Timing Synchronization Method for MIMO-OFDM Systems with CAZAC Sequences

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***Abstract*—Multiple-Input Multiple-Output (MIMO) Orthogonal Frequency Division Multiplexing (OFDM) systems are very sensitive to carrier frequency offset (CFO) and timing synchronization. In this paper, a new timing synchronization preamble designed for MIMO-OFDM systems is presented. Constant Amplitude Zero Auto Correlation (CAZAC) sequences are used in order to construct this preamble. CAZAC sequence has a sharp correlation peak and zero side lobes. Simulation results show that the proposed method presents a good performance at a low Signal to Noise Ratio (SNR) in AWGN and multipath fading Rayleigh channels.**

***Keywords*-MIMO-OFDM systems; Timing Synchronization; CAZAC sequences; orthogonal preamble.**

I. INTRODUCTION

Wireless communications can be regarded as the most important development that has an extremely wide range of applications. In this new information age, high data rate and reliability features are required for any wireless communication system. MIMO-OFDM (Multiple Input Multiple Output - Orthogonal Frequency Division Multiplexing) is the most recent wireless broadband technology. This technology has gained great popularity for its capability of high rate transmission and its robustness against multi-path fading and other channel impairments. Therefore, the combinaison between MIMO and OFDM systems is proposed in 802.11n [1].

The OFDM [2] became a very popular multi-carrier modulation technique for transmission of signals over wireless channels. It converts a frequency-selective fading channel into different parallel flat fading sub-channels, thanks to the FFT's algorithm (Fast Fourier Transform) [3]. The inverse FFT algorithm (IFFT) [3] is also used to demodulate the message at the receiver. Hence, the bandwidth is utilized efficiently in OFDM systems without causing the Inter-Carrier Interference (ICI). OFDM combines multiple low-data-rate subcarriers into high-data-rate with a long symbol duration in order to eliminate the Inter-Symbol Interference (ISI).

MIMO exploits the space dimension to improve wireless systems capacity, range and reliability. It offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. MIMO achieves this goal by spreading the same total transmit power over the antennas to achieve an array gain that improves the spectral efficiency (Spatial Multiplexing (SM)) or to achieve a diversity gain that improves the link reliability (Space Time Coding (STC)).

The SM transmits independent data rates over different N_t transmit antennas in order to increase the throughput between the transmitter and the receiver. Foshini [4] has 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). The STC is increasing the performance by sending redundant data over different transmit antennas [5]. In this paper, the MIMO-OFDM system is based on the STC technique. In order to improve the link reliability, we will focus on Space-Time Block Code (STBC) Alamouti code [6] [7].

A major challenge for MIMO-OFDM system is the synchronization between transmitter and receiver. Two types of synchronization are necessary, namely, the timing and the frequency synchronization. The coarse timing synchronization is to detect the beginning of the OFDM frame and the fine timing synchronization is used for coherent detection of OFDM symbols. The frequency synchronization is to correct the phase error caused by the mismatch of the local oscillator (LO) between transmitter and receiver [8]. In this paper, we will focus on timing synchronization.

In the literature, several synchronization approaches have been proposed for MIMO-OFDM systems [9] [10]. Most of the timing synchronization methods are preamble based. Therefore, the synchronization preamble should have a good correlation function in order to detect the packet arrival at the receiver.

In this work, based on [11], we propose a new timing synchronization method for MIMO-OFDM systems with CAZAC sequences. Furthermore, Constant Amplitude Zero Auto-Correlation (CAZAC) sequence [12] has constant amplitude and zero autocorrelation for all non-zero shifts. The main characteristics of CAZAC sequences are their correlation functions. They have a good autocorrelation function and their

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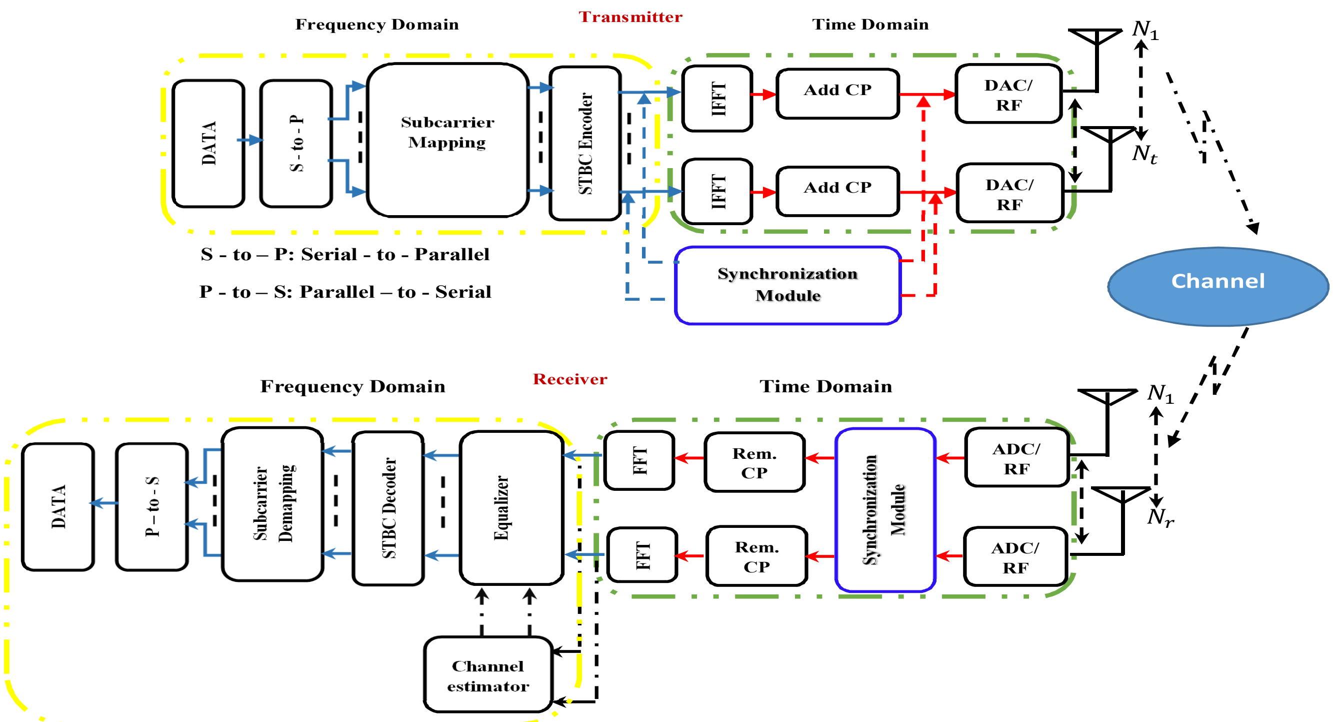

Figure 1. Transmission system MIMO-OFDM-STBC

crosscorrelation function is near zero. Due to their orthogonality, CAZAC sequences reduce inter-code interference between multiple antennas and have a lower Peak-to-Average Power Ratio (PAPR). As a result, CAZAC sequences are regarded as optimum preamble for timing synchronization in MIMO-OFDM systems.

Based on CAZAC sequences, a compact preamble design for synchronization in distributed MIMO-OFDM systems has been proposed in [10]. Training symbols, based on exclusive subband, have designed. The main drawback of this approach is the number of transmit antennas. When this number is increased, the length of the synchronization sequence decreases, and hence, the timing synchronization performance decreases. As result, [10] shows a good timing synchronization with an SNR of 15dB. Furthermore, using the same simulation parameters and the same propagation channel delay, our proposed method shows a perfect timing synchronization against the proposed method in [10] at low SNR.

The aim of this paper is to present a new timing synchronization method for MIMO-OFDM systems with CAZAC sequences. Section II briefly describes the MIMO-OFDM system structure based on STBC. Our proposed method and preamble structure are presented in Section III. Simulation results and conclusion are done in Section IV and V respectively.

II. System Model

The combinaison of MIMO and OFDM systems is one of the most effective techniques to improve spectral efficiency of radio communications. In Figure 1, we consider a MIMO system using OFDM modulation and N_{sc} subcarriers per transmit antenna, where the transmitter and receiver are respectively provided with N_t and N_r antennas ($N_t, N_r \in \{2, 4, 8\}$).

In the following, we describe the MIMO-OFDM system presented in Figure 1.

A parallel data stream is passed through a digital modulator. This modulator encodes the data stream with 16-QAM constellation. The complex symbols are then fed into an STBC encoder in order to encode the data stream with Alamouti encoder. Then, symbols pass through the OFDM modulator. This modulator can be done by using a simple Inverse Fast Fourrier Transform (IFFT) algorithm. In which, the output signal of OFDM modulator, is in time domain. After the IFFT, a Guard Interval (GI) block is presented in order to append the Cyclic Prefix (CP) at the beginning of each OFDM symbol. It refers to a copy of the last portion of the OFDM symbol appended to the front of the symbol, in order to reduce the ISI. Letting T_s is the total symbol period ($T_s = T_g + T_u$), T_g is the period of cyclic prefix, T_u is the period of useful data.

The synchronization block is used in order to insert a known synchronization preamble at the beginning of each OFDM frame. This block could be presented in time domain [13] or in frequency domain [11]. In this paper, we focus in the second approach. At the receiver, the synchronization is performed in the time domain.

The second part of MIMO-OFDM system is the receiver.

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The first block of the receiver is the synchronization block. This block is presented in time domain. After a good synchronization, a CP removal block is applied in order to remove the CP from the beginning of each OFDM symbol. The OFDM symbols are demodulated using FFT algorithm. Equalizer and channel estimator are the first two blocks in frequency domain in order to estimate and detect the channel coefficients. After equalization, the STBC encoder is implemented using Alamouti decoder. After the QAM demodulator, we get the data stream.

A. Transmitted signal

At transmitter, x_k is the symbol on the frequency f_k. The OFDM transmit signal $s_i(t)$ transmitted over i^{th} transmit antenna can be expressed as follows [14]:

$$s_i(t) = \frac{1}{\sqrt{N_{sc}}} \sum_{k=0}^{N_{sc}-1} \Re e \left\{ x_k e^{j.2\pi.f_k.t} \right\} \tag{1}$$

where N_{sc} is the number of sub-carriers.

B. Channel

The transmitted signal reaches the receiver, by undergoing many effects, over several different paths. The multipaths fading channel between transmit antenna T_i, $i \in \{1, N_t\}$ and receive antenna R_j, $j \in \{1, N_r\}$, is written as:

$$h^{i,j}(\tau, t) = \sum_{p=1}^{P_{ij}} \alpha_p(t) e^{-j2\pi f_k \mathcal{T}_p(t)} .\delta\left[\tau - \tau_p(t)\right] \tag{2}$$

where $\alpha_p(t)$ is the attenuation factor for the signal received on the p^{th} path with the propagation delay $\tau_p(t)$.

C. Received signal

The transmitted signal $s_i(t)$ from i^{th} transmit antenna undergoes fading by the channel before reaching the j^{th} receive antenna. The received signal $r_j(t)$ is written as:

$$\begin{aligned} r_j(t) &= \sum_{i=1}^{N_t} \left[h^{i,j}(\tau, t) \star x_i(t) \right] + n_{ij}(t) \\ &= \frac{1}{\sqrt{N_{sc}}} \sum_{i=1}^{N_t} \sum_{p=1}^{P_{ij}} \left[\alpha_p(t) e^{-j2\pi f_k \mathcal{T}_p(t)} .s_i\left[\tau - \tau_p(t)\right] \right] e^{j2\pi f_k(t)} \\ &\quad + n_{ij}(t) \end{aligned} \tag{3}$$

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, α_p is the attenuation for the p^{th} path, $s_i(t)$ is the OFDM transmitted signal, P_{ij} is the number of path between T_i and R_j and n_{ij} is the AWGN noise between T_i and R_j.

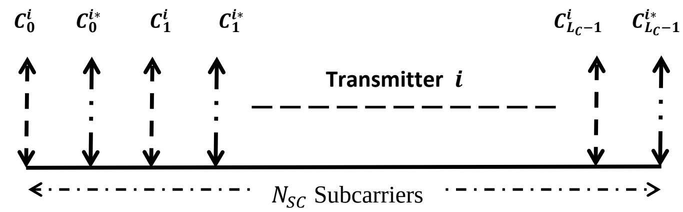

Figure 2. Preamble Structure in Frequency Domain

III. Proposed Method

Based on Rachini et al. [11], a new timing synchronization preamble is presented, in this section. This structure is used in order to estimate the beginning of the OFDM received frame and to detect the beginning of useful OFDM symbols in each frames. This preamble structure is generated in the frequency domain, as shown in Figure 2.

Let i is the transmit antenna in MIMO-OFDM system and C is a CAZAC sequence. C is given by the following equation:

$$C(k) = \begin{cases} e^{j\left(\dfrac{\pi M k(k+1)}{L_C}\right)} & \text{if } L_C \text{ is odd} \\ e^{j\left(\dfrac{\pi M k^2}{L_C}\right)} & \text{if } L_C \text{ is even} \end{cases} \tag{4}$$

where $L_C = L_{FFT}/2$ is the length of the CAZAC sequence, $n \in \mathbb{N}$, $M \in \mathbb{N}$ is a prime number with L_C and $k \in \{0, L_C - 1\}$ is the index of the sample.

In this structure, we combined a CAZAC sequence with its $conjugate$. This combinaison gives a time-domain complex envelope form that have a good cross-correlation and autocorrelation functions. This combination retains the orthogonality between different preambles over different transmit antennas. Figure 3 shows the preamble structure in time domain.

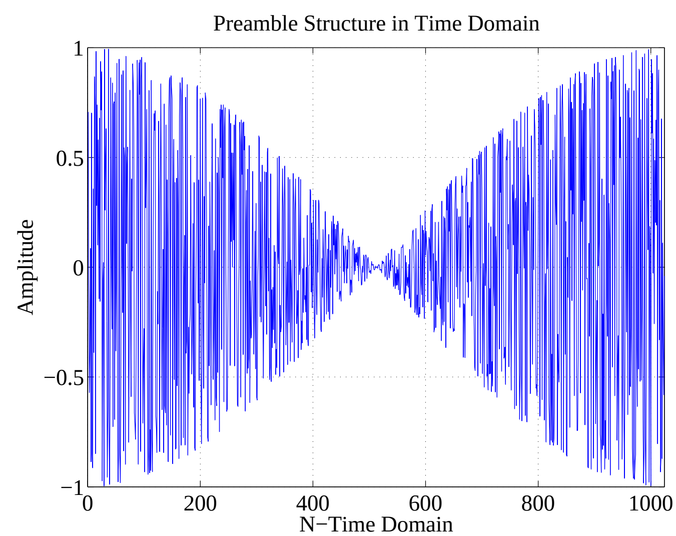

Figure 3. Preamble structure in time domain

Figure 4 represents the different orthogonal preamble structure over different N_t transmit antennas. This preamble structure can be applied regardless of the number of transmit or receive antennas.

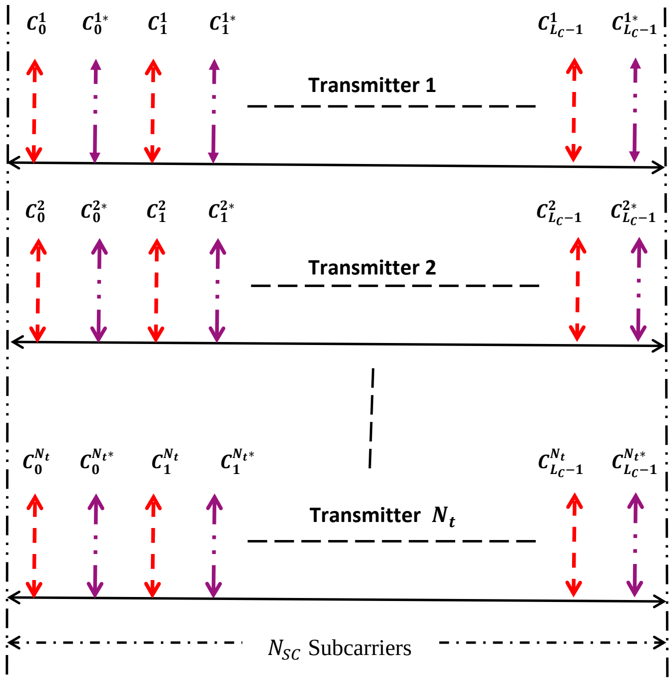

Figure 4. Frame structure in frequency domain

In Figure 4, each preamble contains a CAZAC sequence C mapped on the odd subcarrier and the conjugate of C is mapped on the even subcarrier.

At receiver, a correlation function is applied between the received signal r_j and the local sequence seq_j, in order to detect the timing synchronization peak. The correlation function $\mathcal{R}_{r_j,seq_j}$ is calculated as:

$$\mathcal{R}_{r_j,seq_j}(n) = \sum_{n=1}^{L} [r_j(n) * seq_j(n-\tau)] \quad (5)$$

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

The timing synchronization estimator, $\widehat{ind}_n$, is given by:

$$\widehat{ind}_n = \underset{n}{\operatorname{argmax}}\{\|\mathcal{R}_{r_j,seq_j}(n)\|\} \quad (6)$$

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

IV. Simulation Result

Simulation results have been conducted to validate the performance of the proposed preamble structure, in both AWGN channel and multipaths fading channel. In order to evaluate the performance of our proposed preamble against [10], a SISO-OFDM and MIMO-OFDM systems up to 8×8 transmit and receive antennas were simulated.

A. Simulation parameters

An OFDM system was developed, with 512 and 1024 subcarriers ($L_{FFT} = 512, L_{FFT} = 1024$ resp.) was considered in Rayleigh multipaths fading channel with 6 paths sample-spaced with T_s (Sampling Time) suggested by the IEEE 802.11 Working Group [15]. The parameters used for the simulations are summarized in Tables I and II.

TABLE I: Simulation parameters.

Simulation Parameters	Value
MIMO system	up to 8×8
FFT/IFFT Length	1024 & 512
Cyclic Prefix Length	$L_{FFT}/4$
Channel Type	Multipath Rayleigh and AWGN channel
Sequences	CAZAC
Length of orthogonal code L_C	$L_{FFT}/2$
Number of channel taps between different antennas [15]	6 Taps
SNR over all the OFDM Frame	from 0 dB to 25 dB

TABLE II: The average power profile of the multipath Rayleigh channel model.

Multipath propagation delays [15]	$[0.T_s, 1.T_s, 2.T_s, 3.T_s, 4.T_s, 5.T_s]$
The power of each multipath Tap [15]	[0.8111, 0.1532, 0.0289, 0.0055, 0.0010, 0.0002]

The correlation function $\mathcal{R}_{r_j,seq_j}$, at the j^{th} receive antenna, is calculated in time domain. Due to the frequency distribution of CAZAC sequence, C and C^*, in each preamble, the $\mathcal{R}_{r_j,seq_j}$ may have a high peak's value. The timing synchronization estimator, $\widehat{ind}_n$, detects the beginning of each OFDM received frame once the value of the correlation peak reaches a defined threshold value.

B. Results

In this section, the acquisition probability (P_{SYNC}) is evaluated in term of different value of SNR (Signal to Noise Ratio). P_{SYNC} represents the probability of successful timing synchronization. Simulation parameters are shown in Tables I and II.

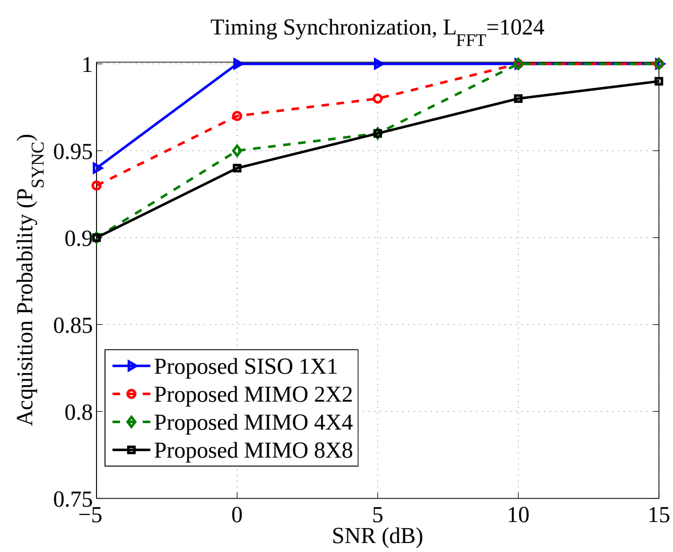

Figure 5. Timing synchronization performance of the proposed method ($L_{FFT} = 1024$)

Figure 5 represents the acquisition probability, in term of SNR, for different OFDM systems (SISO-OFDM 1×1, MIMO-OFDM up to 8×8) using CAZAC sequences where the length of preamble is $L_{FFT} = 1024$.

Figure 5 presents a good timing synchronization for a low SNR. For an $SNR = -5dB$, the $P_{SYNC} \geq 90\%$ for all MIMO-OFDM system up to 8×8. Therefore, for an $SNR = 0dB$, the proposed timing synchronization preamble shows a perfect timing synchronization for SISO-OFDM system. The $P_{SYNC} \geq 97\%$ for MIMO-OFDM system 2×2 for the same SNR. For a MIMO-OFDM system 4×4 the $P_{SYNC} \geq 96\%$ at an $SNR = 5dB$. On the other hand, for MIMO-OFDM system 8×8, the acquisition probability P_{SYNC} reaches 98% at an $SNR = 10dB$.

Figure 6 presents the performance of our synchronization preamble of length $L_{FFT} = 512$. In this Figure, the acquisition probability P_{SYNC} is greater than 97% for both SISO-OFDM and MIMO-OFDM 2×2 systems at an $SNR = 0\,dB$. Therefore, $P_{SYNC} \geq 90\%$ for MIMO-OFDM 4×4 system at an $SNR = 0dB$. In the other hand, the P_{SYNC} reaches 80% at an $SNR = 5\,dB$ for MIMO-OFDM system8×8.

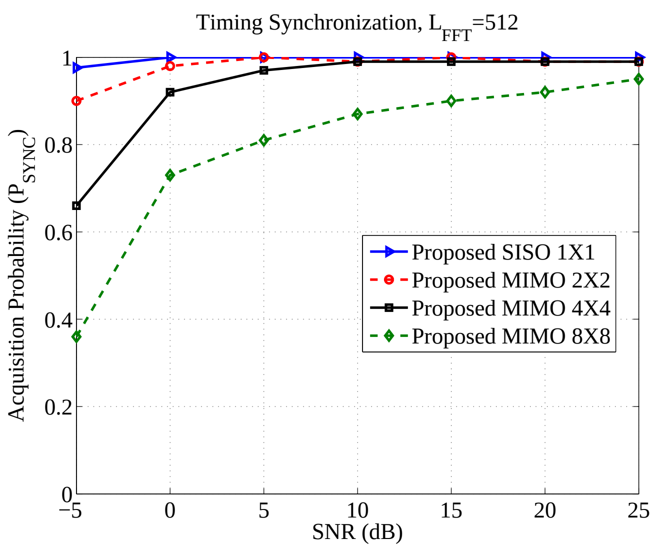

Figure 6. Timing synchronization performance of the proposed method ($L_{FFT} = 512$)

In Table III, the simulation results of Figures 5 and 6, are summarized. It can be shown that the performance of our timing synchronization method increases with the length of L_{FFT}. Moreover, the results of Figure 5 ($L_{FFT} = 1024$) show a good performance against those presented in Figure 6 ($L_{FFT} = 512$).

In order to evaluate the performance of our proposed method, we conducted an extensive comparison of our approach with the synchronization scheme of [10]. Hung and Chin [10] Wang used a subband-based preamble based on CAZAC sequences. The main drawback of this method is the number of transmit antennas. As the number of transmit antennas increases, the length of synchronization sequence, on each transmit antenna, decreases. Therefore, the value of the synchronization peak at the receiver decreases.

Figure 7 presents the performance between our proposed approach and the synchronization scheme of [10]. Simulation results in Figure 7 are done with the simulation parameters of Tables I and II with a synchronization preamble of length $L_{FFT} = 256$, and MIMO-OFDM system 2×2 and 3×3.

TABLE III: COMPARISON BETWEEN THE ACQUISITION PROBABILITY OF DIFFERENT MIMO-OFDM SYSTEMS, IN TERM OF SNR AND LENGTH OF FFT

Acquisition probability			
MIMO-OFDM system	P_{SYNC}	**SNR (dB)**	L_{FFT}
MIMO-OFDM 2x2	≥97%	>0 dB	1024
	≥96%	>0 dB	512
MIMO-OFDM 4x4	≥95%	>0 dB	1024
	≥93%	>0 dB	512
MIMO-OFDM 8x8	≥94%	>0 dB	1024
	≥78%	>0 dB	512

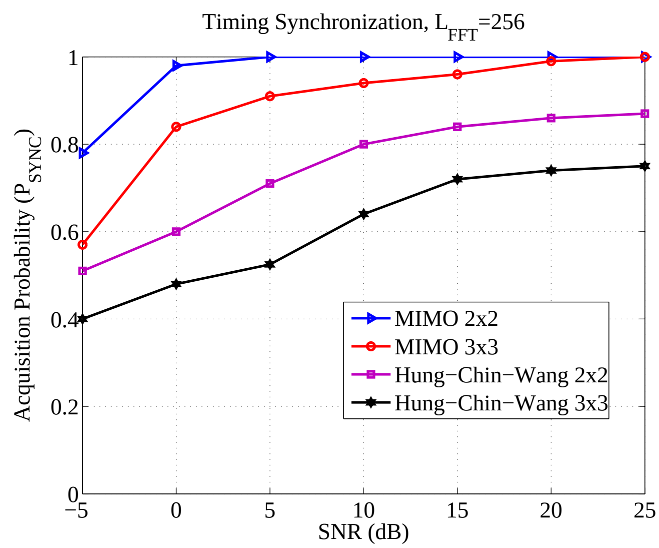

Figure 7. Comparisons between the proposed approach and subband-based preamble [10]

Simulation results of our proposed approach, have a good performance against [10] at a low SNR. The acquisition probability P_{SYNC} for our method is greater than 90% at an $SNR \geq 5\,dB$ for both MIMO-OFDM 2×2 and 3×3 system. Therefore, the proposed method in [10] shows that the acquisition probability is between 0.5 and 0.75 at the same value of SNR.

V. CONCLUSION AND FUTURE WORK

The major challenges in MIMO-OFDM communication systems are the synchronization and the channel estimation. In this paper, we proposed a new timing synchronization preamble structure, based on [11], in order to detect the timing frame synchronization. At the receiver, a correlation function, between received signal and local sequence, is applied in order to detect the beginning of OFDM received frames. Hence, due to the combination of CAZAC sequence C and C^* in the synchronization preamble, the correlation function shows a good frame detection as the number of transmit antenna increases. Simulation results of our proposed method presents good timing frame synchronization against the subband-based preamble timing synchronization method in [10]. Therefore, this preamble structure shows a good timing acquisition probability at a low SNR.

Furthermore, this approach can be implemented with a large number of transmit antennas of MIMO-OFDM system.

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