# Channel Availability Assessment for Cognitive Radios

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**Abstract.** This work addresses two problems related with the assessment of channel availability for cognitive radio systems. We start to characterize the performance of an energy detector for the case when PUs can change their state during the sensing period. The theoretical performance is validated through simulations and compared with a theoretical model where the PUs' state remains constant during the sensing period. The second point addressed in this work is the characterization of the channel availability, which is based on the output of the energy detector weighted by the probabilities of detection or false alarm computed in real-time. Several scenarios were evaluated and for each scenario the channel availability was correctly assessed by the SUs.

**Keywords:** Cognitive radio networks, Energy Sensing, System Analysis.

## 1 Introduction

Cognitive Radio (CR) has been proposed as a solution to alleviate the increasing demand for radio spectrum [1]. The nodes equipped with CRs, usually denominated Secondary Users (SUs), must be aware of the activity of the licensed users, denominated Primary Users (PUs), in order to dynamically access the spectrum without causing them harmful interference.

Spectrum Sensing (SS) aims at detecting the availability of vacant portions (holes) of spectrum and has been a topic of considerable research over the last years [1]. It plays a central role in CR systems. The traditional SS techniques include Waveform-based sensing (WBS) [2], a coherent technique that consists on correlating the received signal with *a priori* known set of different waveform patterns; Matched Filter-based sensing (MFBS) [3], an optimal sensing scheme where the received signal is also correlated with a copy of the transmitted one; and Cyclostationarity-based sensing (CBS) [4], a technique that exploits the periodic characteristics of the received signals, *i.e.*, carrier tones, pilot sequences, etc. MFBS assumes prior knowledge of the primary's signal, while WBS assumes that the received signal matches with one of the patterns previously known. This means that these sensing

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techniques are not feasible in some bands, where several communication technologies may operate without *a priori* knowledge. On the other hand, CBS is impracticable for signals that do not exhibit cyclostationarity properties.

Energy-based sensing (EBS) [5], [6] is the simplest spectrum sensing technique and its main advantage is related with the fact that it does not need any *a priori* knowledge of PU's signal. At the same time, it is well known that EBS can exhibit low performance in specific comparative scenarios [7], or when noise's variance is unknown or very large. EBS has been studied in several CR scenarios, namely on local and cooperative sensing schemes [1]. More recently, several EBS schemes adopting sub-Nyquist sampling have been proposed, which are advantageous in terms of the sensing duration [8]. However, they consider that PUs only change their behavior in the beginning of the sensing period, which is a quite unrealistic assumption because they consider PU’s synchronization with SUs.

In this work we characterize the performance of the EBS, not only for the scenario where PUs presents a constant behavior during the sensing period, but also for the scenarios where PUs can change their ON/OFF state, during the sensing period, which impacts on the spectrum sensing decision. In addition to the characterization of the EBS performance, we also characterize the channel availability, based on the output of the Energy Detector (ED) and for a scenario where the PUs exhibit a constant behavior (ON/OFF) during the sensing period.

The rest of this paper is organized as follows. The next section highlights the main contributions of this work. Section 3 presents the proposed system model and Section 4 validates the described probabilities of detection and false alarm and presents the simulation results of the probability of the channel availability. Finally some concluding remarks are given in Section 5.

## 2 Contribution to the Development of the Internet of Things

As it is well known, Internet of Things will be supported most of the times by wireless access technologies. Wireless communication technologies allow high level of device’s mobility, and are indicated for scenarios where mobility is required. At the same time, wireless technologies avoid the use of physical (wired) connections, being an effective solution that will accelerate the implementation of such a network. As mentioned in the introduction, Cognitive Radio was proposed as a solution to alleviate the increasing demand for radio spectrum and, consequently, as more spectrum becomes available more wireless devices can access the network. Consequently, CR will help the development of the Internet of Things by increasing the number of wireless devices that may access the network.

## 3 System Overview

This work considers a cognitive radio network with a pair of PUs accessing the channel and a pair of SUs that access the channel in an opportunistic way. SUs are equipped with a single radio transceiver. However, because SUs are unable to distinguish SUs and PUs' transmissions, SU's operation cycle includes the sensing and transmission periods, which facilitates the synchronization of the sensing task. Sensing and transmission period durations are represented by $T_S^{SU}$and $T_D^{SU}$ respectively, as illustrated in Figure 1.

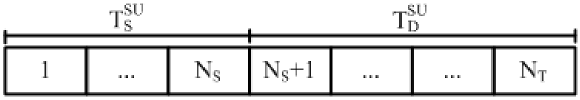


**Fig. 1.** SU's frame structure representing SU's operation cycle

The SU's frame, $T_F^{SU} = T_S^{SU} + T_D^{SU}$, contains $N_T$ slots, where each slot duration is given by the channel sampling period adopted in the spectrum sensing task. The first $N_S$ slots define the sensing period duration, and the remaining ones ($N_S + 1$ to $N_T$) represent the transmission period duration. It is assumed that SUs always have data to transmit and all SUs are synchronized.

### 3.1 Constant PU's Behavior

The assumption of constant PU's behavior adopted in several works [6], [9]-[11], indicates the case when PUs maintain their behavior during the SU's frame duration (equivalent to assume that PUs are synchronized with SU's operation cycle). Under this assumption, PUs will not change their activity state during the SU's frame, *i.e.,* the beginning of PU's transmission always matches with the beginning SU's sensing period. To distinguish between occupied and vacant spectrum bands, SUs sample the channel during the sensing period $T_S^{SU}$, and for each sample $k$ two hypotheses can be distinguished

$$\begin{aligned} &\mathcal{H}_{00}: x(k) = w(k) && k = 1,2,\dots,N_S \\ &\mathcal{H}_{11}: x(k) = w(k) + s(k) && k = 1,2,\dots,N_S, \end{aligned} \tag{1}$$

where $s(k)$ denotes the signal transmitted by the PUs, with distribution $\mathcal{N}(\mu_s, \sigma_s^2)$. $w(k)$ is assumed to be a zero-mean additive white Gaussian noise (AWGN), *i.e.,* $w(k) = \mathcal{N}(0,1)$. The condition $\mathcal{H}_{00}$ represents the case when PUs are absent, while $\mathcal{H}_{11}$ indicates the opposite behavior. During the detection stage, each SU calculates the amount of energy received in the $N_S$ samples $Y = \sum_{k=1}^{N_S} |x(k)|^2$, being then compared with the energy threshold $\gamma$ to decide whether a PU is present or absent. Since $Y$ follows a Chi-square distribution [9], and assuming that the number of samples $N_S$ is large enough, the Central Limit Theorem (CLT) can be used to approximate the Chi-square distribution to a Gaussian distribution [12]:

$$Y \sim \begin{cases} \mathcal{N}(N_S, 2N_S), & \mathcal{H}_{00} \\ \mathcal{N}\big(N_S + \lambda, 2(N_S + 2\lambda)\big), & \mathcal{H}_{11} \end{cases}, \tag{2}$$

where $\lambda = \sum_{k=1}^{N_S} \big(\mu_s/(1+\sigma_s)\big)^2 = \sum_{k=1}^{N_S} \lambda'$ is the noncentrality parameter and represents the sum of $N_S$ samples of SNR collected from the channel during the sensing period. Therefore, for a single SU, the probability of detection $P_D^{\mathcal{H}_{11}}$ and the probability of false alarm $P_{FA}^{\mathcal{H}_{00}}$ are represented by

$$P_D^{\mathcal{H}_{11}} = Pr(Y > \gamma|\mathcal{H}_{11}) = \mathcal{Q}\left(\frac{\gamma - (N_S + \lambda)}{\sqrt{2(N_S + 2\lambda)}}\right) \tag{3}$$

$$P_{FA}^{\mathcal{H}_{00}} = Pr(Y > \gamma|\mathcal{H}_{00}) = \mathcal{Q}\left(\frac{\gamma - N_S}{\sqrt{2N_S}}\right), \tag{4}$$

where $\mathcal{Q}(.)$ is the complementary distribution function of the standard Gaussian.

### 3.2 Non-constant PU's Behavior

Here we consider the case when PUs can randomly arrive or depart during the entire SUs' frame, which may occur during $T_S^{SU}$ or $T_D^{SU}$. When the change occurs during the spectrum sensing period $T_S^{SU}$, two scenarios must be considered. As illustrated in Figure 2(a), during the spectrum sensing task the PU's behavior may change from active to inactive, where the first $N_G$ slots denote the presence of PUs, and the remaining ones ($N_G + 1$ to $N_S$) represent the absence of PUs.

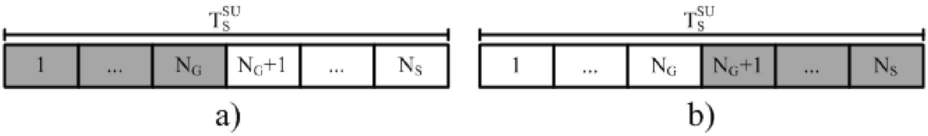


**Fig. 2.** PU's activity change: **(a)** from active to inactive; **(b)** from inactive to active. Gray slots denote PU's activity.

On the other hand, Figure 2(b) illustrates the opposite scenario when PUs may change from inactive to active during the sensing period. These scenarios are respectively represented by hypotheses $\mathcal{H}_{10}$ and $\mathcal{H}_{01}$. The output of the energy detector admits four hypotheses, rather than two. The output of the energy detector under the hypothesis $\mathcal{H}_{01}$ is given by

$$Y_{\mathcal{H}_{01}} = \sum_{k=1}^{N_G} |w(k)|^2 + \sum_{k=N_G+1}^{N_S} |w(k) + s(k)|^2, \tag{5}$$

where the left-hand sum, $Y_{\mathcal{H}_{01}}^a$, follows a central Chi-square distribution with $N_G$ degrees of freedom, while the right-hand sum, $Y_{\mathcal{H}_{01}}^b$, follows a non-central Chi-square distribution with $N_S - N_G$ degrees of freedom, and a non-centrality parameter $\lambda$. If $N_G$ and $N_S - N_G$ are large enough the CLT holds and, consequently, $Y_{\mathcal{H}_{01}}^a \sim \mathcal{N}(N_G, 2N_G)$ and $Y_{\mathcal{H}_{01}}^b \sim \mathcal{N}(N_S - N_G, 2(N_S - N_G + 2\lambda))$. Assuming that $Y_{\mathcal{H}_{01}}^a$ and $Y_{\mathcal{H}_{01}}^b$ are independent and identically distributed (i.i.d.), $Y_{\mathcal{H}_{01}}$ can be stated as the sum of two

Gaussian random variables (r.v.) $Y_{\mathcal{H}_{01}} \sim \mathcal{N}(N_S + \lambda, 2N_S + 4\lambda)$. Since PUs are only active in $N_S - N_G$ samples, $\lambda$ is now given by $\lambda = (N_S - N_G)\lambda'$. Following the same rationale for the remaining hypotheses, the output of the energy detector considering the four hypotheses is written as:

$$Y \sim \begin{cases} \mathcal{N}(N_S, 2N_S), & \mathcal{H}_{00} \\ \mathcal{N}\big(N_S + \lambda' N_G, 2(N_S + 2\lambda' N_G)\big), & \mathcal{H}_{10} \\ \mathcal{N}\big(N_S + \lambda'(N_S - N_G), 2N_S + 4\lambda'(N_S - N_G)\big), & \mathcal{H}_{01} \\ \mathcal{N}\big(N_S + \lambda, 2(N_S + 2\lambda)\big), & \mathcal{H}_{11} \end{cases}. \tag{6}$$

Under the hypothesis $\mathcal{H}_{10}$ a PU is not active at the end of the sensing period and the probability of false alarm is given by

$$P_{FA}^{\mathcal{H}_{10}} = Pr(Y > \gamma | \mathcal{H}_{10}) = \mathcal{Q}\left(\frac{\gamma - N_S - \lambda' N_G}{\sqrt{2N_S + 4\lambda' N_G}}\right). \tag{7}$$

On the other hand, under the hypothesis $\mathcal{H}_{01}$ a PU is always active at the end of the sensing period. In this case the probability of detection is given by

$$P_D^{\mathcal{H}_{01}} = Pr(Y > \gamma | \mathcal{H}_{01}) = \mathcal{Q}\left(\frac{\gamma - N_S - \lambda'(N_S - N_G)}{\sqrt{2N_S + 4\lambda'(N_S - N_G)}}\right). \tag{8}$$

### 3.3 Channel Availability

The channel availability observed by SUs directly depends on the ED performance. Because the ED determines the spectrum occupancy depending on the $N_S$ samples collected from the channel, the ED can also determine the probability of detection and false alarm, which can be used as a figure of merit that evaluates the quality of the ED's decision. The SUs can access the shared channel when:

- There are no PUs transmitting and the SU observes $Y < \gamma$;
- A PU is transmitting and the SU observes $Y < \gamma$.

The first situation corresponds to the case where there is no false alarm and the second situation represents a case of missed detection when a SU may interfere with the PUs.

After performing a decision, the energy detector can compute the probability of the channel being found available, which is given by the following expression:

$$P_\alpha = (1 - P_D)\mathcal{H}_1 + (1 - P_{FA})\mathcal{H}_0, \tag{9}$$

where $\mathcal{H}_1$ and $\mathcal{H}_0$ correspond to the events when the ED observes channel occupied or idle, respectively. Note that $P_D$ and $P_{FA}$ are the probabilities computed by the ED using the $N_S$ samples collected from the channel, being computed using (3) and (4), respectively.

# 4 Performance Evaluation

This section describes a set of simulations and numerical results to validate the probabilities of detection and false alarm and assess the validity of the channel availability probability for different SNR values.

## 4.1 Validation of Probability of Detection and False Alarm

We have considered a scenario formed by one PU transmitter-receiver pair and one SU that observes the channel availability. The operation mode of PUs and SUs is as described in Section 3. In this simulation we consider the case when PUs can randomly arrive or depart during the entire SUs frame. The PUs can change their state ON/OFF accordingly to a uniform distribution. For each value of SNR and $N_S$ the decision threshold was parameterized to achieve a target in terms of probability of false alarm: $P_{FA}^{\mathcal{H}_{00}} = 0.005$ was adopted for the parameterization. For the hypotheses $\mathcal{H}_{10}$ and $\mathcal{H}_{01}$ the slot $N_G$ (which corresponds to the slot where the PU change its state) is given by a uniform distribution.

Figure 3 illustrates the theoretical probability of false alarm for the hypotheses $\mathcal{H}_{00}$ and $\mathcal{H}_{10}$ along with the simulation results for different SNR values.

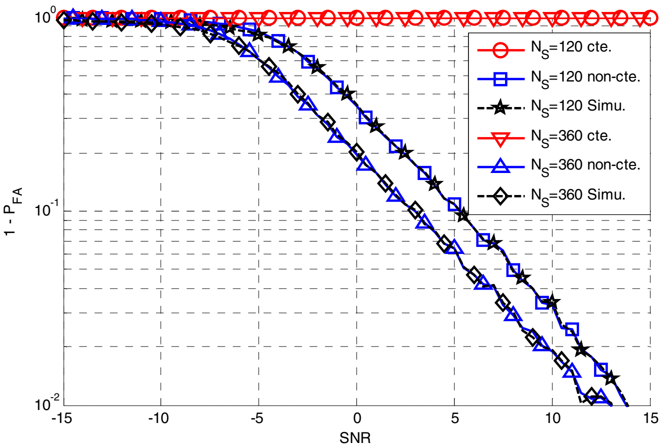


**Fig. 3.** Comparison of simulated and theoretical probability of false alarm

As a first remark, the results plotted in Figure 3 indicate that the simulated results are better validated by the theoretical model where a non-constant ("non-cte") PU's behavior is considered ($P_{FA}$ is given by (7)). The curve titled "cte." represents the theoretical values given by $(1 - P_{FA})$, which represents the case when a constant PU behavior is observed ($P_{FA}$ is given by (4)). Comparing the simulation and the theoretical results, we conclude that, if the constant model is considered in a scenario where the PUs presents a non-constant behavior, the error between the model and the real scenario is huge (for higher SNR values).

Figure 4 compares the theoretical probability of miss detection and the simulation results, where the $(1 - P_D)$ curve computed with (3) is titled "cte." and the $(1 - P_D)$ curve computed with (8) is titled "non-cte.".

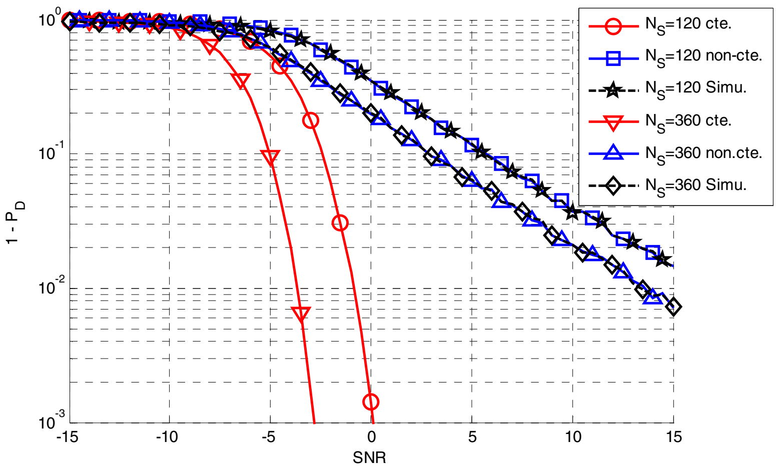


**Fig. 4.** Comparison of simulated and theoretical probability of detection

The plot shows that the theoretical probability expressed in (8) is successfully validated by the simulation results. On the order hand, the theoretical curve computed with (3) exhibits a high deviation from the simulated results, namely for higher values of SNR.

## 4.2 Probability of Channel Availability

This subsection presents the simulation results that evaluate the probability of channel availability computed in real-time by the energy detector. In the simulations, for each value of $N_S$ and SNR, we first defined the detection probability and then the decision threshold was computed to meet the required detection probability. We consider $N$ consecutive SU's operation cycles, and for each operation cycle the SUs calculate the probability of detection or the probability of false alarm depending on the output of the ED. If the ED decides that the channel is occupied then the SU calculates the probability of detection by using the expression (3). On the other hand if the ED decides that channel is idle, then the SU calculates the probability of false alarm by using the expression (4). The probability of a PU being active in each one of the $N$ operation cycles is given by a uniform distribution. In the simulations we only consider a constant PU's activity (the PU remains active or inactive during all SU's operation cycle).

Figure 5 represents the average probability of channel availability (mean of the probabilities computed in each detection decision) for different values of SNR. In the simulations the PU is using the channel with a probability equal to 0.5 and the ED is parameterized for a probability of detection equal to 0.99.

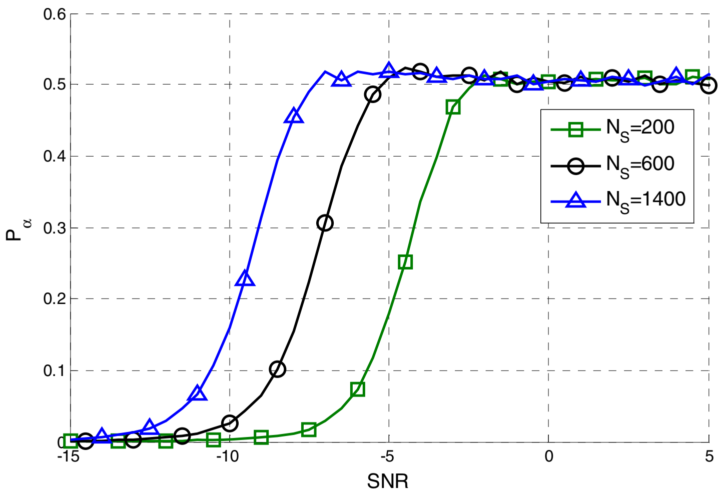


**Fig. 5.** Probability of channel availability

As it is possible to observe in Figure 5, for higher values of SNR the SU presents a probability of channel availability equal to 0.5, which means that the SU can accurately approximate the probability of channel availability. For lower SNR values the channel availability probability is below the real availability of the channel (0.5), which means that the SU observes the channel more occupied than it actually is. Observing the expression (9), we conclude that this error is due to the presence of false alarm events, since the probability of false alarm approaches one as SNR decrease. This observation is mainly due to parameterization method adopted to define the decision threshold ($\gamma$), which aims to achieve a detection probability greater than 0.99 and leads to a higher probability of false alarm, especially for lower values of SNR.

The probability of false alarm does not depend only on the value of SNR but also depends on the $N_S$ samples observed by SUs. As it is possible to observe in expression (9), with the increase of $N_S$ the probability of false alarm decreases, so the probability of channel availability is more close to the real availability of the channel.

## 5 Conclusions

In this work we have addressed two problems related with the assessment of channel availability for cognitive radio systems. We started to characterize the performance of an energy detector for the case when PUs can change their state during the sensing period. The theoretical performance was validated through simulations and compared with a theoretical model where the PUs' state remains constant during the sensing period. For higher SNR values, the theoretical model where the PUs' state is constant during the sensing period shows a huge deviation when compared with the scenario where PUs can randomly arrive or depart during the entire SUs frame.

The second point addressed in this work was the characterization of the channel availability, which was based on the output of the energy detector weighted by the probabilities of detection or false alarm computed in real-time. The validation results show that the probability of channel availability proposed in this work presents a good approximation as the SNR increases. For lower SNR values, the probability of channel availability exhibits a considerable error, but as demonstrated in the simulated results, the probability is almost null, meaning that it does not impacts in terms of PU's interference although it penalizes the SUs in terms of throughput.

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