Evaluation of OFDM-OQAM as Spectrum Sensing Technique

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***Abstract*—Spectrum sensing is a key function of dynamic spectrum access. Filter bank-based multi-carrier communication techniques have been proposed as potential candidates for the physical layer of secondary users since they can be utilized for both data communication and spectrum sensing with no additional cost. In this paper we evaluate one of these techniques, OFDM-OQAM, from the point of view of its probability of misdetection as a function of the SNR, with the false alarm probability and the sensing time as parameters. It is showed that OFDM-OQAM outperforms the periodogram for low SNR values under implicit multipath fading. Not significant differences were found in the performance of OFDM-OQAM under simulated (explicit) multipath fading when compared with the AWGN only case.**

***Index Terms*—Spectrum sensing, Dynamic Spectrum Access, OFDM-OQAM, filter banks.**

I. INTRODUCTION

It has been shown that several licensed bands of the radio-electric spectrum have on average a low percentage of use [1], [2]. This is associated with the existence of idle time-frequency blocks called "white spaces", in which the primary (licensed) user is inactive. The access to those spectral resources by a secondary (non-licensed) user under the constraint of not interfering with the primary user is known as Dynamic Spectrum Access (DSA) [3]. This technology is considered a potential solution to improve the spectrum usage and to satisfy the increasing demand of bandwidth for wireless communication services. A clear example of this is the IEEE 802.22 standard for Wireless Regional Area Networks (WRANs), the first standard proposed to use DSA in TV bands [4].

The success of DSA depends on the reliable detection of white spaces, since it is mandatory for the secondary user (SU) not to interfere with the primary user and the spectrum usage efficiency improvement relies on it. In this way the key operation behind DSA is the spectrum sensing, performed by the SU to decide whether a specific primary channel is vacant and, consequently, whether it could be used for data transmission.

The type of spectrum sensing technique used depends on the information the secondary user has about the primary signal. When this signal has some distinctive characteristics or patterns, like correlation between samples or periodicities in time or frequency, there is a kind of techniques, called feature detectors, that exploit that characteristics through, for instance, the autocorrelation function [12], [13].

If the structure of the signal is completely unknown the best option is the energy detector, also called radiometer [5]. In this technique the input signal energy is estimated and compared with a threshold value to decide if the primary signal is present. If the measured signal energy is greater than the threshold the primary channel is declared as occupied.

The signal energy estimation in the radiometer can be performed through spectral estimation, and this in turn, can be accomplished by a filter bank. Filter bank-based multi-carrier (FBMC) communication techniques have been proposed as candidates for the physical layer of the SU since they can be used for both data communication and spectrum sensing with no additional cost [6].

Energy detection is a basic spectrum sensing technique in which the energy detector or radiometer compares the received signal energy with a threshold. If the measured energy is above the threshold, the detector decides that the primary signal is present.

In this paper we present an evaluation of filter bank-based OFDM-OQAM in the spectrum sensing context when it is used as energy detector. This FBMC technique was first evaluated in the context of spectrum sensing by B. Farhang as a spectral estimator [7]. The focus of our work is the Receiver Operating Characteristic (ROC) curve, represented by the probability of misdetection as a function of the signal to noise ratio (SNR). The evaluation was done through simulation for two different scenarios. In the first simulation scenario we compare OFDM-OQAM with the periodogram and show that this FBMC technique exhibits a better performance mainly for low values of SNR. For this scenario the test signals are RF field ensembles captured under difficult transmission conditions. In the second simulation scenario we compare the performance of OFDM-OQAM under both an AWGN channel and a multipath channel. In this case the test signal is a computer-generated DVB-T signal and the multipath effect is simulated through the six-path COST 207 model for Bad Urban area [8].

F. Sheikh and B. Bing used a similar approach to evaluate their proposed DFT filter bank for spectrum sensing [9]. They computed the misdetection probability versus the SNR for a fixed false alarm probability of 0.05. The simulation was, however, limited to an AWGN channel. In the present work, instead, the multipath effect is considered by the nature of the signals in the first scenario and by the multipath channel model used in the second one, which is a more realistic approach for a wireless environment.

The rest of this paper is structured as follows. In Section II we give a brief review of the spectrum sensing problem. In Section III some important theoretical results related with energy detection are introduced. Section IV review some related works proposing multicarrier techniques in the context of spectrum sensing and the differences with our study are remarked. The OFDM-OQAM implementation used is presented in section V. The simulation scenarios and the simulation methodology are described in Section VI. We report the numerical results in Section VII and the conclusions are stated in Section VIII.

II. The Spectrum Sensing Problem

The reliable detection of white spaces is a required functionality in the physical layer of the SU to avoid interfering the primary user communication. This functionality is known as spectrum sensing. The SU has to analyze the input signal in the frequency bands of interest during a period (the sensing time) and to decide whether the primary signal is present in such bands. In this process the spectrum sensing technique must satisfy some constraints of error probability, time and sensitivity.

Although the spectrum space is multidimensional in the spectrum sensing context [10], our work is limited to the conventional three-dimensional case: time, frequency and geographic area. Under this case spectrum sensing is a signal detection problem that can be formulated as a binary hypothesis testing [11]:

$$\begin{aligned} H_0 &: y[k] = n[k] \\ H_1 &: y[k] = h \cdot s[k] + n[k] \end{aligned} \tag{1}$$

For a particular frequency band, the alternative hypothesis H_1 is that the primary signal s[k] is present, i.e., the channel is occupied. The received signal y[k] is in this case the sum of s[k], scaled by the channel gain *h*, and additive white Gaussian noise (AWGN), denoted by n[k] and with zero mean and variance σ^2. In the null hypothesis H_0 the primary signal is absent, that is, the channel is vacant. The received signal is in this situation only the noise n[k].

Under this formulation, spectrum sensing is the problem of choosing H_0 or H_1 given the observation of the received signal y[k]. To take this decision a test statistic $\Lambda(y)$ is defined in terms of y[k] and compared with a threshold γ:

$$\Lambda(y) \overset{H_1}{\underset{H_0}{\gtrless}} \gamma \tag{2}$$

If the test statistic is greater than the threshold then the secondary user decides H_1, else decides H_0. In this decision the SU can make two kinds of errors: a misdetection or a false alarm.

A false alarm occurs when the SU decides the channel is occupied (H_1) if actually the primary signal is absent (H_0 is true). This error implies missing a spectral opportunity and therefore a reduction in the spectrum usage efficiency. The probability of false alarm is defined as

$$P_{fa} = P(\Lambda(y) > \gamma \mid H_0) \tag{3}$$

The SU runs into a misdetection if it declares the channel as vacant (H_0) when indeed the primary signal is present (H_1 is true). This causes unacceptable interference to the primary user. The probability of misdetection is defined as

$$P_{md} = P(\Lambda(y) < \gamma \mid H_1) \tag{4}$$

The probability of false alarm and the probability of misdetection are performance parameters of a spectrum sensing technique that have to be small to increase the spectrum usage efficiency and to minimize the interference with the primary user communication, respectively. The detector sensitivity, related to the SNR, and the sensing time, are performance parameters that also have to be considered. The detector sensitivity is the minimum level of primary signal power that has to be detected to achieve a desired detection probability. On the other hand, a small sensing time is necessary to increase the SU data transmission time. The IEEE 802.22 standard specifies a sensing time of 2 seconds, a detection probability of 0.9, a false alarm probability of 0.1 and a receiver sensitivity of -116 dBm for digital TV signals [4].

III. The Energy Detector

The problem of detecting a signal of unknown structure through the radiometer was first studied by H. Urkowitz [14]. This problem is formulated as in equation 1 but in continuous time and with *h* equals to 1 (AWGN channel). If the test statistic is the received signal energy over an interval T, normalized by the noise spectral density (N_0), and given by

$$V' = \frac{2}{N_0} \int_0^T y^2(t)\,dt, \tag{5}$$

then through the sampling theorem Urkowitz showed that the test statistic under the null hypothesis (H_0) has a chi-square distribution with 2TW degrees of freedom, where W is the noise bandwidth in Hertz; and under the alternative hypothesis (H_1) it has a non central chi-square distribution with 2TW degrees of freedom and a noncentrality parameter $\lambda = 2{*}Es/N_0$, where Es is the energy of s(t). For 2TW > 250 Urkowitz uses a Gaussian approximation for the distribution of the test statistic under both hypothesis by means of the Central Limit Theorem.

A. Ghasemi and E. Sousa study the same detector as Urkowitz but in a channel with multipath fading [11]. They find analytical expressions to compute the false alarm probability and the detection probability in an AWGN channel using the chi-square and noncentral chi-square distribution for the test statistic under H_0 and H_1, respectively, something that Urkowitz does in an approximated way through tables and nomograms. Those expressions are

$$P_d = 1 - P_{md} = Q_m(\sqrt{\lambda}, \sqrt{\gamma}) \tag{6}$$

$$P_{fa} = \frac{\Gamma(m, \gamma/2)}{\Gamma(m)} \tag{7}$$

where m = TW, $\Gamma(\alpha, x) = \int_x^\infty e^{-t} t^{\alpha-1}\,dt$ is the incomplete gamma function, $\Gamma(x)$ is the gamma function and $Q_m(\cdot,\cdot)$ is the Marcum Q-function.

The detection probability when *h* (see equation 1) varies due multipath fading is derived by the authors by averaging equation 6 over the probability distribution of the SNR, denoted f_{SNR}. For Rayleigh fading f_{SNR} is the exponential distribution and the detection probability becomes

$$P_d = \frac{\Gamma(m-1,\gamma/2)}{\Gamma(m-1)} + \exp\left(\frac{-\gamma}{2+\lambda}\right)\left(1+\frac{2}{\lambda}\right)^{m-1} \times \left[1-\frac{\Gamma\left(m-1,\frac{\gamma\lambda}{2(2+\lambda)}\right)}{\Gamma(m-1)}\right]. \tag{8}$$

IV. THE MULTICARRIER APPROACH

Since the end of the 20th century the advantages of multicarrier modulation for data transmission has been widely recognized [15]. OFDM is one of the most used multicarrier communication techniques, mainly due to its robustness under multipath fading, with several communication standards based on it like IEEE 802.11 and DVB-T.

More recently OFDM was proposed by T. Weiss and F. Jondral in the context of DSA for the transceiver architecture of the secondary user [16]. This strategy has two key advantages. The first one is the flexibility in the transmission since it is possible to match the bandwidth of a vacant licensed subband with an integer multiple of the carrier spacing used in the secondary system and to deactivate the set of subcarriers corresponding to occupied licensed subbands. The second one is that the FFT in the OFDM receiver, required for the demodulation process, can also be used for spectrum sensing with no additional cost. In this way OFDM has a dual functionality in the physical layer of the secondary user.

OFDM has, however, an important drawback in the context of DSA. The power spectral density of each subcarrier in OFDM has the form of the sinc function by virtue of the squared waveform of each OFDM symbol and the IFFT applied at the transmitter. The spectral leakage effect caused by the large side-lobes in the sinc pulse may result in an unacceptable interference to the primary users.

This OFDM limitation is highlighted by B. Farhang and R. Kempter to propose the use of filter bank-based multicarrier (FBMC) communication techniques as an alternative in the physical layer of the SU [6]. In their work it is showed that FBMC can overcome the spectral leakage problem of OFDM and provides a higher spectral efficiency. OFDM-OQAM is one of the FBMC techniques suggested by the authors.

Other work by Farhang compares OFDM-OQAM and the Thomson's multitaper (MT) method [7] as spectral estimators in the context of spectrum sensing. The comparison is made from the point of view of the bias and the 95% confidence interval of the spectral estimates. It is showed that OFDM-OQAM outperforms to the MT method in the regions where the power spectral density (PSD) has low level.

One of the contributions of our work is the performance analysis of OFDM-OQAM as spectrum sensing technique from a different perspective to the presented by Farhang. The evaluation we present here considers the performance parameters mentioned before: the probability of false alarm, the probability of misdetection, the sensing time and the receiver sensitivity. This is done by computing the ROC curve, which is the probability of misdetection as a function of the SNR, with the false alarm probability and the sensing time as parameters of that function.

F. Sheikh and B. Bing propose a Discrete Fourier Transform filter bank (DFB) for spectrum sensing and compare it with an overlapping FFT with rectangular window [9]. In this case a simulation is carried out to compute the probability of misdetection versus the SNR for a fixed probability of false alarm equals to 0.05, and clearly the DFB has better performance than the overlapping FFT. Although they use a similar evaluation approach to the presented here, the simulation is limited to the AWGN channel, the fading effect is not considered.

The multipath fading effect is implicit in our first simulation scenario since the test signals are RF field ensembles (DTV captured signals) collected by the Advanced Television Test Center (ATTC) and the Association for Maximum Service Television (MSTV) at sites where reception was difficult. Multipath fading it also considered explicitly in our second simulation scenario by means of the six-path COST 207 model for Bad Urban area used.

V. OFDM-OQAM IMPLEMENTATION

Traditional OFDM uses QAM to modulate the subcarriers. OFDM-OQAM (Offset QAM) was first proposed by Saltzberg for data communication [17]. In this system a half symbol period delay is introduced between the in-phase and quadrature components of the QAM symbol. Additionally, adjacent subcarriers are staggered oppositely, i.e., one subcarrier has the delay in the in-phase component and the other one in the quadrature component.

The OFDM-OQAM demodulator architecture used in this work is a filter bank-based scheme suggested by Siohan in [18] (see figure 1). The parameters of the system are defined as follows:

L is the prototype filter length
K is the number of carriers
M is the decimation factor and is equal to K/2.
$\alpha = \lceil (L-1)/M \rceil$, where $\lceil \cdot \rceil$ denotes the ceiling function
$\beta = \alpha M - L + 1$
α is a reconstruction delay and β is a delay that has to be considered at the transmitter output or at the receiver input
$G_i(z)$ is the i-th polyphase component
$\Re\{\cdot\}$ extracts the real part of its argument
$x_i[n]$ is the output signal at i-th band of the OFDM-OQAM receiver

The input signal is first delayed by a factor β and then through a delay chain it is divided in 2M sub-band signals. Each of these signals is decimated by a factor M and low-pass filtered by the corresponding polyphase component. A 2M-point IFFT is applied at the output of the 2M polyphase components, each sub-band signal is scaled by a different complex number and the first α samples are dropped because of the reconstruction delay. Finally, the real part of each sub-band signal is taken.

The prototype filter is a root Nyquist filter with a roll-off factor of 1 and was designed following the method proposed by Farhang in [19]. In that method, an optimum compromise

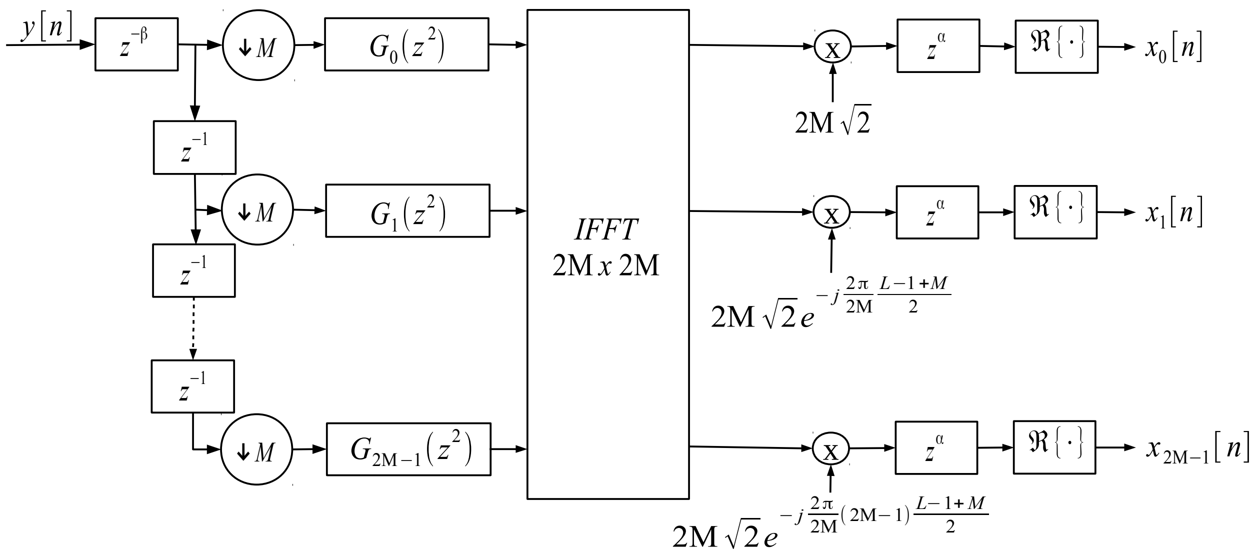

Fig. 1. OFDM-OQAM receiver architecture

between the stopband energy and the accuracy of Nyquist conditions (to avoid ISI) is achieved, a key feature in the spectrum sensing context to minimize interference with primary users, as was previously mentioned.

VI. SIMULATION

We evaluate OFDM-OQAM as spectrum sensing technique in two different scenarios. The difference between both scenarios relays in the nature of the test signals and the simulation goals.

In the first scenario the test signals are a group of 12 field ensembles recommended by Tawil for evaluating spectrum sensing techniques for the IEEE 802.22 standard [20]. These ensembles are a subset of 50 Digital TV (DTV) captured signals recorded in Washington D.C. and in New York City to test DTV receivers under difficult transmission conditions [21]. The recorded signals are ATSC compliant, with sampling frequency of 21.524476 Msamples/sec and central IF frequency of 5.38 MHz. The goal of this scenario is the performance comparison of OFDM-OQAM with the periodogram.

In the second scenario we use a computer-generated baseband DBV-T signal with 6 MHz bandwidth, 2048 carriers (FFT size), 2K transmission mode and guard interval factor of 1/4. The scope of this scenario is the performance comparison of OFDM-OQAM under AWGN channel and multipath fading channel. The multipath channel model used is the six-path COST 207 model for Bad Urban area [8].

Although we evaluate OFDM-OQAM in two different scenarios, the core of the simulation methodology is the same. This is based on the first simulation scenario defined by the IEEE 802.22 working group for evaluating the performance of spectrum sensing techniques [20]. The main objective of this simulation is to find ROC curves for an SU carrying out local spectrum sensing. These curves represent the misdetection probability as a function of the SNR, with the sensing time, the false alarm probability and the multipath channel characteristics as parameters.

In the following subsections we will explain the simulation steps.

A. Setting the sensing time

The sensing time it is the time required to achieve a given probability of detection. This time is set to a value lower than two seconds, which is the maximum allowed in IEEE 802.22. It determines the number of samples that will be taken from the input signal.

B. Setting the threshold level

OFDM-OQAM is used as radiometer, and the test statistic is therefore the power of y[n]. The estimate of the power spectral density (PSD) at the i-th subband is given by [7]

$$\hat{S}\left(\frac{i}{K}\right) = \mathrm{avg}\left[\left|x_i(k)\right|^2\right], \tag{9}$$

where $\mathrm{avg}[\cdot]$ denotes time average of the argument. The total power of y[n] is consequently the sum of the power at each band, and it is expressed as

$$\Lambda(y) = \frac{1}{N}\sum_{i=0}^{K-1}\sum_{k=0}^{N-1}\left|x[k]\right|^2, \tag{10}$$

where N is the number of output samples in each band of the demodulator.

The threshold value γ is computed for a desired false alarm probability. Since a false alarm is conditioned to the occurrence of the null hypothesis H_0, we have to find the distribution of the test statistic under that hypothesis. In this case, the received signal y[k] is only the noise n[k] (see equation 1) and since the system in figure 1 is linear the output signals $x_i[k]$ are a set of i.i.d Gaussian random variables with zero mean and variance σ^2/K. By the Central Limit Theorem the test statistic defined in equation 10 has also Gaussian distribution with the following parameters:

$$\Lambda(y) \sim N(\sigma^2, 2\frac{\sigma^4}{KN}) \tag{11}$$

Using this approximation equation 3 can be written as

$$P_{fa} = Q(\gamma_0), \tag{12}$$

where $Q(\cdot)$ is the Q-function and γ_0 is given by

$$\gamma_0 = \sqrt{\frac{KN}{2}}\frac{\gamma-\sigma^2}{\sigma^2} \tag{13}$$

From equations 12 and 13 we find the expression to compute the threshold for a desired false alarm probability,

$$\gamma = \sqrt{\frac{2}{KN}}\sigma^2 Q^{-1}(P_{fa})+\sigma^2 \tag{14}$$

C. Setting the SNR value

A fixed noise power of -95.2 dBm is used when the signal bandwidth is 6 MHz [20]. The input signal is scaled to achieve the desired SNR value.

D. Processing the DTV signal

A number of samples equivalent to the sensing time is taken from the test (received) signals. For the first simulation scenario the test signal is first demodulated from IF to baseband. After this the test signal is scaled to achieve the desired SNR value and passed through the OFDM-OQAM demodulator. The output power on each band of the demodulator is computed and then the power of all bands is summed to get the total power, as expressed in equation 10. The total power is compared to the threshold and a misdetection is counted if the former is lower.

E. Computing the misdetection probability

For the first scenario step D is repeated for all of the 12 field ensembles to average the multipath effect. For both scenarios step D is in general executed for a total of 10^5 iterations. Hence, the number of misdetections is divided by 10^5 to compute the misdetection probability.

VII. NUMERICAL RESULTS

For both scenarios we use OFDM-OQAM with 256 carriers and a prototype filter length equals to 1536. In the first scenario we additionally implemented the periodogram with rectangular window and as filter-bank, as it is suggested by Farhang [7], with scalar polyphase components equal to its window coefficients. The number of bands (the IFFT size) for the periodogram is the same as in the OFDM-OQAM case.

Figures 2 and 3 presente ROC curves for OFDM-OQAM and the periodogram with a false alarm probability of 0.1 and sensing times of 0.2 ms and 0.7 ms, respectively. OFDM-OQAM has a better performance when the SNR is between -25 dB and -8 dB, as it is expected since its proved superiority as spectral estimator [7]. Additionally it can be observed a performance improvement when the sensing time increases, something expected since a greater number of samples allows a better spectral estimation.

Figure 4 illustrates the ROC curve for OFDM-OQAM and the periodogram with a false alarm probability of 0.01 and sensing time of 0.7 ms. The comparison of this figure with figure 3 shows the existent trade-off between false alarm probability and misdetection probability since a more exigent false alarm probability implies a higher misdetection probability, especially for low SNR.

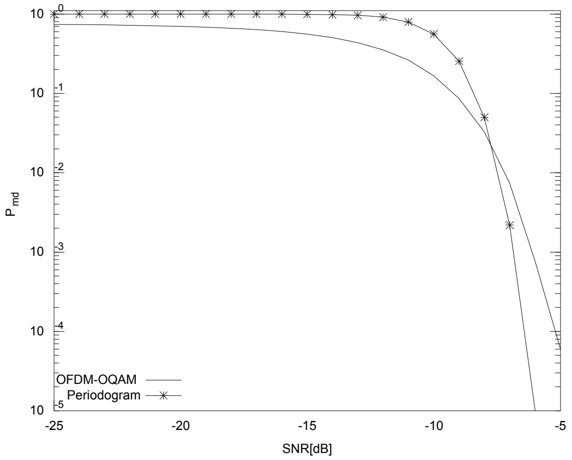

Fig. 2. Misdetection probability vs SNR for OFDM-OQAM and the periodogram. P_{fa}=0.1 and sensing time equals to 0.2 ms.

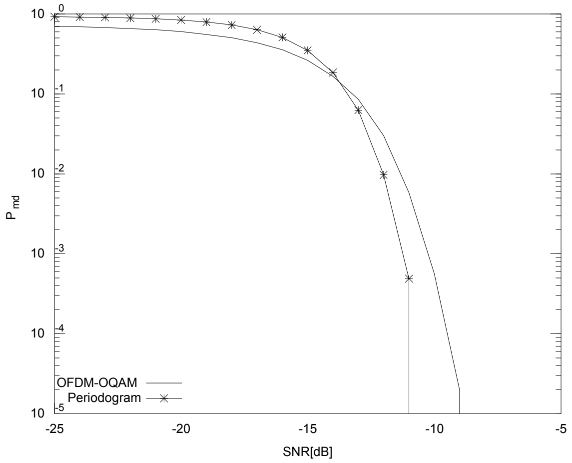

Fig. 3. Misdetection probability vs SNR for OFDM-OQAM and the periodogram. P_{fa}=0.1 and sensing time equals to 0.7 ms.

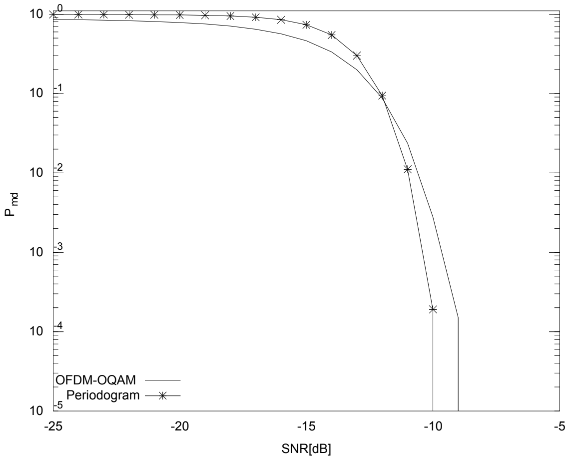

Fig. 4. Misdetection probability vs SNR for OFDM-OQAM and the periodogram. P_{fa}=0.01 and sensing time equals to 0.7 ms.

In Figure 5 the ROC curve for OFDM-OQAM under AWGN channel and multipath fading channel is presented. The fading effect, for the SNR values considered here, is not

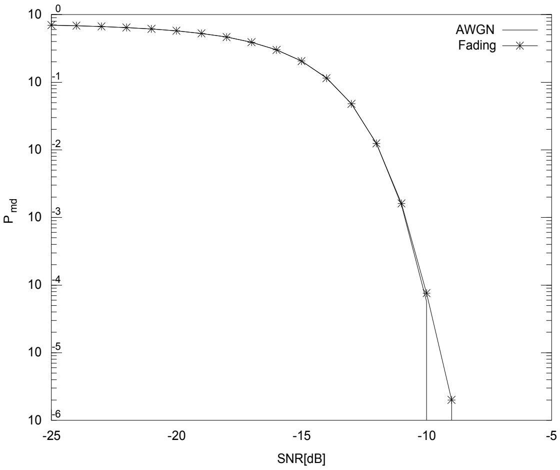

Fig. 5. Misdetection probability vs SNR for OFDM-OQAM under AWGN channel and multipath fading channel. P_{fa}=0.1 and sensing time equals to 0.7 ms.

significant, a result influenced by the small sensing time and the signal bandwidth [22].

VIII. CONCLUSIONS

OFDM-OQAM was evaluated as power detector in the context of spectrum sensing from the perspective of its ROC curve and it is showed that has better performance than the periodogram for low SNR. This result match with the comparison made by Farhang in [7] from a spectral estimation point of view.

Additionally it was found that for the multipath channel model used the performance of OFDM-OQAM was very similar compared with the obtained for an AWGN channel. Here it is necessary more research to better understand the performance of the proposed spectrum sensing technique under multipath fading effect.

Although has been showed that the power detector is a very limited sensing technique due the noise uncertainty [23], the results presented here show that OFDM-OQAM can be a good alternative in recent works where the energy detection is used as a coarse sensing technique in a two-stage scheme [24]-[26].

Finally it is important to remember that a remarkable characteristic of OFDM-OQAM is the dual functionality that offers for a secondary user for both data communication and spectrum sensing. This can also make a difference in the overall computational load.

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