can be differentiated by modifying the metric as

$$\hat{\tau}_{ij} = \arg\max_{d}\left(M_i(d)\right), \tag{8}$$

and

$$M_i(d) = \left|\sum_{n=0}^{N/2-1} r\left(d+\frac{N}{2}+n\right) r^*\left(d+\frac{N}{2}-n\right)\right|^2. \tag{9}$$

Because of the orthogonality of the weighted factors and self-invertible property [10] of CAZAC sequences, the outputs of the symmetrical correlation display N_t pulses, each pulse indicates the start point of the relevant transmitter, and the values at other points are almost zero. Consequently, the estimation for all the time offsets can be detected simultaneously, and the ITDs between different transmitters can be calculated by

$$ITD_{m,n} = \hat{\tau}_n - \hat{\tau}_m - D_m - D_n \qquad m,n = 1,2,\cdots,N_t, \tag{10}$$

where $ITD_{m,n}$ denotes the ITD between the mth transmitter and the nth transmitter.

IV. Performance Evaluation and Discussion

TABLE 1
SIMULATION PARAMETERS

Parameter	Value
Bandwidth	5 MHz
Sampling rate	7.68 MHz
Number of transmitters and receivers (N_t and N_r)	$N_t = 2$ $N_r = 1$
Inter-Transmitter Delay ($ITD_{m,n}$)	$ITD_{1,2} = 0,10,100$
Cyclic-Shift Length (D_i)	$D_1 = 0$ $D_2 = 20$
OFDM Symbol Length (N)	$N = 512$
CP Length (N_g)	$N_g = 48$
Zero Power Length (L_0)	$L_0 = 952$
Weight Factor (w_i)	$w_1 = 1$, $w_2 = j$
Channel	AWGN and ITU M.1225 Channel A

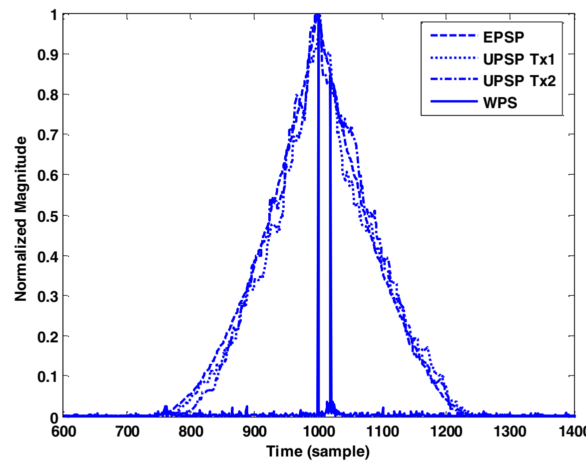

Fig. 2. Comparison of the timing synchronization metric $M_i(d)/\arg\max(M_i(d))$ with $ITD_{1,2} = 0$, at SNR=10dB.

The performance of the proposed timing synchronization method is evaluated for both centralized and distributed systems in this section. The performance of the conventional synchronization methods EPSP and UPSP will be studied and compared with the proposed method. The simulation parameters are listed in Table 1.

Using the parameters listed in Table 1, the performance of a two-transmitter one-receiver system employing EPSP, UPSP and WPS is investigated. When EPSP is applied, L_{SP} is set to be 256. When utilizing UPSP for the timing synchronization, 256 and 253 are chosen for $L_{SP,1}$ and $L_{SP,2}$, respectively. Therefore, the correlation lengths of the three methods are almost the same.

For comparative purposes, three optional values 0, 10, 100 are discussed for ITD. When the ITD is zero, it means there is no delay between the two transmitters. The data from the transmitters arrive at the receiver at the same time, and the system is considered to be a centralized one, otherwise, it may be described under the distributed scenario. As shown in Fig.2, under the centralized MIMO-OFDM transmission scenario, the traditional EPSP using the same sequence for different transmitters can give a clear spike to locate the start of the synchronization sequence at the receiver. However, the values around the correct starting point are almost the same, so the points around the correct point may be mistaken for the correct one when the SNR is low, which makes the accuracy of this method not be so high. The UPSP uses various sequences for different transmitters, and the sequences add with noise at the receiver. The interference of different sequences leads to poor estimation accuracy under the centralized scenario. Compared to the previous two methods, the WPS can obtain two sharp pulses for the two transmitters, and the distance of the two pulses is $D_2 - D_1$. Different from EPSP and UPSP, the correlation values of WPS around the correct start point are almost zero, so the probability of mistaking the points around

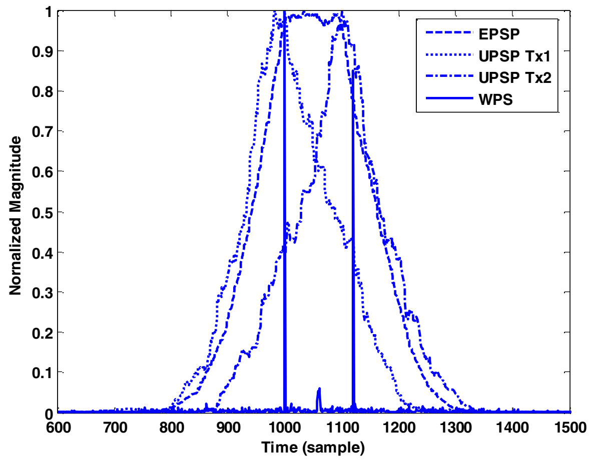

Fig. 3. Comparison of the timing synchronization metric $M_i(d)/\arg\max(M_i(d))$ with $ITD_{1,2}=100$, at SNR=10dB.

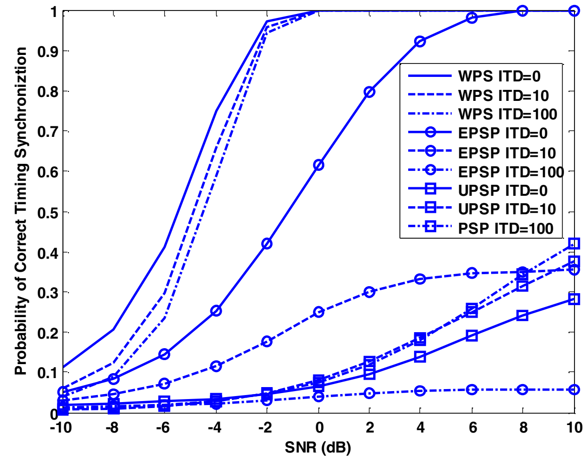

Fig. 5. The probabilities of correct detection using different timing synchronization methods.

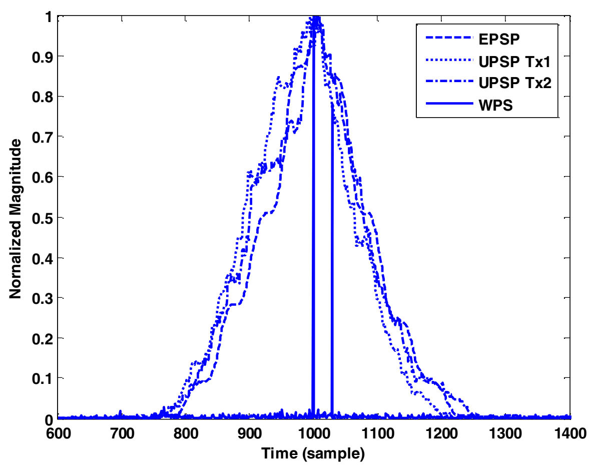

Fig. 4. Comparison of the timing synchronization metric $M_i(d)/\arg\max(M_i(d))$ with $ITD_{1,2}=10$, at SNR=10dB.

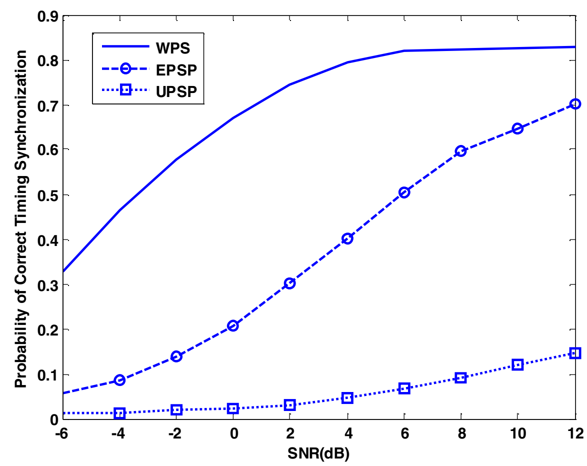

Fig. 6. The probabilities of correct detection using different timing synchronization methods with $ITD_{1,2}=10$ in multipath channel.

for the correct point is much lower, and the accuracy of WPS is accordingly higher than that of the other two.

In Fig.3, we can see when the value of ITD is 100, the correlation results of EPSP have a plateau between the start points of the two transmitters. In other words, the points of the plateau have equal chance to be considered as the start points. This means that EPSP is not able to differentiate the start of different transmitters in distributed systems. Upon invoking two individual estimators at the receiver, the ITD may be identified by UPSP. It can be found that when UPSP synchronization approach is utilized, the synchronization sequences of other transmitters do not contribute to the summation of the correlation. More explicitly, the UPSP can mitigate the interference between different synchronization sequences when the ITD is large enough. However, from Fig.4, it shows that with the reduction of inter-transmitter delay, the robust of UPSP is reduced quickly. When the value of ITD is 10, the spikes for different transmitters can not be distinguished clearly. As shown in Fig.3 and Fig.4, the proposed WPS approach is demonstrated with excellent performance. No matter what value of the ITD, two pulses can be detected consistently by WPS, and the ITD can be calculated from (10).

In Fig.5, the probability of correct timing synchronization in AWGN is evaluated. As it is readily apparent in the figure, upon utilizing the proposed WPS method, it turns out that the accuracy of timing synchronization is improved greatly. No matter what value of the ITDs, WPS can find the exact start and achieve probabilities of the successful detection nearly 100% at $SNR=0dB$, while the traditional EPSP and UPSP methods can only locate the positions within half of a CP length away from the start points. Furthermore, from the analysis and the demonstration, EPSP can be only utilized under the centralized scenario, and when ITDs exist, it becomes unreliable. As shown by the curves, UPSP is able to find the individual time offset for the distributed systems at large ITDs, but unable to give successful detection in centralized systems. Fig.6 illustrates the simulation results in multipath channel. Compared to EPSP and UPSP, significant performance improvement is obtained by using the proposed WPS method.

V. CONCLUSION

In this contribution, a novel time synchronization method is proposed for MIMO OFDM systems. Based on weighted phase-shift CAZAC sequences, the synchronization sequence can be utilized to detect the time offsets for different transmitters. Simulations illustrate the WPS method can provide high accuracy in both centralized and distributed systems. Especially, when small ITDs are taken into account, the method can achieve excellent performance in distinguishing the ITDs without extra computational complexity.

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