A Novel Compact Preamble Structure for Timing Synchronization in MIMO-OFDM Systems Using CAZAC Sequences

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***Abstract*— To increase the throughput of transmission systems, MIMO-OFDM technology allows for a better reach and rate of transmission and improves the reception. The synchronization between the transmitter and the receiver has become a big challenge. A bad timing synchronization causes the loss of a lot of information in a MIMO-OFDM system. In this paper, we propose a novel compact preamble structure based on orthogonal CAZAC sequences. Simulations results show that the proposed solution presents a good performance at a low SNR in AWGN and multipath fading Rayleigh channels.**

Keywords- MIMO-OFDM system; Timing synchronization; CAZAC sequences; Compact preamble.

I. INTRODUCTION

The world of wireless communications and mobile communication is currently at a very important crossroads in its evolution. This crossroads introduces a variety of challenges such as multi-path signal reflections, and interference. These can reduce the performance of a receiver. To address these challenges, Orthogonal Frequency Division Multiplexing (OFDM) modulation combined with Multiple Input-Multiple Output (MIMO) is proposed in 802.11n [1].

The OFDM [2]-[5] is a transmission technique of distributing symbols on multiple orthogonal carrier frequencies. To transmit a signal, OFDM divides a frequency range into several closely spaced sub-carrier frequencies to carry data thanks to the Fast Fourier Transform's algorithm (FFT). The Inverse Fast Fourier Transformer (IFFT) algorithm is also used to demodulate the message at the receiver.

The main advantage of OFDM system is the orthogonality between subcarriers. The orthogonality of frequencies is primordial to eliminate the Inter Carrier Interference (ICI). The ICI occurs, especially, when the duration of a symbol is short compared to the delay spread involved by the channel. On the other hand, it should be noted that the most important disadvantage of the OFDM is the sensitivity to Doppler shift and frequency synchronization problems.

MIMO technique can be divided into two main categories: Space Time Code (STC) and Space Division Multiplexing (SDM). SDM transmits independent data streams over different transmit antennas. SDM can increase throughput rate of wireless communication links between transmitter and receiver. Foshini et al. [6] and Telatar [7] have shown that the theoretical capacity of the MIMO channel, with N_t transmit antennas and N_r receive antennas, increases linearly with min(N_t, N_r). MIMO systems are mainly used to increase the flow of wireless communications. The STC increases the performance by sending redundant data over different transmit antennas [8].

In this paper, we will focus on Space-Time Block Code (STBC) [9] [10]. Several applications, based on MIMO technology, are already considered in wireless and local area networks, and 3rd and 4th generation of mobile network. The combination of MIMO-OFDM systems is proposed in the standard of wireless LAN IEEE 802.11n [1], where the objective is to achieve 100 Mbps for video applications.

One of the main challenges for MIMO-OFDM system is the synchronization between transmitter and receiver. Two types of synchronization are necessary, the timing and the frequency synchronization. The frequency synchronization is based on the detection of the frequency offset between the transmitter and the local oscillator at the receiver [11], while the coarse timing synchronization detects the arrival of the OFDM frame and the fine timing synchronization needed to detect the beginning of OFDM symbols.

In the literature, several synchronization approaches have been proposed for OFDM and MIMO-OFDM systems [12]-[16]. The main idea is the use of good synchronization preamble, at the transmitter, in order to detect the packet arrival, at the receiver.

In this paper, we propose a novel compact preamble structure for timing synchronization in MIMO-OFDM systems using Constant Amplitude Zero Auto-Correlation (CAZAC) sequences. The CAZAC sequences [17] are a class of complex-valued sequences with cyclic autocorrelation equal to zero. The main characteristics of CAZAC sequences are their Zero Auto-Correlation; it means that a CAZAC code is always orthogonal with its cyclic shifted versions. Furthermore, they have constant amplitude. The main benefits of CAZAC sequences are the reduction of

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Inter-Symbol Interference (ISI), they avoid interferences between multiple antennas, and have a lower Peak-to-Average Power Ratio (PAPR). As a result, CAZAC sequences are regarded as preamble for timing synchronization in MIMO-OFDM systems.

Based on this approach, a compact preamble design for synchronization in distributed MIMO-OFDM Systems has been proposed in [18]. Wang et al. [18] have designed training symbols based on exclusive subband. The main drawback of this approach is that this approach is limited when the number of transmit antennas increases. With a Signal to Noise Ratio (SNR) of 15dB, [18] shows a good timing synchronization. On the other hand, our proposed method at low SNR shows a perfect synchronization against the proposed method in [18].

The aim of this paper is to present a novel timing synchronization approach based on CAZAC sequences. Section II briefly describes the MIMO-OFDM system structure based on STBC code. The proposed method and preamble structure are presented in Section III. Simulation results and conclusion are given in Sections IV and V, respectively.

II. SYSTEM MODEL

Like any telecommunications system, MIMO-OFDM system consists of a transmitter, a channel, and a receiver. Figure 1 presents a MIMO-OFDM system with N_t transmit antennas and N_r receive antennas using M-ary Modulation and N subcarriers per transmit antenna. A parallel data stream is generated by data generator's block. The parallel data is encoded according to a QAM constellation and distributed over different sub carriers with OFDM modulator. The output of the OFDM modulator is fed into STBC encoder in order to encode the data stream with Alamouti encoder [9].

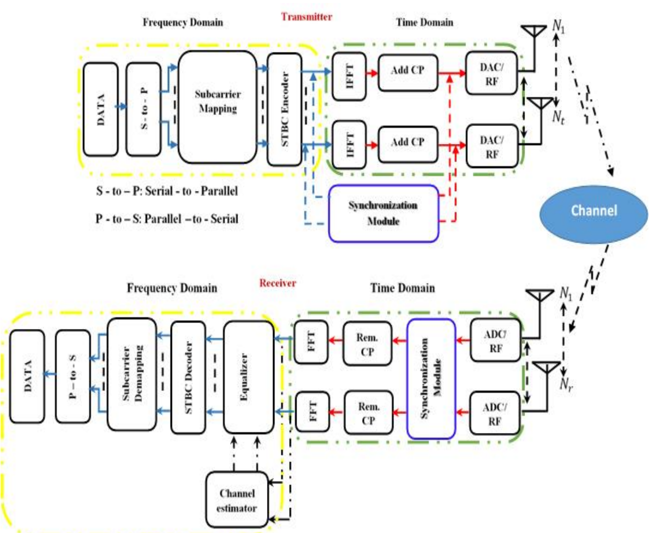

Figure 1 . Transmission system MIMO-OFDM-STBC

Then, we apply the IFFT on these symbols to convert the signal into time domain. A cyclic prefix (CP) is appended to the beginning of each OFDM data symbol, containing a copy of the latest samples.

A synchronization preamble is added at the beginning of each OFDM frame. The preamble may be generated in the time domain [19] or in the frequency domain. In our case, the preamble is generated in the frequency domain. At the receiver, the synchronization is performed in the time domain.

Let $C(l,k)$ denote the transmit data, corresponding to symbol number *l* and carrier number *k*. The OFDM transmit signal $x_i(t)$ from i^{th} transmit antenna, can be expressed as follows:

$$x_i(t) = e^{j(2\pi f_c t + \phi)} \sum_{l=-\infty}^{+\infty} \sum_{k=0}^{K-1} C(l,k)\Psi(l,k,t) \tag{1}$$

Here:

$$\Psi(l,k,t) = \begin{cases} e^{j2\pi \frac{k-K_c}{T_u}\left(t-T_g-lT_s\right)} & lT_s < t < (l+1)T_s \\ 0 & t < lT_s, (l+1)T_s < t \end{cases} \tag{2}$$

where *k* is the current carrier number, *K* is the total number of sub-carriers, *l* is symbols numbers, T_s is the length of symbol period ($T_s = T_g + T_u$), T_g is the length of guard-interval period, T_u is the length of effective symbol period, f_c is center frequency of RF signal, K_c is the carrier number corresponding to center frequency of RF signal, and ϕ is the carrier phase.

The multipaths fading channel between transmit antenna T_i and receive antenna R_j is given by:

$$h_{i,j}(t) = \sum_{p_{ij}=1}^{P_{ij}} \left[\alpha_{p_{ij}} . \delta_{p_{ij}}\left(t - \tau_{p_{ij}}\right)\right] \tag{3}$$

where $i = 1, 2, \cdots, N_T$, $j = 1, 2, \cdots, N_R$, P_{ij} is the number of multipaths between the transmit antenna T_i and the receive antenna R_j , and $\alpha_{p_{i,j}}, \delta_{p_{i,j}}$ are respectively the gain and the propagation delay of the path p_{ij} .

At the receiver, a synchronization module is presented in time domain, in order to detect the beginning of frame and then the beginning of useful OFDM symbols. After

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good timing frame synchronization, a CP removal block is presented to remove the cyclic prefix, because it has no value as information. The FFT is applied to work in the frequency domain. The output of the FFT is fed into a STBC-Alamouti decoder. In order to retrieve the digital data, the received signal is demodulated, using OFDM demodulator.

The transmitted signal from i^{th} transmit antenna undergoes fading by the channel before reaching the j^{th} receive antenna. Let the received signal r_j be:

$$r_j(t) = \sum_{i=1}^{N_t} h_{ij}(t,\tau) * x_i(t)\, e^{-j(2\pi f_c t + \phi)} + n_{ij}(t) \qquad (4)$$

$$r_j(t) = \sum_{i=1}^{N_t} \sum_{p_{ij}=1}^{P_{ij}} x_i(t) * \alpha_{p_{ij}} . \delta_{p_{ij}}\left(t - \tau_{p_{ij}}\right) e^{-j(2\pi f_c t + \phi)} + n_{ij}(t) \qquad (5)$$

where h_{ij} is the channel between the transmit antenna T_i and the receive antenna R_j, τ is the propagation delay for the different channels paths, x_i is the OFDM transmitted signal, * is the convolution, and n_{ij} is the Additive White Gaussian Noise (AWGN) noise between T_i and R_j.

III. PROPOSED METHOD

The proposed frame timing synchronization method aims to estimate the beginning of the OFDM received frame and to detect the beginning of OFDM symbol. Our timing synchronization method relies on sending a preamble structure performed in the frequency domain, as shown in Figure 2.

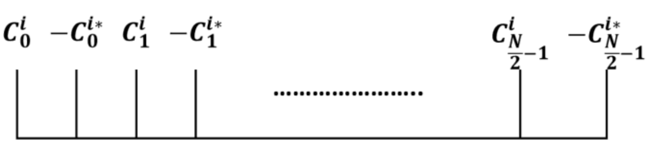

Figure 2. Preamble Structure in Frequency Domain

The combination of a CAZAC sequence with its minus conjugate (-Conj) gives a time-domain complex envelope form that have a good autocorrelation and cross-correlation functions. This combination does not destroy the orthogonality between subcarriers, and it retains the orthogonality between different transmit preambles over different transmit antennas. The preamble structure in time domain is presented in Figure 3.

Different orthogonal preambles are transmitted on each transmit antenna T_i, as shown in Figure 4. Each preamble contains a CAZAC (C) sequence mapped on the odd subcarrier, and the "-Conj" of C is mapped on the even subcarrier. The length of each sequence L_C is:

$$L_C = L_{FFT}/2 \qquad (6)$$

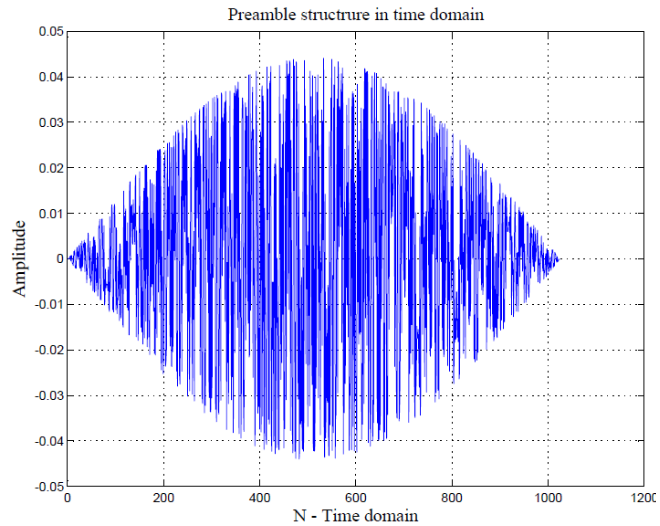

Figure 3. Preamble structure in time domain

Figure 4 represents the different preamble structure over different transmit antennas. The proposed method can be applied regardless of the number of transmit or receive antennas for different Quadrature Amplitude Modulation (M-QAM).

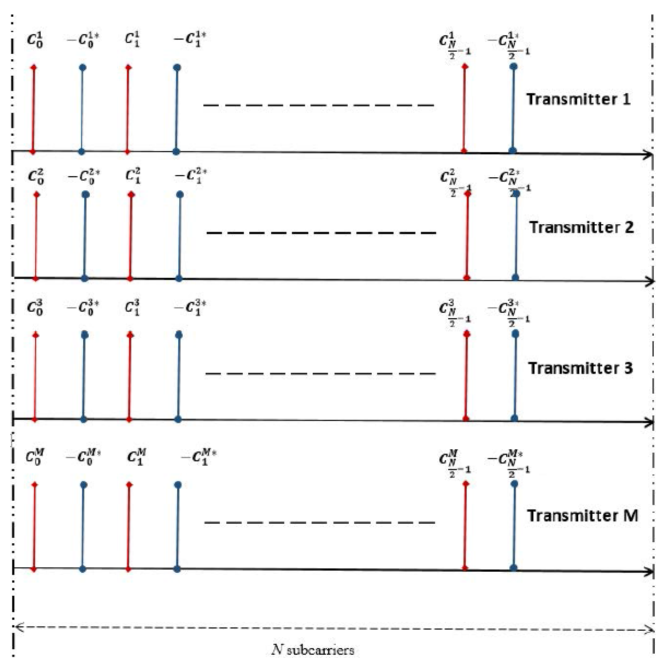

Figure 4. Frame structure in frequency domain

In order to detect the timing synchronization peak, the correlation function $\Re_{r_j seq_j}$ between the received signal r_j

and the local sequence seq_j at the receive antenna R_j is calculated as:

$$\Re_{r_j seq_j}(n) = \sum_{n=1}^{L} \left[r_j(n) * seq_j(n-\tau) \right] \quad (7)$$

where n is the index of the sample, equivalent to the subcarrier index.

IV. SIMULATION RESULTS

The simulations have been done, in both AWGN channel and multipaths fading channel, to evaluate the performance of our proposed preamble against existing preamble. A Single-Input/Single-Output (SISO) and MIMO-OFDM systems up to 8x8 transmit and receive antennas were simulated. An OFDM system with 512 and 1024 subcarriers (L_{FFT}=512, L_{FFT}=1024 resp.) was considered in Rayleigh multipath fading channel with 6 paths sample-spaced with T_S (Sampling Time), suggested by the IEEE 802.11 Working Group [20]. The simulations parameters are summarized in Tables I and II.

TABLE I. SIMULATION PARAMETERS

Simulations parameters	Values
MIMO	up to 8x8
FFT/IFFT Length	1024 & 512
Cyclic Prefix Length (N_C) in samples	$L_{FFT}/4$
Channel Type	Multi-path Rayleigh and AWGN channel
Synchronization sequences	Orthogonal CAZAC
Length of each code L_C	$L_{FFT}/2$
Number of synchronization symbol	1
Number of channel taps between different antennas	6
Signal to Noise Ratio (SNR)	from -5dB to 25dB

TABLE II. THE AVERAGE POWER PROFILE OF THE MULTIPATH RAYLEIGH CHANNEL MODEL

Simulations parameters	Values
Propagation delay between different multipath	[0.Ts, 1.Ts, 2.Ts, 3.Ts, 4.Ts, 5.Ts]
The power of each multipath	[0.8111, 0.1532, 0.0289, 0.0055, 0.0010,0.0002]

At each j[th] receive antenna a correlation function $\Re_{r_j seq_j}$ (7), in time domain, is applied in order to detect the synchronization point. Due to the distribution of CAZAC sequence C and $-C^*$ in each preamble, the correlation between received signal and the local sequence may give a high peak's value.

By correlating the received signal r_j with a local sequence seq_j at each receive antenna R_j, a timing synchronization estimate ($\hat{ind}_n$) is presented and given by:

$$\hat{ind}_n = \arg\max_n \left\{ \left\| \Re_{r_j seq_j}(n) \right\| \right\} \quad (8)$$

The $\hat{ind}_n$ is the timing estimate where n is considered as the timing synchronization point.

The probability of successful timing frame synchronization P_{SYNC} is evaluated in Figures 5 and 6. The figures showed the acquisition probability for different OFDM systems (SISO-OFDM 1x1, MIMO-OFDM up to 8x8), using CAZAC sequences. The lengths of preamble are 1024 and 512, respectively (L_{FFT}=1024, L_{FFT}=512 resp.).

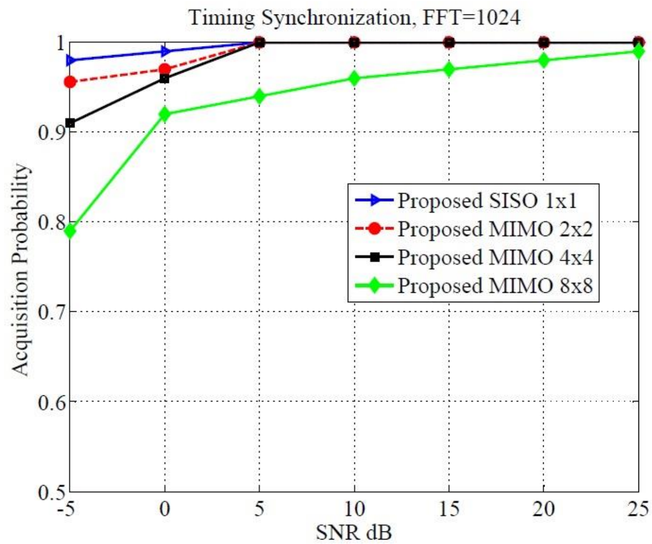

Figure 5. Timing synchronization performance of the proposed method (L_{FFT}=1024)

Figure 5 shows that the system has achieved a synchronization probability over ***95%*** at an SNR=-5dB for both SISO-OFDM and MIMO-OFDM 2x2 systems. For a MIMO-OFDM 4x4 system the P_{SYNC} > 95% at an SNR=0dB. On the other hand, for MIMO-OFDM 8x8 system the acquisition probability P_{SYNC} reaches 90% at an SNR=0dB.

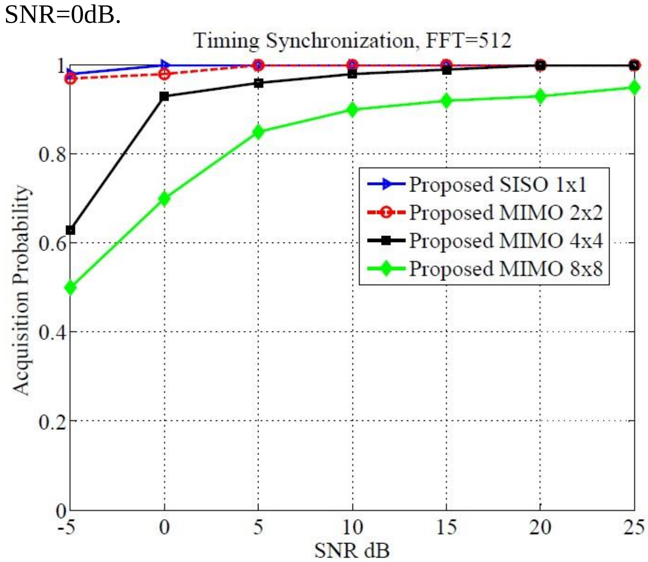

Figure 6. Timing synchronization performance of the proposed method (L_{FFT}=512)

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In Figure 6 and for L_{FFT} = 512, it should be mentioned that the acquisition probability P_{SYNC} is greater than 99% for both SISO-OFDM and MIMO-OFDM 2x2 systems at an SNR=-5dB, and P_{SYNC}>90% for MIMO-OFDM 4x4 system at an SNR=0dB. For MIMO-OFDM 8x8 system the P_{SYNC} reaches 80% at an SNR=3dB.

For MIMO-OFDM systems, the limitations of all timing synchronization methods, are the large number of transmit antennas and the length of the synchronization preamble.

The simulation results of our proposed method (Figure 5) show a good performance in terms of timing synchronization acquisition probability for MIMO-OFDM system up to 8x8, where the length of preamble is equal to 1024 (samples). A degradation of performances in term of P_{SYNC} (Figure 6) is observed when the length of preamble is smaller than the length used in Figure 5. The degradations of P_{SYNC}, for a large number of transmit antennas, are due to the length of the synchronization preamble. Otherwise, at the receiver, as the length of the preamble is longer, the value of the correlation peak is higher.

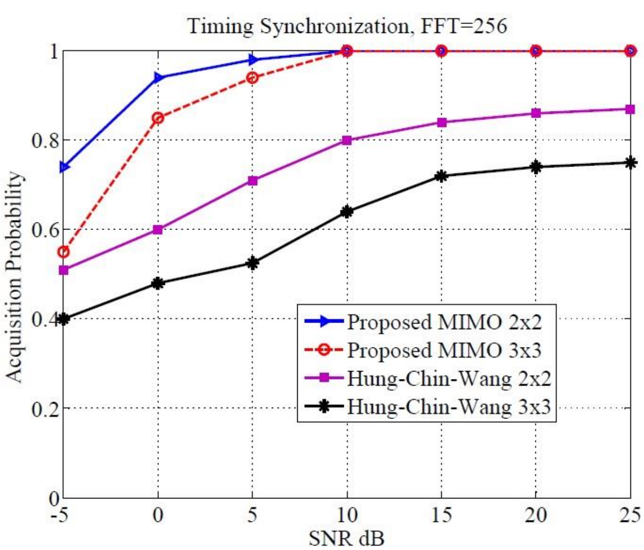

Figure 7. Comparisons between the proposed approach and subband-based preamble [18]

In Figure 7, we compared the performance between our proposed approach and the synchronization scheme of [18], based on a compact preamble design for synchronization, using Zadoff-Chu sequences [17] to generate the training preamble in distributed MIMO-OFDM systems. At a low SNR and by using the same simulation parameters presented in Tables I and II, our proposed method has a good performance against those obtained by [18]. The acquisition probability P_{SYNC} of our method is greater than 90% at an SNR > 3dB for both MIMO-OFDM 2x2 and 3x3 system, while the method proposed by [18] shows that the acquisition probability is between 50% and 75% at the same SNR value.

V. CONCLUSION

One of the main challenges in a MIMO-OFDM system is the synchronization. We proposed a novel compact preamble structure, in order to detect the timing frame synchronization. At the receiver, and due to the combination of CAZAC sequence C and $-C^*$, the correlation function between received signal and local sequence shows a good frame detection with a large number of transmit antennas. In comparison to the subband-based preamble timing synchronization method proposed by [18], our approach presents a better timing frame synchronization at a low SNR. This approach can be implemented in MIMO-OFDM systems, with a large number of transmit antennas.

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