An OFDM-IDMA Scheme for an Overlay Cognitive Radio System

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***Abstract*—An overlay system is a cognitive radio (CR) system that can transmit at the same time and at the same frequency band of a primary user (PU) system. By using a precoding strategy, an overlay CR system does not interfere with a PU transmission. When an overlay CR system is considered, it is usually assumed that the CR system knows the channel state information, the messages and the codebooks of the PU system. In this paper, we propose an overlay CR system combining orthogonal frequency division multiplexing (OFDM) and interleaved-division multiple access (IDMA). The overlay scheme allows to recover the sent PU signal at the PU receiver. The CR signal is transmitted using an OFDM-IDMA scheme. At the CR receiver, the IDMA iterative process is able to cancel the interference produced by the PU transmitter, and allows the sent CR symbols to be recovered. Unlike other approaches, our system does not require any knowledge of the power of the transmitted signals to recover the CR transmitted signal.**

The simulation of an overlay OFDM-IDMA CR transmission over Rayleigh fading channels shows the efficiency of the proposed scheme.

I. Introduction

Nowadays, the exponential increase of data rates requirements and the number of users in wireless digital communication standards have produced an overload of the frequency spectrum. Cognitive radio (CR) systems have emerged as a new technology to improve the usage of the limited radio bandwidth [1].

By using dynamic spectrum access, a CR system can transmit at the same frequency band that a primary user (PU) system. A CR system is usually based on one of three main paradigms: interweave, underlay and overlay [2].

Interweave CR systems constantly monitors the frequency spectrum, detects the occupancy of it, and communicates over the free frequency bands without interfering with the PU. Several studies have proved that interweave CR systems can improve the spectrum usage [2]. However, is usually not possible in densely populated areas [3]. In addition, the data rate is usually lower than in the underlay and overlay approaches due to the intermittent transmission [4].

In the underlay paradigm it is assumed that the CR system knows the interference caused by its transmitter to the PU receiver. The CR transmission is performed if the interference generated by the CR transmitter is below a noise floor threshold. However, the interference power restriction allows only short-range communication [2].

Unlike underlay systems, the overlay CR systems can transmit at any power. In addition, the data rate is higher than in the interweave and underlay approaches [4]. By using different precoding strategies, the overlay CR systems can transmit at the same time and at the same frequency band of a PU system [2].

When using an overlay system it is usually assumed that the CR system knows the channel state information (CSI), the messages and/or the codebooks of the PU system. Particularly, in [5], Liangping *et al.* use different techniques at the physical layer of the CR system to propose an overlay approach. Nevertheless, the authors do not address the interference produced by the PU transmitter over the CR receiver. In [6], Cardoso *et al.* propose a Vandermonde precoder to cancel the interference produced by the CR transmitter over the PU receiver. In [7], Zhang *et al.* propose a beamforming design for a multiple input single output (MISO) CR system. The authors propose two approaches to calculate the transmitted signal covariance. They aim to maximize the data rate of the CR system and keep the interference power produced in the PU receiver below a pre-established level. The above CR approaches do not cause any interference over the PU system. However, those approaches have a power restriction. To recover the transmitted CR bits at the CR receiver, the authors consider that the power of the transmitted CR signal is higher than the power of the transmitted PU signal. In [3], the authors propose an overlay system based on a frequency and time domain hierarchical modulation. At the CR receiver, the PU signal is decoded first and then it is subtracted from the received signal to obtain the transmitted CR signal. Nevertheless, the authors consider that the transmitted PU signal is stronger than the transmitted CR signal. In [8], Jaewoon *et al.* propose a cognitive beamforming scheme to produce zero-interference over the PU receiver. However, to recover the transmitted CR bits at the CR receiver, the authors consider that the CR system knows the transmitted PU signal.

In this paper, we propose an overlay CR system combining orthogonal frequency division multiplexing (OFDM) and interleaved-division multiple access (IDMA) [9]. Unlike the above approaches, our system does not require any knowledge of the power of the transmitted signals. By using a precoding strategy, the CR system does not cause any interference over the PU. The CR signal is transmitted using an OFDM-IDMA scheme. Finally, at the CR receiver the IDMA iterative process is able to cancel the interference produced by the PU transmitter, and to recover the sent CR symbols.

The paper is organized as follows: system description is presented in section 2. Section 3 shows the OFDM-IDMA CR receiver scheme. Simulation results are presented in section 4

Description	Parameter
between the PU transmitter and the PU receiver	$H^{pu}(k)$
between the CR transmitter and the CR receiver	$\mathbf{H}^{cr}(k) = [H_1^{cr}(k), H_2^{cr}(k), \ldots, H_m^{cr}(k), \ldots, H_M^{cr}(k)]$
between the PU transmitter and the CR receiver	$H^I(k)$
between the CR transmitter and the PU receiver	$\mathbf{H}^G(k) = \left[H_1^G(k), H_2^G(k), \ldots, H_m^G(k), \ldots, H_M^G(k)\right]$

TABLE I. CSI FREQUENCY RESPONSES ASSOCIATED TO THE kTH SUBCARRIER

and conclusions are given in section 5.
In the following, $(.)^T$ denotes the transposition operation. In addition, $\mathbb{E}(.)$ and $Var(.)$ represent the mean and the covariance of $(.)$, respectively.

II. SYSTEM DESCRIPTION

Let us consider a MISO OFDM-IDMA overlay CR system with M antennas that transmits simultaneously with a single input single output (SISO) PU-OFDM system as shown in figure 1. The CR and the PU systems share a bandwidth W that is divided in K subcarriers.

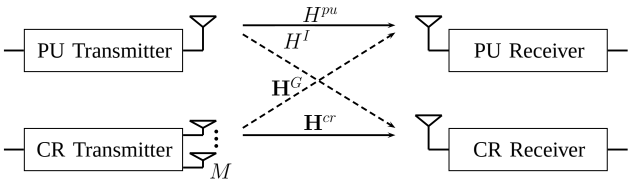

Fig. 1. System description

Previous works have proved that the overlay system does not interfere with the PU system [6], [8]. So in the following, let us focus in the CR system.
The transmitted CR bits are inserted in the IDMA modulator as shown in figure 2. The bits are coded and spread by factor $\mathbb{S}$ in a low-rate encoder (ENC). The interleaver $\prod_u$ is applied and then the bits are modulated [9].

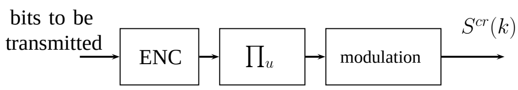

Fig. 2. IDMA modulator, where ENC is the low-rate encoder and $\prod_u$ represents the interleaver

The obtained IDMA symbols are:

$$\mathbf{S}^{cr} = [S^{cr}(0), S(1), \ldots, S^{cr}(k), \ldots S^{cr}(K-1)]^T \tag{1}$$

where $k \in \{0, \ldots K-1\}$ is the subcarrier index.
Then, by knowing the CSI between the CR transmitter and the PU receiver the precoding step is performed. The resulting symbol vector associated to the kth frequency is [8]:

$$\boldsymbol{\mathcal{S}}^{cr}(k) = \mathbf{G}(k) S^{cr}(k) \tag{2}$$

where $\mathbf{G}(k) = [G_1(k), G_2(k), \ldots, G_m(k), \ldots, G_M(k)]^T$ with $m \in \{1, \ldots, M\}$ is the precoding matrix that satisfies:

$$\mathbf{H}^G(k)\mathbf{G}(k) = \mathbf{0} \tag{3}$$

where $\mathbf{H}^G(k) = \left[H_1^G(k), H_2^G(k), \ldots, H_m^G(k), \ldots, H_M^G(k)\right]$ is the frequency response of the CSI between the CR transmitter and the PU receiver, associated to the kth subcarrier. $H_m^G(k)$ is the frequency response of the CSI between the mth antenna of the CR transmitter and the PU receiver, associated to the kth subcarrier. See table I
The OFDM-IDMA CR transmitter operates as shown in figure 3.

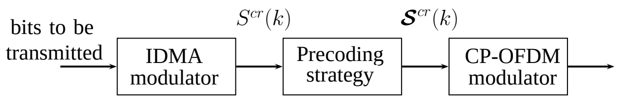

Fig. 3. CR transmitter

Finally, the resulting symbol vector $\boldsymbol{\mathcal{S}}^{cr}(k)$ pass through the cyclic prefix (CP) OFDM modulator and is transmitted over the propagation channel [9].
Then, after passing through the propagation channel, the CR received symbol after the CP-OFDM demodulation is[1]:

$$r^{cr}(k) = \mathbf{H}^{cr}(k)\mathbf{G}(k)S^{cr}(k) + H^I(k)S^{pu}(k) + b(k) \tag{4}$$

where $S^{pu}(k)$ is the transmitted PU symbol associated to the kth subcarrier and $b(k)$ is the fast Fourier transform (FFT) of a zero-mean additive white Gaussian noise (AWGN) with variance σ_b^2. In addition, $\mathbf{H}^{cr}(k) = [H_1^{cr}(k), H_2^{cr}(k), \ldots, H_m^{cr}(k), \ldots, H_M^{cr}(k)]$ is the frequency response of the CSI of the CR link, associated to the kth subcarrier. H_m^{cr} is the frequency response of the CSI between the mth antenna of the CR transmitter and the CR receiver, and can be expressed as:

$$H_m^{cr}(k) = \frac{1}{\sqrt{K}} \sum_{l=0}^{L-1} h_m^{cr}(l) e^{\frac{-j2\pi lk}{K}} \tag{5}$$

where $h_m^{cr}(l)$ is lth coefficient of the CSI of the CR link associated to the mth antenna and L is the maximum length of the CSI of the CR link. $H^I(k)$ is the frequency response of the CSI between the PU transmitter and the CR receiver, associated to the kth subcarrier, and can be expressed as:

$$H^I(k) = \frac{1}{\sqrt{K}} \sum_{l=0}^{L^I-1} h^I(l) e^{\frac{-j2\pi lk}{K}} \tag{6}$$

where $h^I(l)$ is lth coefficient of the CSI between the PU transmitter and the CR receiver and L^I is the maximum length of the CSI between the PU transmitter and the CR receiver.
In the next section, the proposed OFDM-IDMA CR receiver architecture is presented.

III. THE OFDM-IDMA COGNITIVE RECEIVER

In this section, we present the OFDM-IDMA CR receiver. In figure 4, the OFDM-IDMA CR receiver is shown. First,

[1] It is assumed that the received CR signal is synchronized in time and frequency. Time-delays between the incoming signal and the CR receiver can be avoided by using a sufficiently long CP between two adjacent OFDM-IDMA symbols.

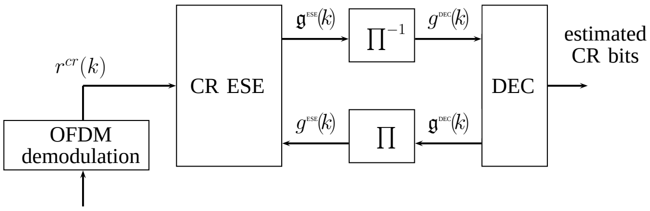

Fig. 4. OFDM-IDMA CR receiver, where $g^{\text{ESE}}(k)$ and $g^{\text{DEC}}(k)$ are the *a priori* LLRs of the symbol $S^{cr}(k)$ used by the ESE and the DEC, respectively.

the CP-OFDM demodulation is performed, which consists in removing the CP and performing an FFT. Then, to estimate the transmitted CR bits, the resulting symbol $r^{cr}(k)$ is inserted in the iterative IDMA receiver, which consists of a CR elementary signal estimator (ESE) and an *a posteriori* probability decoder (DEC) [9].

In the following let us denote $g^{\text{ESE}}(k)$ and $g^{\text{DEC}}(k)$ the *a priori* extrinsic logarithm likelihood ratios (LLRs) of the symbol $S^{cr}(k)$ used by the CR ESE and the DEC, respectively.

Given the output $r^{cr}(k)$ of the OFDM demodulation, the CSI frequency responses $\mathbf{H}^{cr}(k)$ and $H^{I}(k)$, the precoding matrix $\mathbf{G}(k)$, the AWGN variance σ_b^2 and $g^{\text{ESE}}(k)$, the ESE process generates the *a posteriori* LLRs $\mathfrak{g}^{\text{ESE}}(k)$ of the symbol $S^{cr}(k)$. The cognitive characteristic of the CR system permits to obtain the pilot signal from the PU transmitter, and know the[2] CSI $H^{I}(k)$. Then, $\mathfrak{g}^{\text{ESE}}(k)$ is deinterleaved to obtain the values of $g^{\text{DEC}}(k)$ that is inserted in the DEC. The DEC generates the *a posteriori* LLR $\mathfrak{g}^{\text{DEC}}(k)$, that are then interleaved to obtain the value of $g^{\text{ESE}}(k)$. This process is iterated several times to estimate the transmitted CR bits.

Let us now detail the CR ESE process. The proposed IDMA receiver may be applied to real and complex signals [9]. For the sake of simplicity, let us consider a BPSK modulation for both systems, the CR and the PU system. The symbol $S^{cr}(k)$ is treated as a random variable, and its mean and its covariance are computed as follows:

$$\begin{aligned} \mu^{cr}(k) &= \mathbb{E}(S^{cr}(k)) = \tanh\left(\frac{g^{\text{ESE}}(k)}{2}\right) \\ \upsilon^{cr}(k) &= Var(S^{cr}(k)) = 1 - (\mu^{cr}(k))^2 \end{aligned} \tag{7}$$

For the initialization process $g^{\text{ESE}}(k) = 0$ for $i = 1$, where i denotes the iteration number with $i \in \{1, \ldots, \mathcal{I}^{max}\}$. It is assumed that $S^{cr}(k)$ are independent and identically distributed. Then, by applying the central limit theorem a Gaussian approximation can be considered [10] for $\varsigma^{cr}(k) = H^{I}(k)S^{pu}(k) + b(k)$ and $r^{cr}(k)$. Thus, they can be characterized by their mean and variance:

$$\begin{aligned} \mathbb{E}(\varsigma^{cr}(k)) &= \mathbb{E}(r^{cr}(k)) - \mathbf{H}^{cr}(k)\mathbf{G}(k)\mu^{cr}(k) \\ Var(\varsigma^{cr}(k)) &= Var(r^{cr}(k)) - (\mathbf{H}^{cr}(k)\mathbf{G}(k))^2\upsilon^{cr}(k) \end{aligned} \tag{8}$$

where

$$\begin{aligned} \mathbb{E}(r^{cr}(k)) &= \mathbf{H}^{cr}(k)\mathbf{G}(k)\mu^{cr}(k) + H^{I}(k)\mu^{pu}(k) \\ Var(r^{cr}(k)) &= \sigma_b^2 + (\mathbf{H}^{cr}(k)\mathbf{G}(k))^2\upsilon^{cr}(k) \\ &\quad + (H^{I}(k))^2\upsilon^{pu}(k) \end{aligned} \tag{9}$$

where $\mu^{pu}(k)$ and $\upsilon^{pu}(k)$ are the mean and the variance of $S^{pu}(k)$. For the initialization process $\mu^{pu}(k) = 0$ and $\upsilon^{pu}(k) = 1$. Unlike a conventional OFDM-IDMA receiver [9], the distortion is a contribution of the PU signal and the AWGN.

The CR ESE calculates the values of the mean and the variance of $S^{pu}(k)$ as follows:

$$\begin{aligned} \mu^{pu}(k) &= \mathbb{E}(S^{pu}(k)) = \tanh\left(\frac{g^{pu}(k)}{2}\right) \\ \upsilon^{pu}(k) &= Var(S^{pu}(k)) = 1 - (\mu^{pu}(k))^2 \end{aligned} \tag{10}$$

where

$$g^{pu}(k) = 2H^{I}(k) \times \frac{r^{cr}(k) - \mathbb{E}(\varsigma^{pu}(k))}{Var(\varsigma^{pu}(k))} \tag{11}$$

and

$$\begin{aligned} \mathbb{E}(\varsigma^{pu}(k)) &= \mathbb{E}(r^{cr}(k)) - H^{I}(k)\mu^{pu}(k) \\ Var(\varsigma^{pu}(k)) &= Var(r^{cr}(k)) - (H^{I}(k))^2\upsilon^{pu}(k) \end{aligned} \tag{12}$$

For the initialization process $g^{pu}(k) = 0$ for $i = 1$.

Then, the CR ESE at the ith iteration generates the value of the *a posteriori* LLR as follows:

$$\mathfrak{g}^{\text{ESE}}(k) = 2\mathbf{H}^{cr}(k)\mathbf{G}(k) \times \frac{r^{cr}(k) - \mathbb{E}(\varsigma^{cr}(k))}{Var(\varsigma^{cr}(k))} \tag{13}$$

The output of the CR ESE $\mathfrak{g}^{\text{ESE}}(k)$ is updated and used by the *a posteriori* probability DEC. Then, the output of the *a posteriori* probability DEC are updated to obtain the values of $g^{\text{ESE}}(k)$. It should be noted that the value of $g^{pu}(k)$ is not deinterleaved and is not inserted in the DEC because the PU transmitted bits do not have to be recovered by the CR receiver. The CR ESE process is again performed. Finally, the DEC produce hard decisions to obtain an estimation of the transmitted CR bits during the final iteration $\mathcal{I}^{max}$ [9].

IV. Simulation Results

We consider an OFDM-IDMA CR system that shares a bandwidth $W = 10$ MHz with a PU-OFDM system. The encoder used at the IDMA modulator [9] consists in the insertion of a spreading code with $\mathbb{S} = 64$. BPSK is used to modulate the CR bits and the PU bits. The carrier frequency f_c is 2.6 GHz. The number of antennas of the CR transmitter is $M = 2$. We define the signal-to-noise ratio as SNR $= 10\log_{10}(\frac{\sigma_s^2}{\sigma_b^2})$ where $\sigma_s^2 = \mathbb{E}(|r^{cr}(k)|^2)$. In addition, we define the signal-to-interference ratio (SIR) as SIR$= 10\log_{10}(\frac{\sigma_s^2}{\sigma_I^2})$ where $\sigma_I^2 = \mathbb{E}(|H^{I}(k)S^{pu}(k)|^2)$.

Firstly, we consider a CSI between the PU transmitter and the CR receiver with a maximum length $L^{I} = 12$. In addition, we consider a CSI between the CR transmitter and the CR receiver with the same length $L = 12$. The bandwidth is divided in $K = 1024$ subcarriers for both systems and the SIR= 0 dB. The number of iterations of the IDMA receiver is set at $\mathcal{I}^{max} = 5$. The results in terms of bit error rate (BER) are shown in figure 5. We can see that the results are close to the theoretical value.

Then, a maximum length for both CSIs $L = 10$ and $L^{I} = 10$ are considered. In this case, the results are farther from the theoretical value in comparison with $L = 12$. For a SNR of 4 dB, the BER is 0.092 when a CSI with a maximum length $L = 10$ is considered and is 0.085 when a CSI with a maximum length of $L = 12$ is considered.

[2] It is assumed that the CR receiver is synchronized with the PU system.

The results shown in figure 5 also present the BER when the bandwidth is divided in $K = 512$ subcarriers. It can be seen that the values are far from the theoretical value in comparison when the bandwidth is divided in $K = 1024$ subcarriers.
We can conclude that the diversity of the CSI and the increase in the number of subcarriers improve the performance of the system. The CSI plays the role of the interleaver for the PU transmitter and allows the sent CR signal to be recovered.

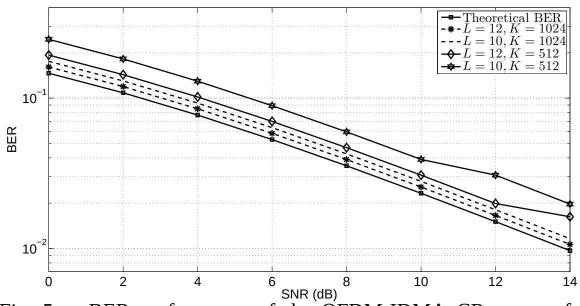

Fig. 5. BER performance of the OFDM-IDMA CR system for different number of subcarriers

In figure 6 the BER performance is also presented for different values of $\mathcal{I}^{max}$. The maximum lengths of the CSIs is $L = 10$ and $L^I = 10$. The bandwidth is divided in $K = 1024$ subcarriers. We can see that for a BER of 10^{-1} the IDMA receiver with $\mathcal{I}^{max} = 5$ outperforms the IDMA receiver with $\mathcal{I}^{max} = 3$ in around 6dB.

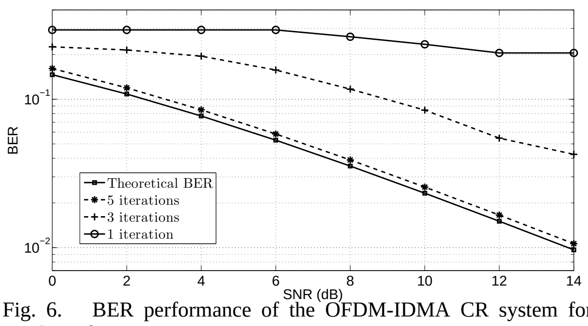

Fig. 6. BER performance of the OFDM-IDMA CR system for different number of iterations

V. CONCLUSION

In this paper an OFDM-IDMA overlay CR system is proposed. Unlike previous proposed works in this field [3], [6], [7], [8], the proposed system does not require any knowledge of the power of the transmitted signals. The MISO overlay scheme allows to recover the sent PU signal at the PU receiver. At the CR receiver, the IDMA iterative process cancel the interference produced by the PU system, and allows the sent CR signal to be recovered. The proposed IDMA receiver may be applied to real and complex signals. However, for the sake of simplicity, in this paper we consider a BPSK modulation. Simulation results show the efficiency of the proposed OFDM-IDMA CR system.

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