Performance Improvements of OFDM Signals Spectrum Sensing in Cognitive Radio

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***Abstract* - This paper addresses the problem of dynamic spectrum access, discussing a new method for spectrum sensing in cognitive radio networks. In particular, an innovative technique for the detection of an OFDM-based primary user signal is here proposed. Performance analysis is carried out in comparison with conventional spectrum sensing method that exploits the autocorrelation coefficients. Unlike the conventional method, our strategy is completely blind and can be applied with no a priori knowledge of any characteristics of the signals of interest. Simulation results have been carried out under operating settings, typical of wireless local area networks.**

***Keywords*-spectrum sensing, dynamic spectrum access, orthogonal frequency division multiplexing, autocorrelation coefficient, cyclix prefix.**

I. Introduction

Driven by the explosion for new wireless services and applications as well as due to the steadily increasing number of wireless users, the demand for radio spectrum has increased dramatically [1], [2]. With almost all the spectrum bands already exclusively allocated, it is becoming extremely hard to find vacant (free) bands to deploy new services or enhance the existing ones [3], [4]. In contrast, measurement of the spectrum occupancy showed that the spectrum usage is concentrated in certain bands, while a significant amount of the spectrum remains unused or is used only sporadically [5]. The under-utilization of spectrum and the inefficiency of the conventional static assignment policy result in the necessity for a new communication paradigm to exploit the existing spectrum bands in a more effective manner. Dynamic Spectrum Access (DSA) is proposed as a possible solution to these inefficiency problems [6]-[8]. In DSA, there is a new category of actors (i.e. secondary or unlicensed providers and users) in addition to the primary (or licensed) ones. Secondary unlicensed systems are allowed to opportunistically employ the unused licensed bands, commonly referred as *spectrum holes* or *white spaces*. Since secondary systems are considered as lower priority users, their fundamental requirement is to avoid interference with primary users. The key enabling technology for DSA is the Cognitive Radio (CR). A CR, built on a Software Defined Radio (SDR) platform, is defined as a context-aware intelligent radio, potentially capable of autonomous reconfiguration by learning from and adapting to the communication environment [9].

Spectrum sensing is the key component of DSA whereby a CR monitors and identifies the spectral bands that are unused by the primary licensed users. Several strategies have been proposed in literature for spectrum sensing [10]. The conventional solution relies on the energy (or power) detector: the detector measures the energy (or power) of the received signal in a certain band, and then compares it with a pre-selected threshold to decide whether a licensed user is present or not [10], [11]. However, in strongly noisy channels the performance of energy detectors suffers a dramatic worsening. Therefore, more sophisticated spectrum sensing strategies have been proposed such as: detection techniques based on cyclostationarity features [12], [13] or on autocorrelation functions [14], [15]. The main idea behind these techniques is to exploit the periodicity of the autocorrelation function of modulated signals in order to distinguish them from the channel noise. Recently, the authors in [16], [17] have proposed an effective method for the detection of an Orthogonal Frequency Division Multiplexing (OFDM) signal. In particular, they exploit the periodicity of the correlation coefficient at delays equal to the symbol length of an OFDM block. The method is quite simple and extremely efficient in terms of computational complexity. Unfortunately, it requires some knowledge about the transmitted signal (e.g. the length of the cyclix prefix). On the other hand, a cognitive radio should be able to operate in many different frequency bands, while detecting the presence of primary signals from various communications standards characterized by different parameters. For example, in the Digital Video Broadcasting-Terrestrial system, different lengths of the cyclic prefix are used [18]. Therefore, effective spectrum sensing strategies should be blind, i.e. they should need no a priori knowledge of the communication scenario.

Addressing some of these issues, this work presents an innovative spectrum sensing strategy for the detection of an OFDM primary user, exploiting the auto-correlation of the signal of interest. The “Rayleigh-ness” test was originally introduced in [19] for code acquisition purposes in a Direct Sequence-Code Division Multiple Access (DS-CDMA) system, while in [20] a modified version of the same test is used for wireless channel modeling. The Rayleigh-ness test aims to state whether a real positive series is a portion of one realization of a Rayleigh-distributed random process. Such a Rayleigh-ness test can be performed to decide on the possible presence of a (statistically relevant) mean of the complex Gaussian model generating both Rayleigh and Rice distributions. Here, we move further proposing an advanced testing method for spectrum sensing in cognitive radio networks. The rationale behind our idea is as follows. The decision whether a primary user is active, or not, can be made on the presence of a non-zero mean value of a Gaussian distributed random variable. This is also equivalent to state whether the observed series is a portion of one realization of a Rayleigh (or Rice) distributed random process. Moreover, we have accordingly modified the conventional Rayleigh-ness test, in order to provide a blind spectrum sensing method, i.e. no assumptions on the system parameters in detecting the primary user are needed in our system. The remainder of this work is organized as follows. In Section II, the system model is depicted and the conventional detection method is discussed. Section III outlines the rationale of our new spectrum sensing strategy, while our simulation results and comparisons are showed in Section IV. Finally the paper's conclusions are briefly depicted in Section V.

II. SYSTEM MODEL

A. Spectrum Sensing for OFDM signals

The OFDM technique has developed into a very popular scheme for wide-band digital wireless communication. For example, it is used in the wireless local area networks standards (i.e. IEEE 802.11x family protocols), in the Long Term Evolution (LTE) as well as in the DVB-T systems. Moreover, it is going to be a key technology for the future of broadband wireless telecommunications [21]. Therefore, it is fairy to assume that many primary users will operate in an OFDM – based system. An OFDM signal consists of the sum of orthogonal narrow-band sub-carriers that are typically modulated by using phase shift keying (PSK) or quadrature amplitude modulation (QAM). An OFDM signal, is constructed by feeding the modulated symbols to an N-points inverse fast Fourier transform (IFFT). The outputs of the IFFT are:

$$c(t) = \frac{1}{\sqrt{T_d}} \sum_{f=0}^{T_d - 1} C(f) e^{j\frac{2\pi f t}{T_d}} \qquad t = 0, \ldots.., T_d - 1 \quad (1)$$

where $\{C(f)\}$ are the modulated symbols to be transmitted over the N sub-carriers, T_d is the OFDM symbol period, t is a discrete time index, and f is a discrete frequency index. They are then converted to a serial stream by parallel to serial conversion and the last T_c symbols are added in front of the block, thus forming a cyclic prefix (CP). The total duration of an OFDM symbol is then $T_s=T_c+T_d$. (see Fig.1) A transmitted OFDM frame may contain several of these blocks.

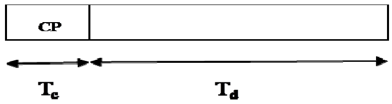

Figure 1. An OFDM block, with CP of length T_c

The task of spectrum sensing is to decide on the presence of a signal of interest in a specific frequency band. In other words, it aims at discriminating between the two testing hypothesis: the H_0 hypothesis, which states the absence of the signal of interest (i.e. a spectrum hole is detected) and the H_1 hypothesis, which conversely states the presence of this signal (i.e. a primary user is detected). Let $s(t)$ be the samples of the transmitted complex OFDM signal, while $n(t)$ are the samples of the additive complex circular Gaussian white noise. The samples of the received signal are expressed by $x(t)=s(t)+n(t)$ under the H_1 hypothesis and $x(t)=n(t)$ otherwise. The samples of the received signal, in both cases, follow a complex Gaussian distribution, as a direct consequence of the central limit theorem. Therefore, the hypothesis testing can be expressed as:

$$\begin{aligned} &H_0 : x(t) \sim N_c\left(0, \sigma_w^2\right) \\ &H_1 : x(t) \sim N_c\left(0, \sigma_w^2 + \sigma_s^2\right) \end{aligned} \qquad (2)$$

where $N_c(\cdot)$ denotes the Gaussian distribution for a complex random variable, while σ_w^2 and σ_s^2 are the variances of the noise and of the OFDM transmitted signal, respectively.

B. Correlation based spectrum sensing

Correlation based techniques, which are already commonly used for hypothesis testing in many different fields [22]-[24], can be effectively applied to the problem of detecting the presence of an OFDM-based primary user in a noisy channel [10],[11].

The presence of the CP gives to the OFDM signals the following well-known characteristic: the autocorrelation coefficients $\rho = E\left[x(t)x(t+\tau)\right] / E\left[x(t)x(t)\right]$ are non-zero at delays equal to $\tau = \pm T_d$, where T_d is the symbol length of an OFDM block with a CP of length T_c and $E[\cdot]$ means expectation operator. The authors in [17] propose a method for the detection of an OFDM signal which is based on this convenient property. Detection is based on the auto-correlation coefficients of the received signal, which should provide a non-zero value in the H_1 hypothesis (i.e. presence of primary signal), and a null value otherwise:

$$\begin{aligned} &H_0 : \rho\left(\pm T_d\right) = 0 \\ &H_1 : \rho\left(\pm T_d\right) = \rho_1 \end{aligned} \qquad (3)$$

where, it can be shown that:

$$\rho_1 = \frac{T_c}{T_c + T_d} \frac{\sigma_s^2}{\sigma_s^2 + \sigma_w^2} \qquad (4)$$

The decision is based on an estimation of the correlation coefficient from a set of M observations (with $M >> T_d$) of the received signal $[x(0), x(1)....x(T_d+M-1)]$. In other terms, the testing variable is expressed as the maximum likelihood estimate of the correlation coefficient [17]:

$$\hat{\rho}_{ML} = \frac{\frac{1}{M}\sum_{t=0}^{M-1} x(t)x(t+T_d)}{\frac{1}{2(M+T_d)}\sum_{t=0}^{M+T_d-1} |x(t)|^2} \tag{5}$$

For large values of M, the testing variable in (5) is asymptotically Gaussian under the two assumptions, because of the central limit theorem. Hence, the hypothesis testing can be written as follows:

$$\begin{aligned} H_0 &: \hat{\rho}_{ML} \sim N\left(0, \frac{1}{2M}\right) \\ H_1 &: \hat{\rho}_{ML} \sim N\left(\rho_1, \frac{\left(1-\rho_1^2\right)^2}{2M}\right) \end{aligned} \tag{6}$$

The test threshold can be now tuned from a straightforward evaluation of the Gaussian integral for a fixed probability of false alarm.

$$v = \frac{1}{\sqrt{M}} erfc^{-1}\left(2\, P_{FA}\right) \tag{7}$$

where P_{FA} is the false alarm probability and $erfc^{-1}()$ is the well-known complementary error function. Moreover, the detection probability (P_D) can be determined by means of the error function under the H_1 hypothesis:

$$P_D = \frac{1}{2} erfc\left(\sqrt{M}\,\frac{v-\rho_1}{1-\rho_1}\right) \tag{8}$$

In the case that the CP is known to the receiver, the performances of the overall system can be strongly improved. In fact, in this case, and assuming perfect synchronization between the receiver and the transmitter, the test statistics in (6) can be expressed as:

$$\begin{aligned} H_0 &: \rho_{cML} \sim N\left(0, \frac{1}{2M_c}\right) \\ H_1 &: \rho_{cML} \sim N\left(\rho_{c1}, \frac{\left(1-\rho_{c1}^2\right)^2}{2M_c}\right) \end{aligned} \tag{9}$$

with:

$$\rho_{c1} = \frac{\sigma_s^2}{\sigma_s^2 + \sigma_w^2} \tag{10}$$

and $M_c = T_c \cdot N_s$, where N_s is the number of OFDM blocks over which the autocorrelation coefficient is estimated. As a consequence, the mean of the estimate has increased by a factor T_s/T_c under the hypothesis H_1, thus increasing the detection probability. It has to be noted that, even if the CP length may be known to the receiver, since it is related to the communications standard, perfect synchronization between the transmitter and the receiver is not a typical operating case. Hence, we can consider this case an upper bound of the system performances.

III. Proposed Procedure

In this section, we discuss the proposed detection strategy that exploits the autocorrelation of the received signal. The testing procedure is based on the recently introduced "Rayleigh-ness test" [19], [20]. This method was originally proposed for non-coherent initial synchronization (code acquisition) of DS-CDMA systems. This technique aims to state whether a real positive series is a portion of one realization of a Rayleigh-distributed random process. This test is used to determine the presence (or absence) of a useful signal (with the correct code offset) from the observation of the (magnitude of the) cross-correlation samples $|R_k|$ detected at the output of the receiver's matched filter. The statistical distribution of these samples (i.e. a real and positive series) is the Rice probability density function (PDF) in the H_1 hypothesis while it reduces to the Rayleigh PDF otherwise [19]. Such a Rayleigh-ness test can be performed to decide on the presence of a (statically relevant) mean vale μ of a complex Gaussian model generating both a Rayleigh ($\mu = 0$) or Rice ($\mu \neq 0$) distribution. The conventional hypothesis testing for primary user's detection in (6) and (9) follows a similar approach, where the H_0 hypothesis (i.e. absence of a primary user) is accepted when the maximum likelihood estimate of the correlation coefficient has zero mean. Therefore, the decision whether a primary user is active, or not, can be made on the presence of a non-zero mean value of a Gaussian distributed random variable. This is also equivalent to state whether the observed series is a portion of one realization of a Rayleigh (or Rice) distributed random process. Therefore, the Rayleigh-ness test can be effectively applied to the problem of detecting the presence of an OFDM-based primary user in a noisy channel. The main drawback of this procedure is that the Rayleigh-ness test is based on a matched filter correlation. Matched filter is known as the optimal detector in stationary Gaussian noise, but it requires some *a priori* knowledge about the signal of interest.

In cognitive radio scenarios, *a priori* knowledge about signals under investigation is generally very low, and so matched filter detectors are rarely used in practices [25]. Therefore, in order to effectively apply the Rayleigh-ness test for the detection of a primary signal, we need to replace the cross-correlation samples with the auto-correlation samples of the received signal. The testing variable of the new method is then expressed as:

$$X_c = 2\left[\frac{1}{M}\sum_{t=0}^{M-1}\left|x(t)\right|^2\right]^2 - \frac{1}{M}\sum_{t=0}^{M-1}\left|x(t)\right|^4 \tag{11}$$

The testing variable is asymptotically Gaussian. In fact, the first term is the square of an asymptotically Gaussian variable with non-zero mean, whose variance goes to zero like $1/M$. The second term, consisting of a sum of random variables, is asymptotically Gaussian from a direct application of the central limit theorem. The testing variable is the compared to a preselected threshold in order to discriminate between the two hypotheses. The correlation method discussed in Section II is based on the assumption of having some a priori knowledge on the signal of interest. In particular in (6), the symbol duration T_d has to be known, while in (9) even the length of the CP is needed. On the other hand, a cognitive radio should be able to operate in many different frequency bands, while detecting the presence of primary signals belonging to various communications standards. Therefore, effective spectrum sensing strategies should be as blind as possible. The new method addressed in this section has the great advantage of requiring no additional information about the primary user's system, without any noteworthy performance losses, as shown in the results' section.

IV. SIMULATION RESULTS

Several simulations trials have been performed to validate the new method we propose for spectrum sensing, versus the conventional approach, based on the correlation coefficient. The probability of detection of the new detector is evaluated under the CFAR procedure versus Signal-to-Noise-Ratios (SNR) of practical interest. In the reported analysis, a $P_{FA}=10^{-3}$ and white Gaussian noise have been used. Moreover, several Monte-Carlo simulation trials have been implemented to numerically evaluate the detection probabilities of the two methods. Following the same approach of [17], we have considered an OFDM signal with a 16-QAM modulation and a symbol length of T_d=256.

In order to validate the applicability of the proposed test for the detection of a CP-OFDM -based signal, we replaced the testing variable of the conventional method, based on the estimate of the correlation coefficient, with the autocorrelation samples, as detailed in Section III. The probability of detection versus different values of SNRs for both the conventional and the innovative method are shown in Fig.2. The performance of the two detection strategies under examination perfectly overlaps, thus validating the applicability of our strategy for spectrum sensing purposes.

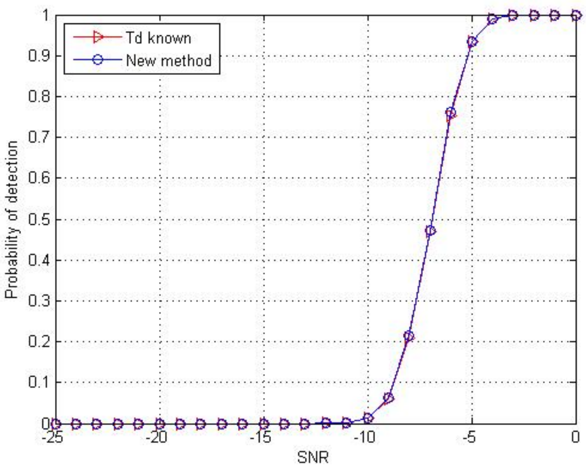

Figure 2. P_D versus SNR ($P_{FA}=10^{-3}$), of both the new (non-blind) and conventional method: applicability of the method to spectrum sensing.

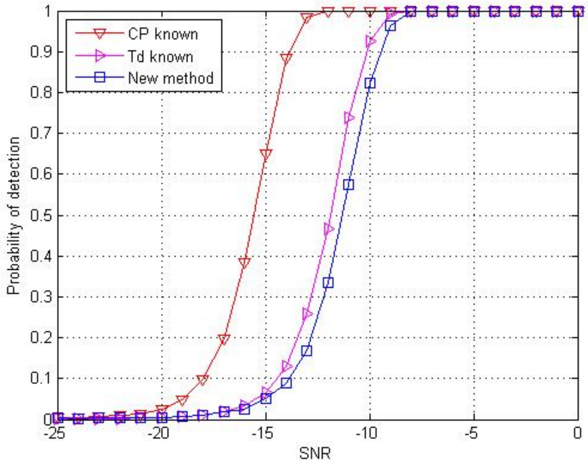

Figure 3. P_D versus SNR ($P_{FA}=10^{-3}$), of both the new (blind) and conventional method (non-blind) for a CP length of $T_c=T_d/4$

The simulated results (from 10^6 independent runs) of the P_d of both the conventional and new procedure are shown in Fig. 3 for a CP length of $T_c=T_d/4$ (i.e. the length of the CP for the WLAN system). Even if the curves referring to new procedure are very close to the one referring to the conventional procedure, the conventional test slightly outperforms the new method. However, this behavior is greatly compensated by the "blindness" of our method that requires no additional information on the parameters of the signal of interest. Moreover, if the CP duration is known to the receiver the performance of the conventional test can be obviously even higher (see again Fig. 3). It has to be underlined that this is the best case, where all the signal's parameters are known to the detector. However, this is not a typically operating case; hence we refer to this situation as the upper limit of the system performance.

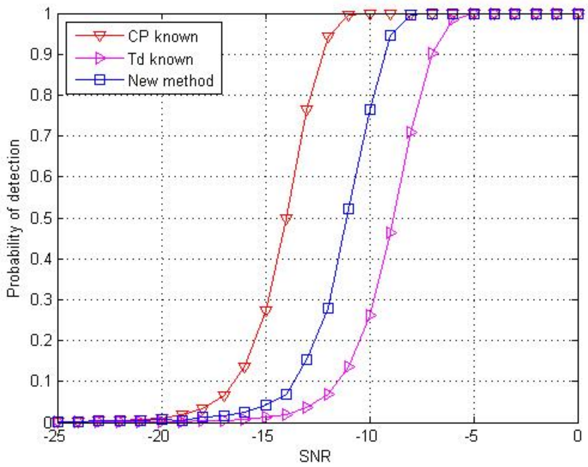

Figure 4. P_D versus SNR ($P_{FA}=10^{-3}$), of both the new (blind) and conventional (non-blind) methods for a CP length of $T_c=T_d/8$

Then, we have evaluated the performance of the two methods varying the length of the CP. In particular, we have considered $T_c= T_d/8$ and we have evaluated the performance of the two methods in this situation. Results are shown in Fig.4, where it can be easily seen that our new method drastically outperforms the conventional one. This is due to the blindness of our procedure that is not affected by variations in the CP length. On the other hand, the performance of the conventional method becomes worsening, decreasing the CP length.

V. CONCLUSIONS

This paper has presented an effective detection strategy for an OFDM-based primary signal. The method we propose requires no a priori knowledge of the signal interest, exploiting the autocorrelation of the received signal. The performance of the new method has been analyzed in comparison with the conventional spectrum sensing approach, based on the autocorrelation coefficient. We have applied our method using typical operating parameters for OFDM signal of wireless local area networks (i.e. IEEE 802.11x protocols).

Wide simulation trials were performed to evidence the effectiveness of the devised method in different operating scenarios. Hence, our procedure can be efficiently applied for spectrum sensing in cognitive radio networks.

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