Methodological Aspects of Spectrum Occupancy Evaluation in the Context of Cognitive Radio

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Abstract—**Several spectrum measurement campaigns have been performed in diverse locations and scenarios in order to assess the degree to which spectrum is currently used in real wireless communication systems. Although such measurement campaigns follow similar approaches, there is a lack of common and appropriate evaluation methodology, which would be desirable not only to prevent inaccurate results but also to enable the direct comparison of results from different sources. In this context, this work presents a comprehensive and in-depth discussion of several important methodological aspects to be accounted for when evaluating spectrum occupancy. Moreover, a quantitative evaluation of the impact of different factors on the obtained results and various useful guidelines are also provided. The results presented in this work highlight the importance of carefully designing an appropriate methodology when evaluating spectrum occupancy in the context of cognitive radio.**

I. INTRODUCTION

Cognitive Radio (CR) has emerged during the last years as a promising solution to the so-called *spectrum scarcity problem*. This concept relies on the basic premise that spectrum is currently underutilized. Several spectrum measurement campaigns covering both wide frequency ranges [1]–[6] and some specific licensed bands [7]–[11] have already been performed in diverse locations and scenarios in order to determine the degree to which allocated spectrum bands are occupied in real wireless communication systems. Measurements of the radio environment can provide valuable insights into current spectrum usage. This information can be very useful in the definition of adequate dynamic spectrum policies, the selection of appropriate frequency bands for the deployment of future CR networks and the identification of usage patterns that can be exploited in the development of useful spectrum usage models and more efficient CR techniques. The success of the previous activities depends however on the availability of accurate spectrum utilization statistics.

Although previous measurement campaigns followed similar approaches, there is a lack of common and appropriate evaluation methodology, which would be desirable not only to prevent inaccurate results but also to enable the direct comparison of results from different sources. As pointed out in [12], different measurement strategies can result in widely divergent answers. In this context, this work presents a comprehensive and in-depth discussion of several important methodological aspects that need to be carefully taken into account when evaluating spectrum occupancy. Some of the issues discussed in this work are intuitive but have never been evaluated in a rigorous and quantitative manner in the context of cognitive radio. This paper presents various useful results that quantify the impact of different factors on the obtained results and reveal which of them require more attention. Various practical guidelines based on such results are also provided. The results presented in this work highlight the importance of carefully designing an appropriate methodology when evaluating spectrum occupancy in the context of CR.

II. MEASUREMENT SETUP

There are many factors that need to be considered when defining a strategy to meet a particular radio spectrum occupancy measurement need. As detailed in [12], there are some basic dimensions that every spectrum occupancy measurement strategy should clearly specify, namely *frequency* (frequency span and frequency points to be measured), *location* (measurement site selection), *direction* (antenna pointing angle), *polarization* (receiving antenna polarization) and *time* (sampling rate and measurement period). The measurement setup employed in the evaluation of spectrum occupancy should be designed taking into account the previous factors since they play a key role in the accuracy of the obtained results. The measurement setup should be able to detect, over a wide range of frequencies, a large number of transmitters of the most diverse nature, from narrow band to wide band systems and from weak signals received near the noise floor to strong signals that may overload the receiving system.

Depending on the purposes of the study, different configurations have been used in previous spectrum measurements ranging from simple setups with a single antenna directly connected to a spectrum analyzer [10] to more sophisticated designs [1], [3]. Different configurations between both extreme points may determine various tradeoffs between complexity and measurement capabilities. Our study is based on a spectrum analyzer setup where different external devices have been added in order to improve the detection capabilities of the system and hence obtain more accurate and reliable results. A simplified scheme of the measurement configuration is shown in figure 1. The design is composed of two broadband antennas, a switch to select the desired antenna, several filters, a low noise amplifier and a high performance spectrum analyzer.

When covering small frequency ranges or specific licensed bands a single antenna may suffice. However, in broadband spectrum measurements from a few megahertzs up to several gigahertzs two or more broadband antennas are required in order to cover the whole frequency range. Most of spectrum measurement campaigns are based on omni-directional measurements in order to detect primary signals coming for any directions. To this end, omni-directional vertically polarized

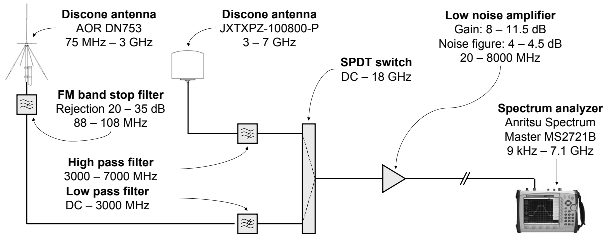


Fig. 1. Measurement setup employed in this study.

antennas are the most common choice. Our antenna system comprises two broadband discone-type antennas, which are vertically polarized antennas with omni-directional receiving pattern in the horizontal plane. Even though some transmitters are horizontally polarized, they usually are high-power stations (e.g., TV stations) that can still be detected with vertically polarized antennas. Directive antennas (e.g., log-periodic antennas) may be used in order to improve the system's sensitivity at the cost of increased measurement complexity. For example, if a directive antenna with α-degree beamwidth is used in order to provide an additional G-dB gain with respect to an omni-directional antenna, it would be necessary to repeat the measurements $N = 360/\alpha$ times in order to cover the entire 360-degree range of azimuths.

An alternative way to obtain additional gain is by means of amplification. Most spectrum analyzers include built-in high-gain pre-amplifiers. Nevertheless, in some measurement conditions there may be high losses between the antenna port and the spectrum analyzer. In this case a better option to improve the system's noise figure is to place a low-noise pre-amplifier right after the antenna system, as show in figure 1. It is worth noting that choosing an amplifier with the highest possible gain not always is the best option in broadband spectrum surveys, where very different signal levels may be present. The existing tradeoff between sensitivity and dynamic range must be taken into account. To choose the correct pre-amplifier, we must look at our measurement needs. If we want absolutely the best sensitivity and are not concerned about measurement range, we would choose a high-gain, low-noise pre-amplifier. If we want better sensitivity but cannot afford to give up any measurement range, we must choose a lower-gain pre-amplifier. A reasonable design criterion is to guarantee that the received signals lie within the overall system's Spurious-Free Dynamic Range (SFDR), which is defined as the difference between a threshold or lower limit at which signals can be detected without excessive interference by noise (constrained by the system's noise floor) and the input level that produces spurs at levels equal to the noise power [13]. If the maximum level is exceeded, some spurs might arise above the system's noise floor and would be detected as *signals* in truly unoccupied bands, thus resulting in inaccurate results and erroneous conclusions about the primary activity. As shown in figure 1, band stop filters to remove undesired strong signals as well as low/high pass filters to remove out-of-band frequencies can help to satisfy the SFDR criterion without any loss in sensitivity at other frequencies.

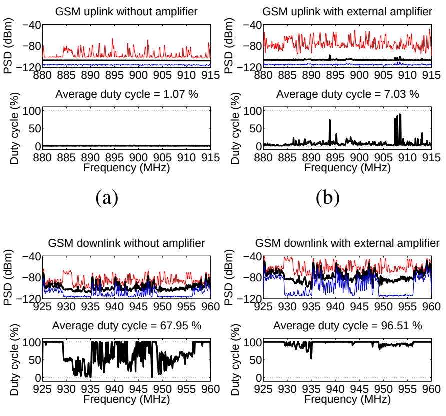
Figures 2 and 3 quantitatively exemplify the impact of the overall system's sensitivity on the detected primary activity. In each subfigure, the upper graph shows the Power Spectral Density (PSD) in average value (thick line) as well as minimum and maximum values. When considered together, average, minimum and maximum PSD provide a simple characterization of the temporal behavior of a channel. For example, if the results are quite similar, it suggests a single transmitter that is always on, experiences a low level of fading and so is probably not moving either. At the other extreme, a large difference among average, minimum and maximum PSD suggests more intermittent use of the spectrum [10]. To more precisely quantify the detected primary activity, the lower graph of each subfigure shows the duty cycle. For each measured frequency point, the duty cycle is computed as the percentage of PSD samples, out of all the recorded PSD samples, that lied above a certain threshold. This metric represents the fraction of time a given frequency is used.

Figure 2 shows the results obtained for the Global System for Mobile communications (GSM). As depicted in figure 2(a), when the uplink direction is measured without any amplification (external pre-amplifier of figure 1 or spectrum analyzer's built-in amplifier), some signals are detected (see PSD) resulting in an overall duty cycle of 1.07% for the entire band. When only the external amplifier is connected, a higher number of primary signals are detected and the resulting average duty cycle is 7.03% in this case, as shown in figure 2(b). These results indicate that, when measuring the GSM uplink primary activity at our measurement location, an estimation error of nearly 6% was observed due to insufficient amplification. In the case of GSM downlink, poor sensitivity levels resulted in severe underestimation of primary activity since an estimation error of 28.56% was observed in this case. While the results obtained without amplification in figure 2(c) conclude that the GSM downlink band is subject to moderate/high usage levels (67.95%), the results obtained with amplification in figure 2(d) reveal that such band is actually overcrowded, with an average duty cycle of 96.51%. These results highlight the importance of sensitivity: if the measurement setup is not sensitive enough, the occupancy statistics may be subject to high estimation errors, thus leading to wrong conclusions on primary activity and spectrum usage.

Figure 3 shows the results obtained for Broadband Wireless Access (BWA) systems operating in the 3.4–3.6 GHz band. Without amplification, figure 3(a) shows that the band is detected as unoccupied (the average duty cycle of 0.72% is due to the criterion employed to select the decision threshold, which is explained in section V). By comparing figures 3(b) and 3(c) it can be observed, as expected, that the use of pre-amplifiers near the antenna system provide better sensitivity improvements than the use of the spectrum analyzer's built-in amplifier. Although the external pre-amplifier's gain was only 8-11.5 dB, it was able to detect some signals that were not detected by the spectrum analyzer's 25-dB gain built-in amplifier. However, figure 3(d) demonstrates that both amplifiers are required in order to properly detect the presence of primary systems operating in the measured band. These results indicate that amplification by itself is not enough: an appropriate amplification configuration is required in order to accurately estimate spectrum usage.

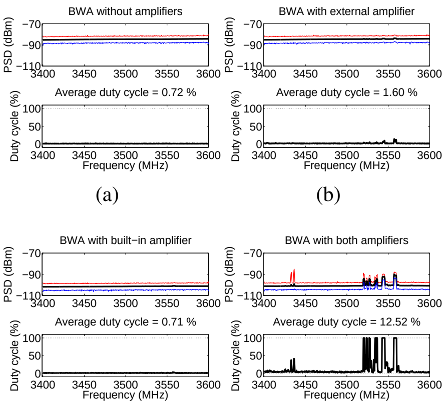
III. FREQUENCY DIMENSION

When the measurement equipment is designed, the next step is to decide the frequency spans to be measured across the entire frequency range. A reasonable option is to divide the



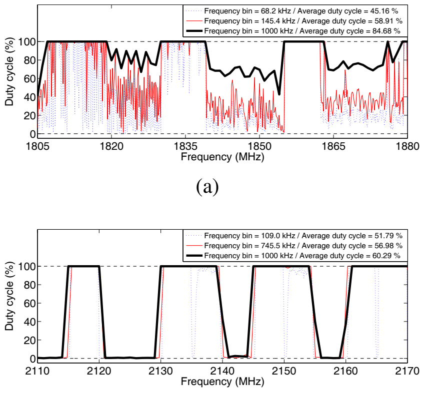
(a) (b) (c) (d)

Fig. 2. Impact of amplification on the activity detected for GSM: (a) uplink without amplifier, (b) uplink with external amplifier, (c) downlink without amplifier, and (d) downlink with external amplifier.



(a) (b) (c) (d)

Fig. 3. Impact of amplification on the activity detected for BWA: (a) without amplifiers, (b) with external amplifier, (c) with built-in amplifier, and (d) with both amplifiers.



(a) (b)

Fig. 4. Impact of frequency bin on the activity detected for: (a) DCS 1800 downlink, and (b) UMTS downlink.

frequency range in wide spectrum blocks and perform measurements in order to obtain a first picture of which spectrum bands are occupied [5]. Based on this first impression and following the local spectrum allocations, the entire frequency range can then be divided into smaller bands in such a way that higher frequency resolutions are obtained in those bands where some activity was detected and/or the bandwidth of the transmitted signals is narrower [2].

TABLE I
IMPACT OF RESOLUTION BANDWIDTH ON THE ACTIVITY DETECTED BETWEEN 146 AND 235 MHZ.

Resolution bandwidth	Average duty cycle	Average sweep time
3 kHz	58.04%	7.49 s
10 kHz	56.08%	2.81 s
30 kHz	50.84%	1.85 s
100 kHz	43.30%	0.92 s
300 kHz	40.36%	0.79 s

The relation between bandwidth of transmitted signal and frequency resolution is an important aspect to be accounted for. For a given number of frequency points per span, the frequency bin size (i.e., the separation between two consecutive measured frequency points) increases as the frequency span becomes wider. As shown in figure 4, higher frequency bins tend to result in higher spectrum occupancy rates. This is verified in figure 4 for the Digital Cellular System (DCS) downlink band and the Universal Mobile Telecommunications System (UMTS) downlink band. However, the behavior in both cases is different. In the case of DCS 1800, for frequency bins lower than the bandwidth of the transmitted DCS signal (200 kHz), the average duty cycles of the band (45.16% and 58.91%) indicate that the band is subject to moderate usage. For a frequency bin of 1 MHz, which is quite greater than the signal bandwidth, the obtained duty cycle of 84.68% incorrectly concludes that the same band experiences a high level of utilization. As it can be observed in figure 4 for DCS 1800, some regions of the band are occupied during the entire measurement period. As a result, the three frequency bin values agree and provide similar duty cycles (nearly 100%) in such portions of the band. In other regions where the activity is lower, different frequency bin values provide very different results. Concretely, large frequency bin values tend to overestimate spectrum occupancy. For example, if a frequency bin of 1000 kHz is used, a single high-power 200 kHz active channel within the bin may result in the entire 1000 kHz bin being declared as occupied. As a result, frequency bin values larger than the signal bandwidth lead to important overestimations of spectrum occupancy in regions with moderate activity levels, which in turn results in greater average duty cycles for the entire band. In the case of UMTS the studied frequency bins were always lower than the signal bandwidth (5 MHz). Although the average duty cycle increases with the frequency bin, the difference is less significant (only 8.5% between 109 and 1000 kHz). This difference could indeed be ascribed to the fact that for the lower frequency bins some frequency points lied within the UMTS channels' guard bands, as shown in the lower graph of figure 4, where the duty cycle is obviously zero. It can be concluded that if the frequency bin is larger than the bandwidth of the signal being measured, spectrum occupancy is notably overestimated. On the other hand, occupancy estimation is reasonably accurate as long as the frequency bin size remains acceptably narrower than the signal bandwidth.

Another aspect related to the frequency dimension is the Resolution BandWidth (RBW) of the spectral measurements. Narrowing the RBW increases the system's ability to resolve signals in frequency and decreases the noise floor [14], which in turn improves the ability to detect weak signals but at the cost of increased measurement time, as it is shown in table I for the frequency band from 146 to 235 MHz. This band comprises transmissions from systems with various signal bandwidths, including Private Mobile Radio (PMR) systems (12.5/25 kHz), wireless microphones (200 kHz) and Digital Audio Broadcasting (DAB) systems (1.54 MHz). As a result, the occupancy statistics shown in table I implicitly include the effects of several RBWs on different signal bandwidths. In our case, a RBW of 10 kHz was proven to be an adequate tradeoff between detection capability and measurement time. For the results shown in table I, the 10 kHz RBW configuration only misses 2% of signals with respect to 3 kHz RBW and is able to capture 2.67 times more PSD samples within the same measurement period. Wider RBWs result in higher estimation errors, up to 17.68% for 300 kHz RBW.

IV. TIME DIMENSION

The time dimension of the spectrum measurements is defined by two parameters, namely the sampling rate, i.e. the rate at which PSD samples are recorded, and the measurement period. While the former is constrained (and in some cases automatically adjusted) by the measurement device, the latter can be easily controlled. Very different measurement periods have been considered in previous measurements such as 20-30 minutes [4], 1 hour [2], 48 hours [2] and 7 days [5].

From a statistical viewpoint, the question is how long should spectrum bands be measured in order to obtain a representative estimate of the actual spectrum usage in such bands. This section tries to answer this question by showing the effects of the measurement period on the obtained results in a quantitative manner. To this end, a portion of the DCS downlink band (1862.5–1875.5 MHz) was selected and measured during 24 hours. The average duty cycle for each measured frequency point was computed over 1-hour periods, thus obtaining the time evolution of the duty cycle for different frequencies along one day. The obtained results are shown in figures 5 and 6.

As it can be appreciated in figure 5, the activity in the measured band was produced by at least two base stations, which can be inferred from the two broadcast channels that can be clearly identified at 1863.2 MHz and 1867.4 MHz for their constant duty cycle. Traffic channels are also distinguishable in figure 5 for their temporal variation.

In the particular case of broadcast channels, the spectral activity is constant and hence the *instantaneous* duty cycle matches the average value at every time instant (broadcast channel at 1863.2 MHz) or provides a very similar value (broadcast channel at 1867.4 MHz). As a result, a 1-hour measurement would report an acceptable estimate of actual occupancy rates regardless of the start time. This conclusion is valid not only for broadcast channels of cellular mobile communication systems but in general for transmitters with a constant temporal activity such as TV and FM broadcast stations, among many other types of wireless systems.

Although broadcast channels in figure 5 show a constant activity, the rest of the band exhibits an oscillating pattern along time. When the entire band is considered, the *instantaneous* duty cycle then differs notably from the average value. For example, while a 1-hour measurement started at 9:32 would report an occupancy rate of 41.58%, the same time span started at 12:32 and 15:32 would report average duty cycles of 68.37% and 33.75% respectively. None of these values is representative of the actual average usage of the band since the true mean over a 24-hour period was obtained to be 35.60%. Based on this discussion, a reasonable option to obtain representative results without any *a priori* information of the band to be measured is to consider measurement periods of at least 24 hours in order not to underestimate or overestimate the occupancy of frequency bands with some temporal patterns.

Although a 24-hour measurement period can be regarded as adequate, it is certainly true that a relatively large number of recorded traces and thus reasonably long measurement periods are required to correctly characterize the primary activity of allocated spectrum bands. For example, 48-hour periods would provide more realistic estimates. Moreover, 7-day periods would also include the potentially different usage patterns of some spectrum bands in weekdays and weekends. A 24-hour measurement period properly chosen can be considered as a reasonable tradeoff between reliability of the obtained results and time required to complete the measurement campaign.

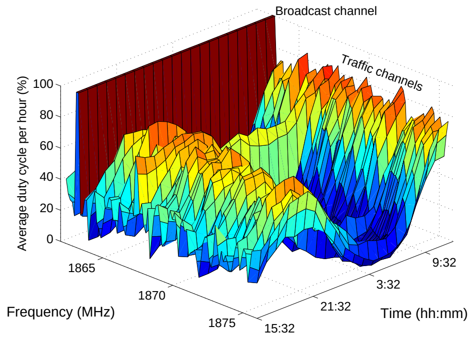


Fig. 5. Average duty cycle per hour for DCS downlink (1862.5-1875.5 MHz).

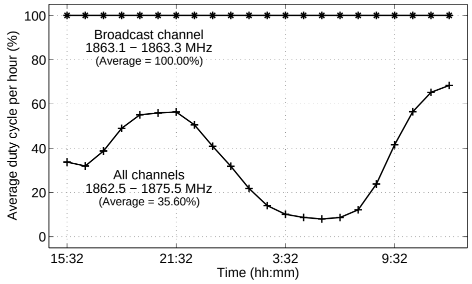


Fig. 6. Average duty cycle per hour for DCS downlink (1862.5-1875.5 MHz).

V. DATA POST-PROCESSING

While the previous sections dealt with aspects to be considered before the measurement phase, this section discusses different methods for post-processing the captured empirical data and their impact on the obtained results. Regardless of the final measurement campaign objective (e.g., definition of adequate dynamic spectrum policies, identification of sparsely used frequency bands or development of spectrum usage models), one of the very first steps of data post-processing is to determine which captured PSD samples correspond to occupied and unoccupied channels.

To detect whether a frequency band is used by a licensed user, different sensing methods have been proposed in the literature [15]. They provide different tradeoffs 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 threshold. If the signal lies above the threshold the band is declared to be occupied by the primary network. Otherwise the band is supposed to be idle. Therefore, the measured PSD samples need to be compared to a threshold in order to determine whether they correspond to occupied channels or not.

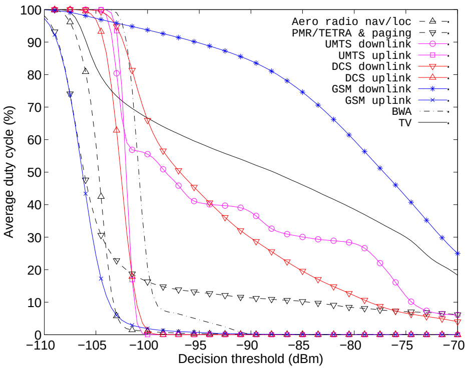


Fig. 7. Average duty cycle as a function of the decision threshold for different systems: TV (470-862 MHz), BWA (3400-3600 MHz), GSM uplink (880-915 MHz) and downlink (925-960 MHz), DCS 1800 uplink (1710-1785 MHz) and downlink (1805-1880 MHz), UMTS uplink (1920-1980 MHz) and downlink (2110-2170 MHz), PMR/TETRA and paging (406.1-470 MHz), and aeronautical radio navigation and location (960-1350 MHz).

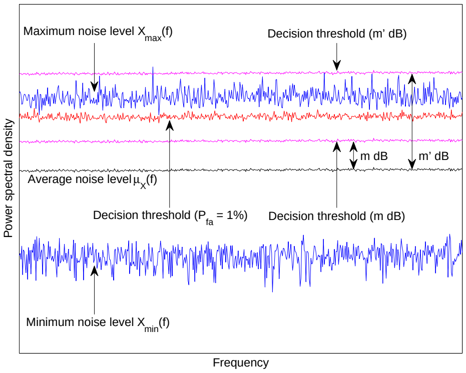


Fig. 8. Different criteria to determine the decision threshold.

The decision threshold is a critical parameter in data post-processing since its value severely impacts the obtained occupancy statistics. High decision thresholds may result in underestimation of the actual spectrum occupancy due to the misdetection of faded primary signals. On the other hand, excessively low decision thresholds may result in overestimation caused by noise samples above the threshold. As shown in figure 7, different systems may exhibit different sensitivities to the variation of the decision threshold. In general, the duty cycle for high-powered transmitters such as TV stations and cellular communication base stations (downlink direction) shows a lower decreasing rate as the decision threshold increases. On the other hand, for bands where the received signal levels are lower the duty cycle is more sensitive to the decision threshold, with changes from 100% to 0% in 5 dB or less. This observation highlights the importance of using an adequate criterion to select the decision threshold.

Several methods to determine the decision threshold have been employed in previous studies. Most of them are based on *a priori* knowledge of noise properties. The simplest approach to determine the threshold is via empirical analysis where the collected measurements are visually inspected and the threshold is manually placed somewhat in the middle between the noise and signal curves [2], [11]. The main shortcomings of these approaches are their subjectivity and their difficulty to be implemented in an automated fashion. Other more rigorous methods to determine the decision threshold are shown in figure 8. These methods assume a perfect knowledge of noise properties, at least of the mean $\mu_X(f)$, minimum $X_{min}(f)$ and maximum $X_{max}(f)$ values, which can be easily measured by simply replacing the antenna with a matched load. A simple possibility would be to select the maximum noise level $X_{max}(f)$ recorded at each measured frequency point f as the decision threshold $\gamma(f)$, which will be referred to as MaxNoise criterion. This option guarantees that no noise samples lie above the threshold and therefore that spectrum occupancy is never overestimated. However, occupancy may be underestimated due to weak signal samples lying below the maximum noise level. To solve this problem, an alternative option is to fix the decision threshold m decibels above the average noise level (m-dB criterion), e.g. $\gamma(f) = \mu_X(f) + 6\ dB$ as in [6] or $\gamma(f) = \mu_X(f) + 10\ dB$ as suggested in [16]. The main drawback of this method is that the noise variance $\sigma_X(f)$ and also the maximum noise level $X_{max}(f)$ may vary band-by-band depending on several measurement configurations. Therefore, a constant m-dB threshold over the entire measurement range may not be appropriate. A different solution that conciliates the previous criteria is the Probability of False Alarm (PFA) criterion. Based on a target PFA for a CR network equal to P_{fa}, the decision threshold $\gamma(f)$ at each measured frequency point f is fixed such that only a fraction P_{fa} of the measured noise samples $X(f)$ (replacing the antenna with a matched load) lie above the threshold, i.e. $\gamma(f) = F^{-1}_{X(f)}(1 - P_{fa})$, where $F^{-1}_{X(f)}(\cdot)$ represents the inverse of $F_{X(f)}(\cdot)$, the cumulative distribution function of $X(f)$. This alternative is an intermediate approach between MaxNoise and m-dB, with P_{fa} being the maximum overestimation error.

There exists a second category of algorithms to determine the decision threshold without any *a priori* knowledge of noise properties. Some examples are the Otsu's algorithm [17] and the Recursive One-Side Hypothesis Testing (ROSHT) algorithm proposed in [18]. The main drawback of these algorithms is that they are more complex and are based on some assumptions that may not hold always and that are not necessary when noise properties can be known as it is our case. This type of algorithms is not considered in our study.

To quantitatively assess the impact of the decision threshold on the obtained occupancy statistics, the same set of empirical data was post-processed based on the energy detection principle but using the MaxNoise, m-dB and PFA criteria. The obtained results are shown in figure 9. The left-hand side of the figure illustrates the average duty cycle for the 146-235 MHz and 235-317 MHz bands, which are occupied by a wide variety of licensed systems. When the decision threshold is lowered from the MaxNoise criterion to the PFA 1% criterion, a maximum amount of 1% noise samples are allowed to lie above the decision threshold and may be detected as signal samples. A maximum increase of 1% in the duty cycle due to noise samples is hence expected in this case. However, the graphs indicate that the average duty cycle for the aforementioned bands increases 12.76% (from 43.32% to 56.08%) and 12.55% (from 28.90% to 41.45%) respectively when moving from MaxNoise to PFA 1%. Since these increments are higher than 1% this clearly means that PFA is able to detect some additional primary weak signals lying around the noise level in these bands. If the decision threshold is further lowered with

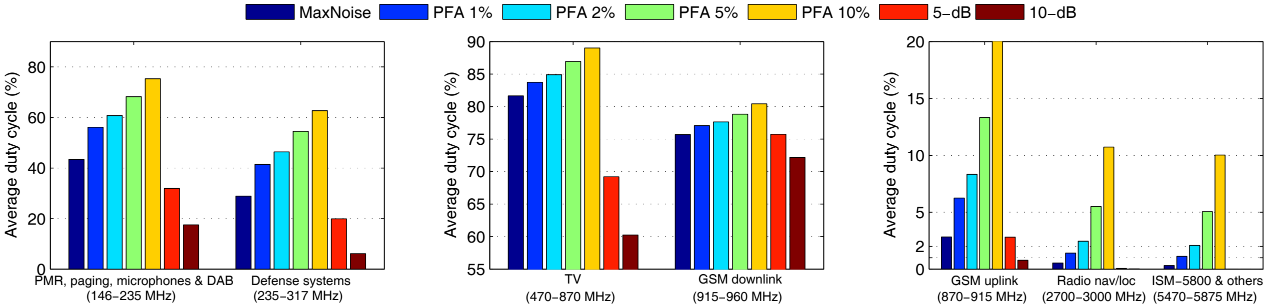


Fig. 9. Impact of different decision threshold selection criteria on the detected activity for various licensed frequency bands.

the PFA 2%, 5% and 10% criteria, more weak primary signals are detected and the resulting average duty cycles increase (and so does the maximum overestimation error). A similar trend is observed in the detection of weak GSM uplink signals, although in this case the PFA improvement is less significant.

In the 5470-5875 MHz band (completely unoccupied) and the 2700-3000 MHz band (with a few military radars), the PFA criterion increases the average duty cycle by the same amount as the P_{fa} parameter of the algorithm, i.e. when moving from e.g. PFA 2% to PFA 5% the duty cycle increases about 3%. Such increase is not caused by true weak signals but noise samples above the threshold. As shown in figure 9, the same trend is observed for bands with high-power transmitters such as TV and GSM (downlink). Such strong signals can certainly be detected even with relatively high decision thresholds (5/10 dB), and lowering the decision threshold below the maximum noise level with the PFA criterion does not translates into the detection of some weak signals, which indeed do not exist in these bands, but the misinterpretation of some noise samples as signals. In such a case PFA results in an occupancy overestimation equal to P_{fa} with respect to MaxNoise.

Based on the previous discussion, the PFA 1% criterion can be considered as a reasonable tradeoff between improvement in the ability to detect weak signals and overestimation error in bands occupied by high-power transmitters. Regarding the m-dB criterion, our experiments demonstrated that a constant value of m over the entire measurement range failed to provide consistent results, as it is verified in figure 9.

VI. CONCLUSION

Although several spectrum measurement campaigns have been performed in the context of cognitive radio, there is a lack of common and appropriate evaluation methodology. This work has presented a comprehensive and in-depth discussion of several important methodological aspects that need to be carefully taken into account when evaluating spectrum usage in order to avoid inaccurate results and properly characterize the activity of primary networks. The paper discussed the design of the measurement setup as well as several aspects related to the frequency and time dimensions. The spatial dimension will be analyzed as a part of our future work.

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