Spectrum Occupancy in Realistic Scenarios and Duty Cycle Model for Cognitive Radio

Miguel López-Benítez and Fernando Casadevall

***Abstract*—Most of the spectrum occupancy measurement campaigns performed to the date in the context of cognitive radio are based on measurements in outdoor high points such as building roofs, balconies and towers. Although these measurement scenarios enable a more accurate estimation of the primary transmitters' spectral activity, they may not be representative of the spectrum occupancy perceived by a cognitive radio user in many other interesting practical situations where users are not placed in a static high point. In this context, this work presents the results obtained in a spectrum measurement campaign performed over a rich diversity of measurement scenarios of practical interest. The considered scenarios include not only high points but also indoor environments as well as outdoor locations at the ground level in open areas and between buildings. The variety of considered measurement scenarios provides a broader view and understanding of dynamic spectrum occupancy under different practical scenarios of interest. The impact of considering various locations on the spectral activity perceived by a cognitive radio user is determined, analyzed and quantified. Moreover, a theoretical model for the occupancy levels observed at different locations is developed and verified with the obtained results.**

***Index Terms*—Cognitive radio; Dynamic spectrum access; Measurement campaign; Spectrum occupancy; Duty cycle model.**

I. Introduction

THE owned spectrum allocation policy in use dates from the earliest days of modern radio communications. This scheme has been proven to effectively control interference among different wireless systems and simplify the design of hardware for use at a known and fixed radio frequency range. However, with the rapid proliferation of new operators, innovative services and wireless technologies during the last decades, the vast majority of the available spectrum regarded as *usable* has already been occupied. Some recent spectrum measurements have demonstrated however that most of spectrum, though allocated, is vastly underutilized. In this context, the Cognitive Radio (CR) paradigm has emerged as a promising solution to conciliate the conflicts between spectrum demand growth and underutilization without changes to the existing legacy wireless systems.

The basic underlying idea of CR is to allow unlicensed users to access in an opportunistic and non-interfering manner some licensed bands temporarily unoccupied by licensed users. The operating principle is to identify spatial and temporal spectrum gaps not occupied by licensed (primary) users, usually referred to as *spectrum holes* or *white spaces*, place unlicensed (secondary) transmissions within such spaces and vacate the channel as soon as primary users return. Secondary unlicensed transmissions are allowed following this operating principle as long as they do not cause excessive, harmful interference levels to the primary network.

The amount of transmission opportunities available to the secondary system depends on the degree to which allocated spectrum bands are used by the primary system. In the real world, the occupancy level of any spectrum band can be quantitatively determined by means of field measurements. Measurements of the radio environment can provide valuable insights into current spectrum usage. A proper understanding of current spectrum usage can be extremely useful, not only to policy makers in order to define adequate Dynamic Spectrum Access (DSA) policies for improving the exploitation of the currently underutilized spectral resources, but also to the research community in order to develop spectrum usage models and identify the most suitable and interesting frequency bands for the future deployment of the CR technology.

To the date, several spectrum measurement campaigns covering wide frequency ranges [2, 6, 11–13, 15] as well as some specific licensed bands [1, 4, 5, 7, 14] have already been performed in diverse locations and scenarios in order to determine the degree to which allocated spectrum bands are used in real wireless communication systems. However, most of previous spectrum occupancy studies are based on measurements performed in outdoor environments and more particularly in outdoor high points such as building roofs, balconies and towers. The main advantage of high points is that they provide direct line-of-sight to many kinds of important transmitters and therefore enable a more accurate measurement of the spectral activity. Nevertheless, this scenario may not be representative of the spectrum occupancy perceived by a secondary network in many other interesting practical situations where the secondary antenna is not placed in a static high point (e.g., a mobile user communicating inside a building or while walking in the street between buildings). The measurement of real network activities in additional scenarios of practical significance is therefore required for an adequate and full understanding of the dynamic use of spectrum.

In this context, this work presents the results obtained in a spectrum measurement campaign performed over a rich diversity of measurement scenarios of interest in a densely populated urban environment in the city of Barcelona, Spain. The considered scenarios include not only high points but also indoor environments as well as outdoor locations at the ground level in open areas and between buildings. The variety of

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considered measurement scenarios provides a broader view and understanding of dynamic spectrum occupancy under different practical scenarios of interest. The aim of this work is to analyze, determine and quantify the impact of considering various locations on the spectral activity perceived by a secondary user with respect to that observed in an outdoor high point. This information will be very useful in the analysis of realistic scenarios as well as the development of simulation tools and theoretical studies. Furthermore, a theoretical model for the occupancy levels observed at different locations is developed and verified with the obtained results. This model can be used to predict the occupancy level of a given spectrum band perceived at any geographical location based on the knowledge of some simple signal parameters.

II. Measurement Setup and Methodology

The measurement configuration employed in this work (see Fig. 1) relies on a spectrum analyzer setup where different external devices have been added in order to improve the detection capabilities and hence obtain more accurate and reliable results. The design is composed of two broadband discone-type antennas covering the frequency range from 75 to 7075 MHz, a Single-Pole Double-Throw (SPDT) switch to select the desired antenna, several filters to remove undesired overloading and out-of-band signals, a low-noise preamplifier to enhance the overall sensitivity and thus the ability to detect weak signals, and a high performance spectrum analyzer to record the spectral activity. The measurement setup and methodology employed in this work have been carefully designed based on the findings of the study presented in [8], where some important methodological aspects to be accounted for when evaluating spectrum occupancy in the context of CR are analyzed and discussed. A detailed description of the measurement setup configuration parameters and measurements setup design principles as well as the methodological procedures considered in this study can be found in [8–10].

III. Measurement Scenarios

The scenarios defined for this measurement campaign include not only outdoor but also indoor locations. Measurements in indoor locations provide information about the spectral activity that would be perceived by secondary users operating in indoor environments. Similarly, outdoor measurements give us some insights into the spectral activity that would be perceived by secondary users operating in outdoor environments, at various physical locations of practical interest. For the measurements in outdoor locations, three different kinds of scenarios have been considered, namely high points, narrow streets and open areas. Measurements in high points provide reliable information about the actual spectral occupancy patterns of several primary transmitters, while narrow streets and open areas give us an idea of the perception of secondary users moving within a urban environment with different levels of radio propagation blocking.

For indoor experiments, the measurement equipment was placed inside an urban building, in the middle floor of a three-floor building belonging to the Department of Signal Theory and Communications of the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain. For outdoor high point measurements, the equipment was placed in the roof of the same building (latitude: 41º 23’ 20" north; longitude: 2º 6’ 43" east; altitude: 175 meters). The selected place is a strategic location with direct line-of-sight to several transmitting stations located a few tens or hundreds of meters away from the antenna and without buildings blocking the radio propagation. This strategic location enabled us to accurately measure the spectral activity of, among others, TV and FM broadcast stations, several nearby base stations for cellular mobile communications and a military head quarter as well as some maritime and aeronautical transmitters due to the relative proximity to the harbor and the airport. For measurements in narrow streets and open areas, the measurement equipment was moved within the UPC’s Campus Nord. The different geographical locations considered in this measurement campaign are illustrated in Fig. 2, where an aerial view of the campus is shown. The description of the measurement locations is provided in Table I.

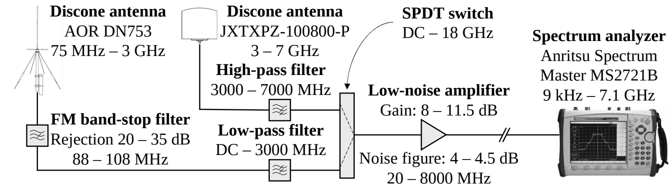

Fig. 1. Measurement setup employed in this study.

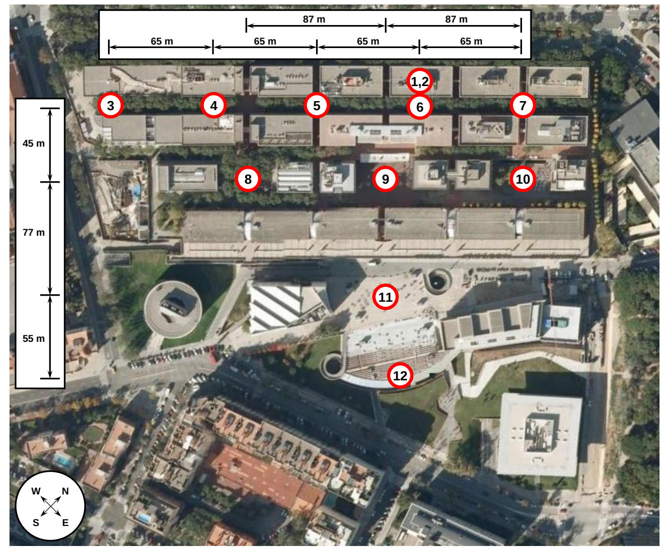

Fig. 2. Measurement locations in urban environment.

TABLE I
Description of the measurement locations.

Measurement point	Environment
1	Outdoor high point (building roof)
2	Indoor (building room)
3 – 7	Outdoor at ground level in narrow streets
8 – 10	Outdoor at ground level between buildings
11 – 12	Outdoor at ground level in open areas

IV. Spectrum Occupancy Results

A. Occupancy Metrics

The occupancy level of various spectrum bands is quantified throughout this work in terms of the duty cycle. This section provides a formal definition for such occupancy metric.

The duty cycle is computed based on a finite set of discrete measurements collected along a range of frequencies $F_{span} = F_{stop} - F_{start}$ (frequency span) and over a period of time $T_{span} = T_{stop} - T_{start}$ (time span).

The measured discrete time instants t_i ($T_{start} \leq t_i < T_{stop}$) are given by

$$t_i = T_{start} + (i-1) \cdot T_r, \quad i = 1, 2, \ldots, N_t \tag{1}$$

where T_r represents the time resolution and is determined by the spectrum analyzer's sweep time, which in turn depends on the selected configuration parameters. For a certain time resolution T_r, the number of traces N_t collected within a time span T_{span} is given by $N_t = T_{span}/T_r$.

The measured discrete frequency points f_j ($F_{start} \leq f_j < F_{stop}$) are given by

$$f_j = F_{start} + (j-1) \cdot F_r, \quad j = 1, 2, \ldots, N_f \tag{2}$$

where the frequency resolution $F_r = F_{span}/N_f$ is the frequency bin, determined by the selected frequency span F_{span} and the number of frequency points N_f measured by the spectrum analyzer.

The set of Power Spectral Density (PSD) samples collected by a spectrum analyzer over a time span T_{span} and along a frequency span F_{span} can be represented by a $N_t \times N_f$ matrix $\mathbf{M}$ as

$$\mathbf{M} = [M(t_i, f_j)] \tag{3}$$

where each matrix element $M(t_i, f_j)$ represents the PSD sample captured at time instant t_i ($i = 1, 2, \ldots, N_t$) and frequency point f_j ($j = 1, 2, \ldots, N_f$).

To compute the duty cycle, the presence or absence of a licensed signal needs to be determined for each PSD sample $M(t_i, f_j)$. In other words, for each captured PSD sample it is necessary to determine whether the sample corresponds to a licensed signal sample or a noise sample. Several signal detection principles have been proposed in the literature to perform such task [16]. They provide different trade-offs between required sensing time, complexity and detection capabilities. Depending on how much information is available about the signal used by the licensed network different performances can be reached. However, in the most generic case no prior information is available. If only power measurements of the spectrum utilization are available, the energy detection method is the only possibility left. Due to its simplicity and relevance to the processing of power measurements, energy detection has been a preferred approach for many past spectrum studies. Energy detection compares the received signal energy in a certain frequency band to a predefined decision threshold. If the signal energy lies above the threshold, a licensed signal is declared to be present. Otherwise, the measured frequency channel is supposed to be idle. Following this principle, a binary spectral occupancy matrix

$$\mathbf{\Omega} = [\Omega(t_i, f_j)] \tag{4}$$

is defined, where each element $\Omega(t_i, f_j) \in \{0, 1\}$ is computed as

$$\Omega(t_i, f_j) = u\left(M(t_i, f_j) - \lambda_j\right) \tag{5}$$

with λ_j being an energy decision threshold for frequency point f_j and $u(\cdot)$ is the unit (Heaviside) step function, thus resulting in

$$\Omega(t_i, f_j) = \begin{cases} 0, & M(t_i, f_j) - \lambda_j < 0 \Rightarrow M(t_i, f_j) < \lambda_j \\ 1, & M(t_i, f_j) - \lambda_j \geq 0 \Rightarrow M(t_i, f_j) \geq \lambda_j \end{cases} \tag{6}$$

Each element $\Omega(t_i, f_j)$ in matrix $\mathbf{\Omega}$ represents the presence $\Omega(t_i, f_j) = 1$ or absence $\Omega(t_i, f_j) = 0$ of a licensed signal at time instant t_i and frequency point f_j, according to the energy detection principle based on an energy decision threshold λ_j. The decision threshold is set according to the Probability of False Alarm 1% (PFA 1%) criterion as explained in [8].

For each measured frequency point f_j, the duty cycle Ψ_j is computed as the fraction of PSD samples, out of all the PSD samples recorded at that frequency, that lie above the decision threshold λ_j and hence that are considered as samples of occupied channels:

$$\Psi_j = \frac{1}{N_t} \sum_{i=1}^{N_t} \Omega(t_i, f_j) \tag{7}$$

For a frequency point f_j, this metric represents the fraction of time that the frequency is considered to be occupied. For a certain frequency span (i.e., range of frequencies $j = 1, 2, \ldots, N_f$), the average duty cycle Ψ of the band is computed by averaging the duty cycle Ψ_j of all the N_f frequency points measured within the band:

$$\Psi = \frac{1}{N_f} \sum_{j=1}^{N_f} \Psi_j = \frac{1}{N_t} \frac{1}{N_f} \sum_{i=1}^{N_t} \sum_{j=1}^{N_f} \Omega(t_i, f_j) \tag{8}$$

This metric represents the average degree of spectrum utilization within certain time (T_{span}) and frequency (F_{span}) spans. The duty cycle is usually given in percentage and this is the convention adopted in this study.

B. Comparison of Location 1 and Location 2

Most of previous spectrum occupancy studies are based on measurements performed in outdoor high points such as building roofs, balconies and towers[1]. This section presents and analyzes the results obtained in a urban indoor environment (location 2) taking as a reference the results obtained in an outdoor high point (location 1). The aim of this section is to determine the impact of considering an indoor environment on the spectral activity perceived by a secondary user with respect to that observed in an outdoor high point. Although the measurement conditions considered in both cases were identical, the time instants were different (i.e., both locations were not measured simultaneously). This circumstance introduces some random component in the obtained results since different transmissions were present in each case. However, it is worth noting that the aim of this section is not to characterize the

[1] In our measurement campaign, this scenario corresponds to location 1.

instantaneous spectrum occupancy in the time domain but the average occupancy rate from a statistical point of view. For sufficiently long measurement periods as those considered in this study (24 hours), the impact of different instantaneous transmissions is averaged and the obtained average duty cycle value can be considered as a representative indication of the spectral activity in the bands under study.

From a qualitative point of view, the results obtained in location 2 follow the same trend as in location 1[2], with higher occupancy rates at lower frequencies. As it can be appreciated in Table II, the average spectrum occupancy is moderate below 1 GHz and very low above 1 GHz. The significantly lower average occupancy rates observed in Table II for the indoor location can be explained by the fact that most of wireless transmitters are located outdoor and the propagation loss due to outdoor-indoor signal penetration leads to lower signal strengths in the indoor scenario, which in turn results in lower occupancy rates. In principle, the lower average duty cycles obtained for the indoor case suggest the existence of a higher amount of free spectrum. However, this result should be interpreted carefully, taking into account the specific circumstances of particular bands.

To analyze the impact of the indoor location on the occupancy rate for various specific bands, it is convenient to distinguish four different possible cases according to the location of transmitters and receivers, as shown in Table III. Based on this classification, the results for various bands of interest are shown in Fig. 3. Notice that for certain bands the classification is not straightforward. For example, in the downlink direction of cellular mobile communication systems the receivers are mobile users that may be located indoor and outdoor simultaneously. In practice, it is not possible to reliably determine the location of every transmitter and receiver operating in a certain band, which results in some uncertainty. In spite of that, some general trends can be inferred from the results shown in Fig. 3.

For bands allocated to systems where the transmitters are always outdoor (cases I/II), the indoor duty cycles are in general notably lower, as expected, due to the outdoor-indoor signal penetration loss. In case I (systems with outdoor receivers) the lower indoor occupancy rates indicate the availability of more free spectrum, since an indoor secondary user transmitting in channels sensed as free would not cause harmful interference to primary outdoor receivers. However, in case II (systems with indoor receivers) the lower indoor duty cycles do not necessarily imply the existence of more white spaces, since in this case transmitting in a channel sensed as unoccupied could potentially result in interference to primary indoor receivers.

For bands allocated to systems with indoor transmitters (cases III/IV), in general the average duty cycles tend to be higher in the indoor location (with some exceptions as the E-GSM 900 uplink band, which might be due to the presence of outdoor transmitters in such band). Following a similar argument, in case IV (systems with indoor receivers) this indicates the availability of a lower amount of free

[2]A detailed analysis of the occupancy results obtained for location 1 can be found in [9].

TABLE II
AVERAGE DUTY CYCLE STATISTICS IN LOCATIONS 1 AND 2.

<table>
<tr><th rowspan="2">Frequency (MHz)</th><th colspan="6">Average duty cycle (%)</th></tr>
<tr><th>Loc.1</th><th>Loc.2</th><th>Loc.1</th><th>Loc.2</th><th>Loc.1</th><th>Loc.2</th></tr>
<tr><td>75-1000</td><td>42.00</td><td>33.70</td><td rowspan="2">31.02</td><td rowspan="2">21.54</td><td rowspan="7">17.78</td><td rowspan="7">12.10</td></tr>
<tr><td>1000-2000</td><td>13.30</td><td>1.94</td></tr>
<tr><td>2000-3000</td><td>3.73</td><td>1.63</td><td rowspan="5">2.75</td><td rowspan="5">1.39</td></tr>
<tr><td>3000-4000</td><td>4.01</td><td>1.44</td></tr>
<tr><td>4000-5000</td><td>1.63</td><td>1.09</td></tr>
<tr><td>5000-6000</td><td>1.98</td><td>1.34</td></tr>
<tr><td>6000-7075</td><td>1.78</td><td>1.38</td></tr>
</table>

TABLE III
CASES CONSIDERED IN FIG. 3.

Case	Transmitter location	Receiver location
I	Outdoor	Outdoor
II	Outdoor	Indoor
III	Indoor	Outdoor
IV	Indoor	Indoor

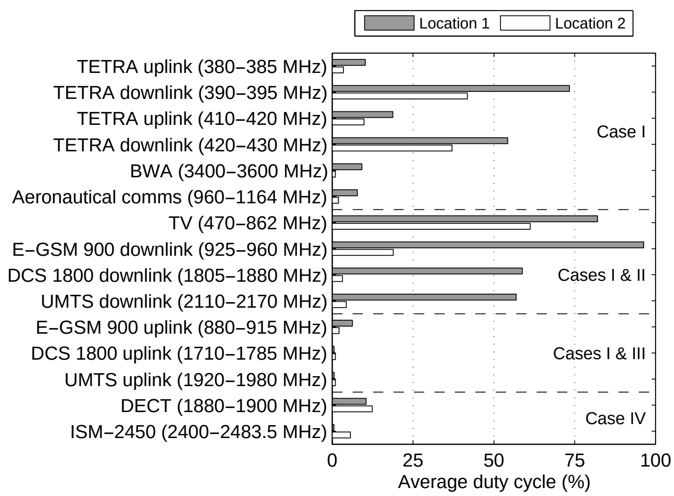

Fig. 3. Average duty cycle statistics in locations 1 and 2 for specific bands.

spectrum, while it could not be necessarily the situation in case III (systems with outdoor receivers). In any case, the differences observed in this experiment between outdoor and indoor occupancy rates in cases III/IV are not as significant as in cases I/II.

In summary, although average duty cycles tend to be lower in indoor locations (with some unimportant particular exceptions), this does not necessarily indicate the existence of more free spectrum. The particular circumstances of the specific bands being sensed and the characteristics of the systems operating over them need to be carefully considered before declaring a band as truly available for a potential secondary usage; otherwise, harmful interference could be caused to the primary licensed system.

Based on the previous results, from a practical point of view it can be stated that the output of spectrum sensing procedures is not enough to declare a band as truly available for secondary access. Some additional techniques may be required such as, for example, sensing both the uplink and downlink directions of FDD-based systems in order to guarantee that the channel can be accessed opportunistically, or employing signal processing techniques as the one described in [9] in order to determine the signal standard present in a certain band before deciding whether a band may be accessed without inducing harmful interference.

C. Comparison of Location 1 and Locations 3-12

This section presents and analyzes the results obtained in urban narrow streets and open areas (locations 3-12) taking as a reference the results obtained in an outdoor high point (location 1). The aim of this section is to determine the impact of considering different outdoor locations at the ground level on the spectral activity perceived by a secondary user with respect to that observed in an outdoor high point. The locations under study in this section can be considered as a representative scenario for secondary mobile users communicating while walking on the street in a urban environment.

As in section IV-B, each location has been measured at a different time instant. As it has been mentioned above, the random component introduced by the presence of different transmissions at different times could be averaged by considering a sufficiently long measurement period. However, since the presence of an operative was required in the measurements, periods of 24 hours as in location 1 were infeasible and were therefore shortened to 1 hour in locations 3-12. To reduce the impact of random components and make the results of locations 1 and 3-12 comparable, the average duty cycle obtained in locations 3-12 has been normalized by the average duty cycle in location 1 obtained when considering the samples corresponding to the same time interval. Therefore, if an average duty cycle Ψ_k is obtained for location k ($k = 3, 4, \ldots, 12$) based on the samples captured during a 1-hour interval between time instants T_{start} and T_{stop}, the samples captured at location 1 between the same T_{start} and T_{stop} values are used to compute an average duty cycle Ψ_1. The normalized average duty cycle for location k is then obtained as $\overline{\Psi}_k = \Psi_k/\Psi_1$. This procedure reduces the randomness of the obtained results and enables a fairer comparison between the outdoor high point and the rest of outdoor positions.

For most of the bands and locations measured in this experiment the obtained normalized average duty cycle is lower than one, meaning that the average duty cycle measured in different locations at the ground level is in general lower than in high points. This is a consequence of the radio propagation blocking caused by buildings and other obstacles: under non-line-of-sight conditions, the direct ray (i.e., the strongest signal component) is lost; only multi path propagation components attenuated by reflection, refraction and diffraction are received, thus resulting in lower received signal levels and therefore in lower average duty cycles. From a practical point of view, this indicates that a secondary user at the ground level would perceive an amount of white space higher than that predicted by measurements performed in high points. Nevertheless, it is worth highlighting that this should be interpreted carefully, taking into account the specific circumstances of each band. In the following, some particular bands of interest are discussed. The obtained results are shown in Fig. 4.

Fig. 4 shows the spatial distribution of the normalized average duty cycle for the TV, UMTS downlink, E-GSM 900 downlink and DCS 1800 downlink bands, respectively. The common feature of these bands is that the transmitters are located outside the region under study. In the TV band, it can be clearly appreciated that the normalized average duty cycle is lower in closed regions. Thus, in locations 4 and 6, where radio propagation blocking caused by buildings is more intense, its value is lower than in other less closed regions such as locations 3, 5 and 7. A similar trend is observed for UMTS, E-GSM 900 and DCS 1800 downlink bands. In the two last cases, however, location 5 constitutes an exception, which could be explained by the different relative position of transmitters and by the fact that the same physical scenario may result in very dissimilar propagation scenarios at different frequencies. Comparing locations 8, 9 and 10, the deepest region (location 9) exhibits the lowest normalized average duty cycle in the case of TV, as expected, but the highest value in the case of the cellular mobile communication bands, which could be explained by the use of micro-cells and repeaters in shadowed regions as location 9. Regarding locations 11 and 12, it is interesting to note that a higher spectral activity level was recorded in location 11 despite the presence of some surrounding buildings with respect to the open region in location 12. The detection by the measurement equipment of some additional signal components reflected in such buildings could explain the recording of higher activity levels in a less open region. Although lower duty cycles have been observed at the ground level in the TV, UMTS, E-GSM and DCS 1800 downlink bands, it is worth noting that this does not necessarily imply the existence of more opportunities for secondary access. As a matter of fact, some faded primary signals might be undetected at the ground level due to blocking buildings and other obstacles, in which case an exceptionally harmful interference would be caused to the intended primary receivers, who in these bands would be operating in the proximity of the secondary users. These experimental results highlight the importance of detection sensitivity in secondary networks and suggest the need of some additional techniques as mentioned in section IV-B.

In the previous bands, where the transmitters were outside the region under study, the results have shown some general occupancy trends. However, for other bands with transmitters operating inside the region under study, no particular occupancy trends have been observed. In this case, the obtained results might depend not on the actual spectral usage of such bands but rather on the random and fluctuating geographical distribution of transmitters inside the considered region.

The main conclusion derived from the obtained results is that the spectral activity perceived by a secondary user for a certain band in realistic urban scenarios strongly depends on the user location, with significant variations even in physical areas as reduced as the one considered in this study ($\approx 180 \times 260$ m). This indicates that the conclusions derived from high point measurements may not be well suited to other realistic outdoor scenarios with users at the ground level.

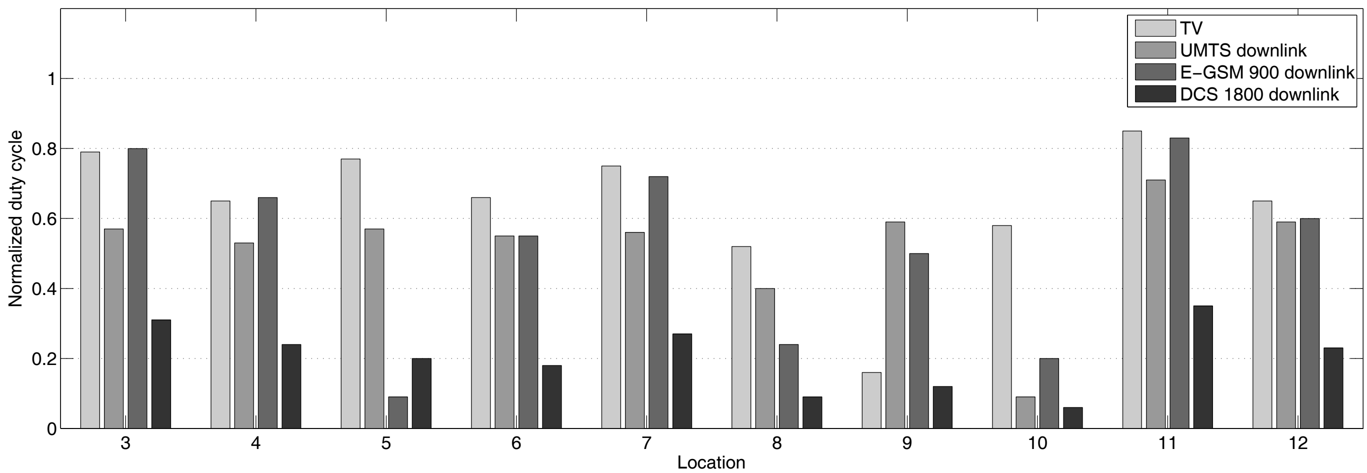

Fig. 4. Normalized average duty cycle statistics in locations 3 to 12 for specific bands: TV (470-862 MHz), UMTS downlink (2110-2170 MHz), E-GSM 900 downlink (925-960 MHz), and DCS 1800 downlink (1805-1880 MHz).

V. Duty Cycle Model for Cognitive Radio

In this section, a model describing the spectral occupancy level perceived at various geographical locations is developed and verified. This model can be used to predict the spectral occupancy, expressed in terms of the duty cycle, that would be perceived by a CR user at any location based on the knowledge of some simple signal parameters. In this section we focus on modeling the duty cycle for TV bands. The interest of considering this band is twofold. On one hand, the first real CR deployments are expected in the TV bands following the IEEE 802.22 standard [3]. Therefore, the development of spectrum usage and prediction models for TV bands is more necessary than for other bands. On the other hand, TV stations are constant-power transmitters with a 100% activity factor, which provides the basis for simple occupancy models that can be extended in the future for non-constant-power transmitters and/or discontinuous transmission patterns.

The model relies on the premise that the average noise channel power and the received average signal channel power can be adequately modeled as Gaussian random variables, which is demonstrated in Fig. 5 and 6, respectively. For a given primary Radio Frequency (RF) channel, the average channel power at time instant t_i is computed as the integral (sum of discrete values) of the PSD levels measured at the frequency points f_j comprised within the RF channel limits, and within a certain time period around t_i. Average channel powers are therefore obtained by averaging the power levels measured at different time instants and frequency points. Hence, the Central Limit Theorem can be employed to explain the Gaussian behavior of Fig. 5 and 6. As shown in Fig. 5, the average noise channel power measured at different TV channels increases with the channel number (i.e., the frequency), but can always be modeled as a Gaussian random variable. Fig. 6 shows that the average signal channel power can also be modeled as a Gaussian random variable. Although the Gaussian curve corresponding to the signal's mean and standard deviation not always provides a perfect fit, it is able to reasonably describe the distribution of the received signal levels.

As stated in section IV-A, the duty cycle represents the fraction of time that a channel is occupied. Following the energy detection principle, a channel is considered to be occupied whenever the average signal channel power is greater than a decision threshold λ. Assuming that the average signal channel power follows a Gaussian law with mean μ_S and standard deviation σ_S, the duty cycle Ψ can be computed (see Fig. 7) as:

$$\Psi = \frac{1}{\sqrt{2\pi}\sigma_S} \int_{\lambda}^{\infty} e^{-\frac{1}{2}\left(\frac{x-\mu_S}{\sigma_S}\right)^2} dx \tag{9}$$

Making the variable change $z = \frac{1}{\sqrt{2}}\left(\frac{x-\mu_S}{\sigma_S}\right)$, the integral is readily obtained to be:

$$\begin{aligned}\Psi &= \frac{1}{\sqrt{\pi}} \int_{\frac{1}{\sqrt{2}}\left(\frac{\lambda-\mu_S}{\sigma_S}\right)}^{\infty} e^{-z^2} dz \quad (10)\\ &= \frac{1}{2}\,\mathrm{erfc}\left(\frac{\lambda-\mu_S}{\sqrt{2}\sigma_S}\right) \quad (11)\\ &= Q\left(\frac{\lambda-\mu_S}{\sigma_S}\right) \quad (12)\end{aligned}$$

where $\mathrm{erfc}(\cdot)$ is the complementary error function and $Q(\cdot)$ is the Gaussian Q-function.

The decision threshold λ in equation 12 can be established according to various methods. The study performed in [8], where some of them were comparatively evaluated and analyzed, concluded that the PFA 1% method represents an adequate trade-off between ability to detect the presence of weak signals and detection errors. In the context of signal detection, the PFA is defined as the probability that a signal is declared to be present in a certain channel when the channel is actually free. For an energy detector, this occurs when the noise power is greater than the decision threshold λ. For a desired target PFA, denoted as P_{fa}, the PFA method sets the decision threshold λ so that a fraction P_{fa} of noise power samples is allowed to lie above the decision threshold λ. Assuming a Gaussian distribution for the average noise channel power with mean μ_N and standard deviation σ_N, this

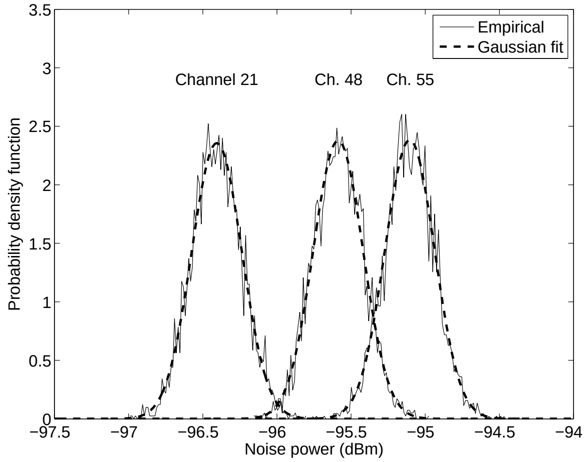

Fig. 5. Probability density function of noise power measured at different TV channels.

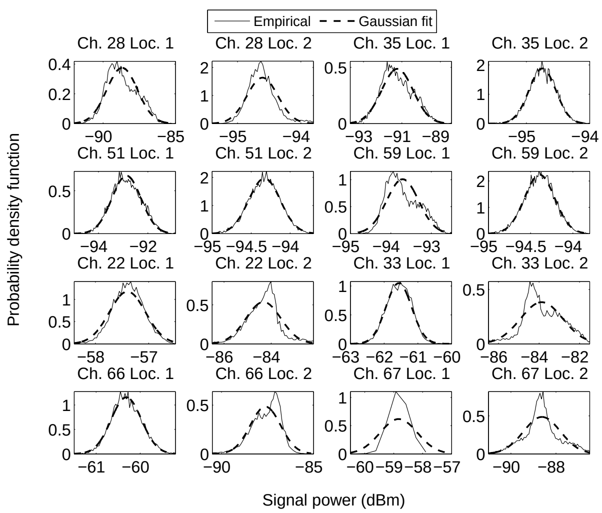

Fig. 6. Probability density function of signal power for analogical (28, 35, 51 and 59) and digital (22, 33, 66 and 67) TV channels.

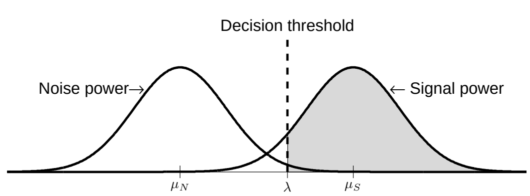

Fig. 7. Model considered for computing the duty cycle (shaded area).

implies (see Fig. 7) that:

$$\frac{1}{\sqrt{2\pi}\sigma_N}\int_{\lambda}^{\infty} e^{-\frac{1}{2}\left(\frac{x-\mu_N}{\sigma_N}\right)^2} dx = Q\left(\frac{\lambda-\mu_N}{\sigma_N}\right) = P_{fa} \quad (13)$$

Solving in equation 13 for λ yields the decision threshold:

$$\lambda = Q^{-1}(P_{fa})\sigma_N + \mu_N \quad (14)$$

where $Q^{-1}(\cdot)$ denotes the inverse of $Q(\cdot)$.

Substituting equation 14 into equation 12 finally yields the duty cycle model:

$$\Psi = Q\left(\frac{Q^{-1}(P_{fa})\sigma_N - SNR}{\sigma_S}\right) \quad (15)$$

where $SNR = \mu_S - \mu_N$ represents the average Signal-to-Noise Ratio (SNR) expressed in decibels, while σ_S and σ_N are the standard deviation of the signal and noise powers also in decibels.

To validate equation 15, Fig. 8 and 9 depict, for analogical and digital TV channels respectively, the empirical duty cycle obtained for the 12 measured locations in Fig. 2. The duty cycle is shown as a function of the difference between the measured average signal and noise powers in dBm, i.e. the SNR in dB. The dependence of the perceived spectral activity with the geographical location is reflected in the different SNR values observed at each location. The theoretical curve of equation 15 corresponding to the measured signal and power standard deviations is also shown for target PFAs of 1% and 10%. As it can be appreciated, the model perfectly agrees with the empirical values for both analogical and digital channels. More interestingly, the fit is reasonably accurate also for those channels for which the Gaussian fit in Fig. 6 was not perfect. These results demonstrate that equation 15 is able to accurately predict the spectral activity that would be perceived by a CR user at any position based on the knowledge of some basic signal parameters.

VI. Conclusion

Most of previous spectrum occupancy measurement campaigns in the context of cognitive radio have been performed in outdoor high points. The results obtained in such measurement locations, however, are not representative of the spectrum occupancy perceived by a cognitive radio user in many other locations of practical interest. In this context, this work has presented the results obtained in a spectrum measurement campaign performed over a rich diversity of measurement scenarios. The obtained results indicate that the occupancy level perceived by secondary users strongly depends on the considered location, with significant variations even in reduced physical areas. A theoretical model for the occupancy levels observed at different locations has been developed and verified with the obtained results.

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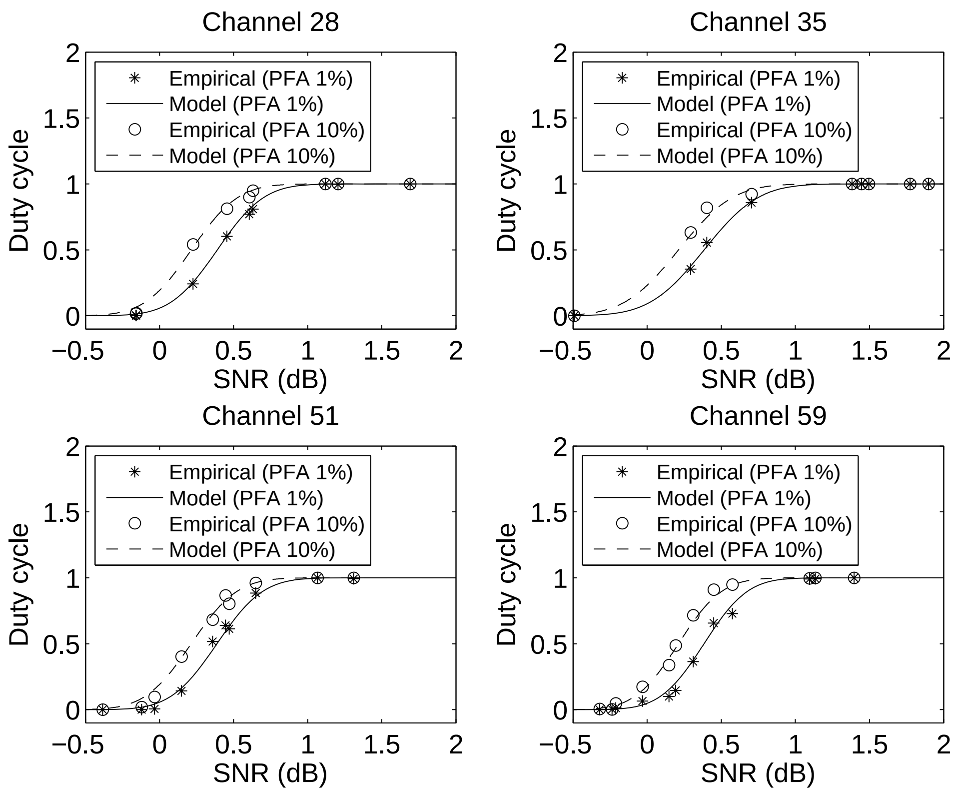

Fig. 8. Validation of duty cycle model for analogical TV channels.

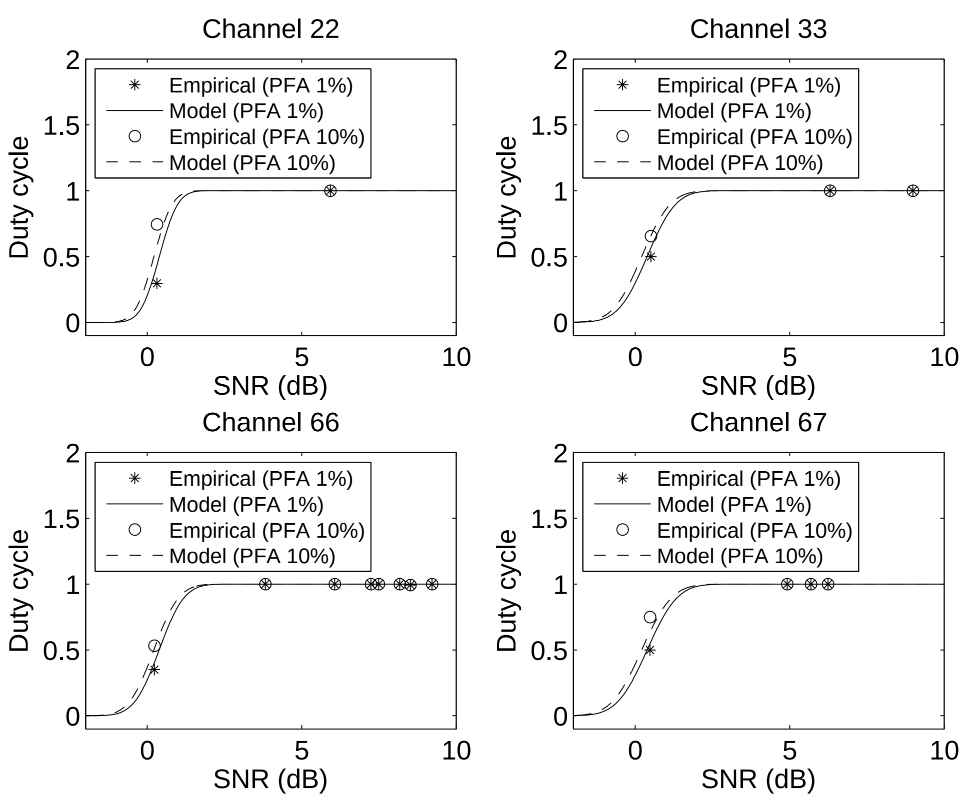

Fig. 9. Validation of duty cycle model for digital TV channels.

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