Spectral Occupation Measurements and Blind Standard Recognition Sensor for Cognitive Radio Networks

Miguel López-Benítez, Fernando Casadevall, Anna Umbert and Jordi Pérez-Romero
Department of Signal Theory and Communications
Universitat Politècnica de Catalunya (UPC)
Barcelona, Spain
[miguel.lopez, ferranc, annau, jorperez]@tsc.upc.edu

Rachid Hachemani, Jacques Palicot and Christophe Moy
SUPELEC/IETR
Avenue de la Boulaie CS 47601 F-35576
Cesson-Sévigné, France
[rachid.hachemani, jacques.palicot, christophe.moy]@supelec.fr

Abstract—**Cognitive radio has been claimed to be a hopeful solution to the existing conflicts between spectrum demand growth and spectrum underutilization. The basic underlying idea of cognitive radio is to allow unlicensed users to access in an opportunistic and non-interfering manner some licensed bands temporarily unoccupied by licensed users. The cognitive radio concept relies on two basic premises: the current spectrum underutilization, which has been demonstrated in some spectrum measurements campaigns, and the ability of unlicensed users to effectively detect and identify the presence of different licensed technologies in order not to cause harmful interference. In this context, this paper reports the joint work on these two areas that is currently being carried out in the framework of the FP7 Network of Excellence in Wireless COMmunications (NEWCOM++). Concretely, this paper presents spectrum occupancy measurements conducted in the frequency range from 75 MHz to 7075 MHz that demonstrate the low degree to which spectrum is currently used in an urban outdoor environment and also describes the blind standard recognition sensor concept, a sensor embedded in a cognitive radio equipment to enable the identification of many commercial wireless standards without the need to connect to any network. The joint research in both areas is a key step in promoting and validating the idea of dynamic spectrum usage.**

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 current 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 primary/licensed users, usually referred to as *spectrum holes* or *white spaces*, place secondary/unlicensed transmissions within such spaces and vacate the channel as soon as primary users return. The CR concept therefore implicitly relies on two basic premises: the existence of enough white spaces caused by primary spectrum underutilization and the ability of secondary users to effectively detect and identify the presence of different licensed technologies in order not to cause harmful interference. In this context, this paper reports the joint work on these two areas that is currently being carried out in the framework of the FP7 Network of Excellence in Wireless COMmunications (NEWCOM++).

The first part of the paper presents spectrum occupancy measurements conducted in the frequency range from 75 MHz to 7075 MHz in an urban outdoor environment. Measurements of the radio environment can provide valuable insights into current spectrum usage. A proper understanding of current spectrum usage patterns can be very useful for policy makers to define adequate dynamic spectrum policies and for the research community in general to identify appropriate frequency bands for the deployment of future CR networks. Although several measurement campaigns covering both wide frequency ranges [1]–[6] and some specific licensed bands [7]–[11] have already been performed, the number of measured locations can arguably be considered as insufficient. To enable a wide scale deployment, the CR technology cannot be based on the conclusions derived from studies conducted in a few geographical areas or under specific spectrum regulations. CR should take into account the possibility to operate under many different spectrum regulations and a wide variety of scenarios. Further spectrum measurements are therefore required, which motivates our spectrum measurement campaign. The obtained results demonstrate the availability of a significant amount of white space that could potentially be used by CR networks.

The second part of the paper presents the Blind Standard Recognition Sensor (BSRS) concept. The BSRS is a sensor embedded in a CR equipment that combines (by a fusion process and using signal processing algorithms) information provided by several other sensors in order to permit the identification of many commercial wireless standards without the need to connect to any external network. This information can be exploited by the CR network in order to properly adapt to the operating environment and hence to improve the overall spectrum utilization and system performance.

The rest of this paper is organized as follows. First, section II describes the measurement setup and methodology employed to perform the measurements reported in this paper. The obtained occupancy results are shown and discussed in section III. Sections IV and V presents the BSRS concept and its internal algorithms. Finally, section VI summarizes the paper.

II. Measurement Setup and Methodology

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 setup employed in this study is shown in figure 1. The design is composed of two broadband antennas, a switch, several filters, a low noise amplifier and a high performance spectrum analyzer Anritsu Spectrum Master MS2721B. Two broadband discone antennas (vertically polarized with omnidirectional receiving pattern in the horizontal plane) of models AOR DN753 (used between 75 and 3000 MHz) and JXTXPZ-100800-P (used between 3000 and 7075 MHz) are connected to a switch, which selects the desired frequency range. Low pass and high pass filters are used to reject undesired out-of-band signals. Additionally, a band stop filter is employed to attenuate overloading FM signals. To compensate for device and cable losses and to increase the system sensitivity, a low noise amplifier is placed close to the antennas. The selected mid-gain amplifier provides a good sensitivity improvement while satisfying the required Spurious-Free Dynamic Range (SFDR).

During the measurements the antennas were placed on a building roof in urban Barcelona (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 headquarter as well as some maritime and aeronautical transmitters due to the relative proximity to the harbor and the airport.

The main configuration parameters for the spectrum analyzer are listed in TABLE I. The measured frequency range was divided into 25 blocks according to the local spectrum allocations and taking into account the transmitted signal bandwidth for each band. For example, frequency bins of 81.8 kHz were used to measure the GSM bands (200 kHz bandwidth) while 745.5 kHz and 727.3 kHz bins were employed for TV (8 MHz) and UMTS (5 MHz) bands respectively. Each block was measured during 24 hours. The measured traces were saved in an external storage device and post-processed off-line.

III. Measurement Results and Analysis

A. Occupancy Metrics

Spectrum occupancy has been evaluated by means of three different occupancy metrics, which are shown in the figures presented in section III.B. The first occupancy metric is Power Spectral Density (PSD), which is shown in the upper graph of

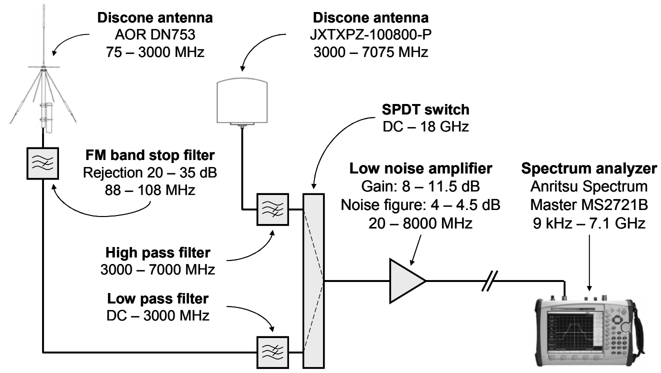

Figure 1. Measurement setup employed in this study.

TABLE I. Spectrum analyzer configuration.

Parameter	Value
Frequency range	75 – 7075 MHz
Frequency blocks / bins	Variable (45-600 MHz / 81.8-1090.9 kHz)
Resolution/video bandwidth (RBW/VBW)	10 kHz / 10 kHz
Sweep time	Auto (selected by the spectrum analyzer)
Reference level	– 20 dBm
Scale	10 dB/div
Detection type	Average (RMS) detector

each figure in minimum, maximum and average values. When considered together, minimum, maximum and average PSD provide a simple characterization of the temporal behavior of a channel. For example, if the three PSD values are quite similar, it suggests a single transmitter that is always on, experiences a low level of fading and is probably not moving. At the other extreme, a large difference among minimum, maximum and average suggests a more intermittent use of the spectrum [10].

The middle graph of each figure shown in section III.B represents the instantaneous evolution of the temporal spectrum occupancy. A black dot indicates that the corresponding frequency point was measured as occupied at that time instant, while the white color means that the frequency point was measured as idle. To determine whether a frequency band is used by a licensed user, different sensing methods have been proposed in the literature [12]. 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 and is also employed in this study. 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 and could be employed by a CR network. The decision threshold employed in this study assumes a probability of false alarm equal to 1%. To compute such decision threshold, the system's noise was measured by replacing the antennas with a 50 Ω matched load. The decision threshold at each frequency point was then fixed such that exactly 1% of the measured noise samples lied above the threshold, which implies a probability of false alarm of 1%. It is worth noting that the decision threshold obtained with this method is not constant since the system noise floor slightly increases with the frequency. Based on the obtained decision threshold, PSD samples above the threshold are assumed to be occupied; the rest of frequencies are assumed to be idle.

To more precisely quantify the detected primary activity, the lower graph of each figure shows the duty cycle as a function of frequency. 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 the decision threshold and hence that were considered as samples of occupied channels. For a given frequency point, this metric represents the fraction of time that a frequency is considered to be occupied. For a certain frequency band, the average duty cycle is computed by averaging the duty cycle of all the frequency points measured within the band.

B. Analysis of Spectrum Occupancy

The obtained measurement results are shown in figures 2, 3 and 4. As it can be appreciated, spectrum experiences a relatively moderate use below 1 GHz and a low usage between 1 and 2 GHz, while remains mostly underutilized between 2 and 7 GHz (with some clear exceptions that will be discussed later on). In fact, while the average duty cycle between 75 and 2000 MHz is 31.02%, the value for this parameter between 2000 and 7075 MHz is only 2.75%, as shown in TABLE II. The overall average duty cycle over the whole frequency range considered in this study is only 17.78%, which reveals the existence of significant amounts of unused spectrum that could potentially be exploited by future CR networks. Although these results clearly indicate low spectrum utilization levels, they do not provide a clear picture of how spectrum is used in different frequency bands allocated to different specific services. Therefore, in the following we discuss in detail the spectrum usage in some allocated bands of interest.

TABLE II. AVERAGE DUTY CYCLE STATISTICS.

Frequency range (MHz)	Average duty cycle		
75 – 1000	42.00 %	31.02 %	17.78 %
1000 – 2000	13.30 %		
2000 – 3000	3.73 %	2.75 %	
3000 – 4000	4.01 %		
4000 – 5000	1.63 %		
5000 – 6000	1.98 %		
6000 – 7075	1.78 %		

Although the highest spectral activity is observed below 1 GHz, some opportunities for CR networks can still be found in this frequency range, even in those bands with the highest observed average duty cycles. For example, the frequency band 470-862 MHz (depicted in figure 5), which is allocated to analogical and digital terrestrial TV in Spain, shows an average duty cycle of 82.08%, one the highest values observed in this study. Although the sub-band 830-862 MHz (exclusively reserved for digital TV systems) exhibits an intensive usage of nearly 100% that precludes any CR applications, the rest of the band between 470 and 830 MHz (allocated to both analogical and digital TV systems) shows some spectrum white spaces. Notice that occupied TV channels show a duty cycle of about 100%, i.e. continuous broadcasting, which impedes temporary opportunistic usage of those channels. Only one channel out of all the TV channels received at our measurement location (channel 38, 606-614 MHz) was disconnected during a short period in the night, which might be due to maintenance operations since this behavior was not observed in some previous experiments. In general, occupied TV channels show an average duty cycle of 100%. Spectrum opportunities in this band usually come from TV channels that are received with very weak signal levels. In our case, the measured average duty cycle between 470 and 830 MHz was 80.49%, meaning that one fifth of the TV band (approximately 80 MHz) is unoccupied due to the weak reception of the signals broadcasted from distant TV stations. Therefore, although the TV band appears as considerably populated in our study, it provides some interesting opportunities for secondary usage.

Another interesting case below 1 GHz is observed in the frequency bands allocated to the Global System for Mobile communications (GSM). The Enhanced GSM (E-GSM) 900 system operates in the 880-915 MHz (uplink) and 925-960 MHz (downlink) bands as shown in figure 6. The uplink band appears as a potential candidate for CR applications with an average duty cycle equal to 6.26%. However, in this case it is important to highlight that the low activity recorded in this band does not necessarily imply that it could be used by CR networks. As a matter of fact, the maximum PSD observed in figure 6 reaches significant values, revealing the presence of primary signals in uplink. The considerably higher activity in downlink (96.33%) and the fact that GSM is based on Frequency-Division Duplex (FDD) suggest that the actual usage of the uplink band might be higher than the activity level recorded by our system at our measurement location. The unbalanced occupancy patterns observed between uplink and downlink in figure 6 can be explained as follows. First, the transmission power of GSM base stations is considerably higher than that of cellular phones. Therefore, the presence of GSM downlink signals can be more easily detected. Moreover, the antenna employed in our study was placed on the roof of a building with direct line-of-sight to several nearby base stations, which enabled us to accurately measure the high spectral activity of the downlink. On the other hand, the low usage observed in the uplink may be due to the usually low transmission power of cellular phones and the resulting weak uplink signal received at the antenna. The detection of such signals might be hindered by the fact that cellular phones usually operate at the ground level or low altitudes and usually have no direct line-of-sight neither with the serving base station nor the antenna employed in our study, which makes more difficult to detect the uplink activity. In fact, the maximum PSD observed in uplink in figure 6 may be due to phone calls from nearby locations, e.g. the upper floors of the building. Therefore, from the obtained results we cannot conclude low activity levels in the E-GSM 900 uplink. Similar trends were observed in previous studies, e.g. [6].

In the lower spectrum bands 75-235 MHz, 235-400 MHz and 400-470 MHz, low to moderate average duty cycles of 48.59%, 24.88% and 29.85% are observed respectively. These bands are populated by a wide variety of narrowband systems, including Professional Mobile Radio/Public Access Mobile Radio (PMR/PAMR) systems (75.2-87.5 MHz, 223-235 MHz, 406-430 MHz and 440-470 MHz), FM analogic audio broadcasting (87.5-108 MHz), aeronautical radionavigation and communication systems, maritime systems (GMDSS), paging systems (ERMES) and fixed links (108-174 MHz), audio applications such as wireless microphones (174-195 MHz) and Digital Audio Broadcasting (DAB) systems (195-223 MHz), satellite systems (137-138 MHz and 400-406 MHz) and amateur systems (144-146 MHz and 430-440 MHz). Although these bands exhibit low to moderate average duty cycles, the free spectrum gaps found in this region of the spectrum are of considerably narrow bandwidths due to the narrowband nature of the systems operating within these bands. Moreover, the whole band from 235 to 400 MHz is exclusively reserved for security services and defense systems of the Spanish Ministry of Defense, which in principle precludes the use of such spectrum bands for CR applications. Other bands below 1 GHz with low or moderate levels of activity but narrower available free bandwidths are those assigned to wireless microphones and RFID (862-870 MHz), CT1 cordless phones (870-871 and 915-916 MHz), cellular access rural telephony (874-876 and 919-921 MHz) and R-GSM 900 (876-880 and 921-925 MHz).

Between 1 and 2 GHz, spectrum is subject to a low level of utilization, while remains mostly unused between 2 and 7 GHz. Above 1 GHz the highest spectrum usage is observed for the bands allocated to the Digital Cellular System (DCS) 1800 operating at 1710-1785 MHz and 1805-1880 MHz (figure 7), the Universal Mobile Telecommunication System (UMTS) operating at 1920-1980 MHz and 2110-2170 MHz (figure 8), and Broadband Wireless Access (BWA) systems operating in the 3.4-3.6 GHz band between 3520 and 3560 MHz (figure 9).

Notice that the differences between uplink and downlink usage patterns that were appreciated for E-GSM 900 are also observed for DCS 1800 and UMTS. In the case of DCS 1800 the differences are more accentuated due to the fact that mobile stations in DCS 1800 have lower transmission powers than in GSM 900, which results in a reduced occupancy in the uplink. In the case of UMTS the difference is higher due to the spread spectrum nature of the Wideband Code Division Multiple Access (WCDMA) radio technology employed by UMTS. WCDMA signals are modulated over large bandwidths, which results in very low transmission powers. Such signals are difficult to detect with spectrum analyzers (but techniques such as the BSRS presented in section IV could enhance the detection). As a result, a very low activity was recorded in UMTS uplink. Although DCS 1800 and UMTS show higher levels of occupancy in downlink (58.82% and 56.93% respectively), these bands also provide some opportunities for secondary access. In the case of DCS 1800 some portions of the downlink band show a well defined periodic usage pattern, as it is illustrated in figure 10 where the average duty cycle computed over 1-hour periods is shown. Such temporal patterns could be exploited by some secondary CR applications by accessing spectrum during low-occupancy periods. In the case of UMTS, spectrum opportunities are due to several 5-MHz channels that appear to be unoccupied. Moreover, the UMTS bands reserved for the Time Division Duplex (TDD) component (1900-1920 and 2010-2025 MHz), the satellite component (1980-2010 MHz and 2170-2200 MHz) and extension (2500-2690 MHz) are not used.

Although the highest activity above 1 GHz is observed for DCS 1800, UMTS and BWA systems, some other bands are also clearly occupied but at lower occupancy rates, which in principle offer additional opportunities for CR applications. Some examples are the 1400-1710 MHz band, allocated to different wireless systems such as Satellite Personal Communication Systems (S-PCS) as well as aeronautical radionavigation, audio broadcasting and defense systems, or the 3800-4200 MHz band, occupied by analogical links for telephony.

Finally, it is worth noting that some spectrum bands appear as unoccupied when judged by their average duty cycles. Nevertheless, the maximum PSD reveals that some primary users, although difficult to detect, are present in such bands. Some examples are the uplink bands for mobile communications, the 2400-2500 MHz band (ISM-2450), the 2900-3100 MHz band (radio navigation and location defense systems) and the 4200-4400 MHz band (allocated to aeronautical radionavigation).

C. *Final Remarks*

Figure 11 summarizes the band by band average spectrum occupancy statistics. The obtained results demonstrate that some spectrum bands are subject to intensive usage while some others show moderate utilization levels, are sparsely used and, in some cases, are not used at all. In general, the average spectrum occupancy observed in frequency and time in this study was found to be significantly low, concretely 17.78% for the whole measured frequency range between 75 and 7075 MHz.

The highest occupancy rates were observed for bands allocated to broadcast services (TV as well as analogical and digital audio), followed by digital cellular services as PMR/PAMR, paging, and mobile cellular communications (E-GSM 900, DCS 1800 and UMTS) among others. Other services and applications, e.g. aeronautical radio navigation and location or defense systems, show different occupancy rates depending on the considered allocated band. In general, spectrum experiences a relatively moderate use below 1 GHz, a low usage between 1–2 GHz, and remains mostly underutilized between 2–7 GHz.

Most of spectrum offers possibilities for secondary CR usage, even those bands with the highest observed activity levels in terms of average duty cycle. Nevertheless, it is worth highlighting that the average duty cycle by itself is not a sufficient statistic to declare a spectrum band as unoccupied. Indeed, the maximum PSD of some portions of the spectrum reveals that some allocated frequency bands with null average duty cycles are actually being occupied by some operating primary systems. This issue should carefully be taken into account when selecting frequency bands for potential CR applications.

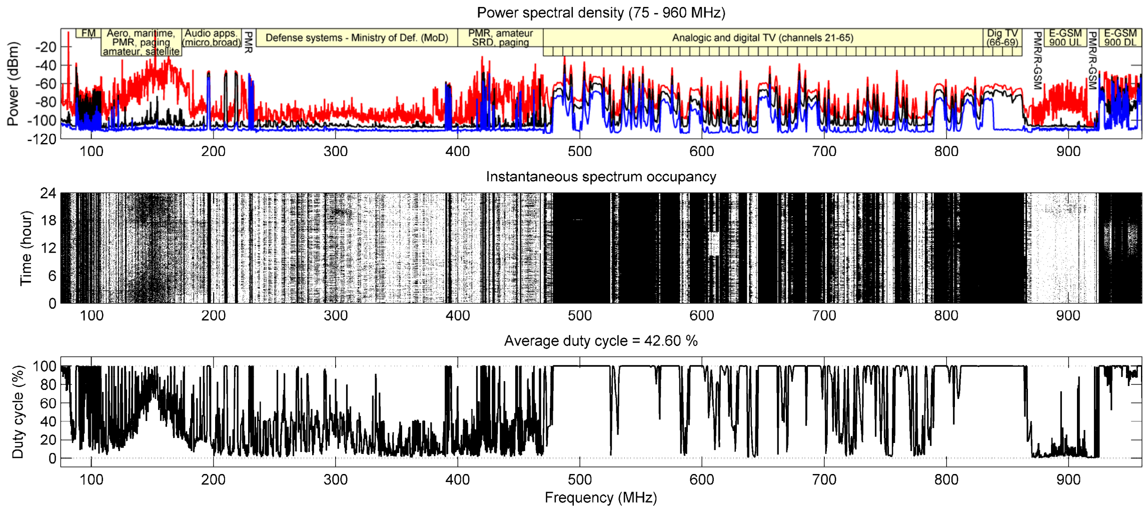

Figure 2. Spectrum occupancy between 75 and 960 MHz.

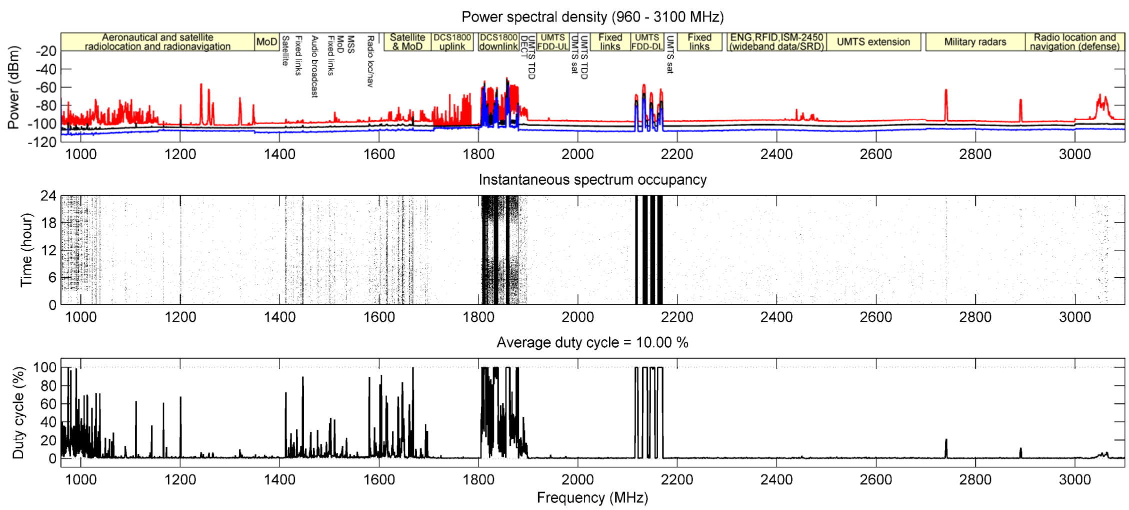

Figure 3. Spectrum occupancy between 960 and 3100 MHz.

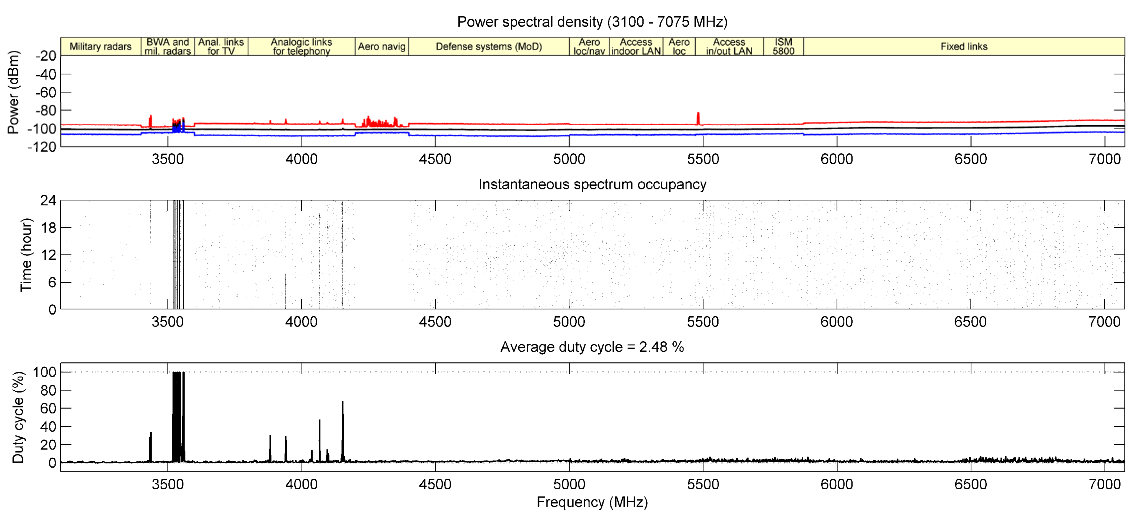

Figure 4. Spectrum occupancy between 3100 and 7075 MHz.

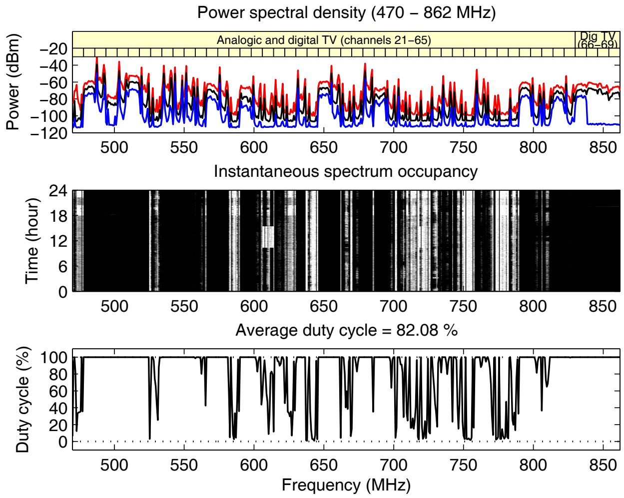

Figure 5. Spectrum occupancy for TV bands (470-862 MHz).

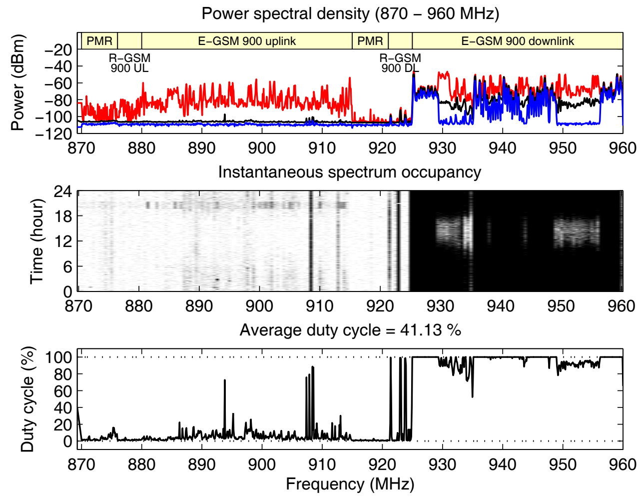

Figure 6. Spectrum occupancy for E-GSM 900 (870-960 MHz).

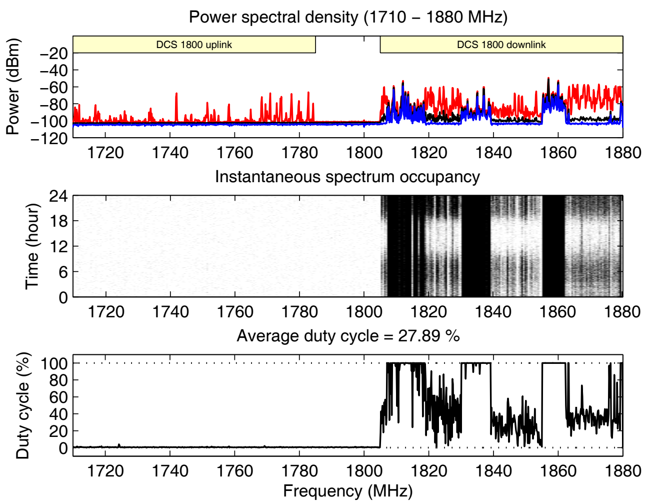

Figure 7. Spectrum occupancy for DCS 1800 (1710-1880 MHz).

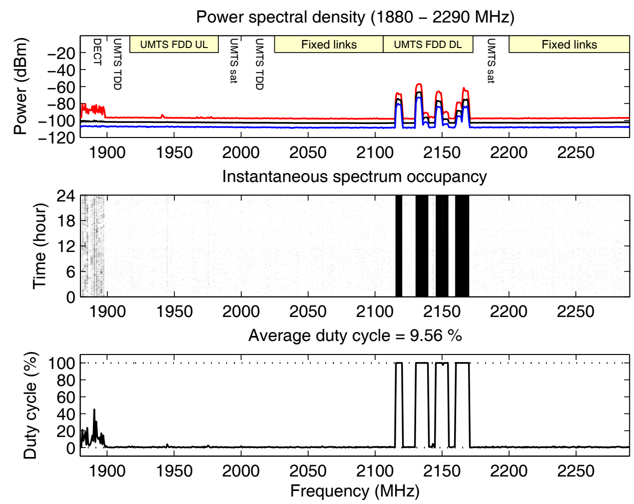

Figure 8. Spectrum occupancy for UMTS (1880-2290 MHz).

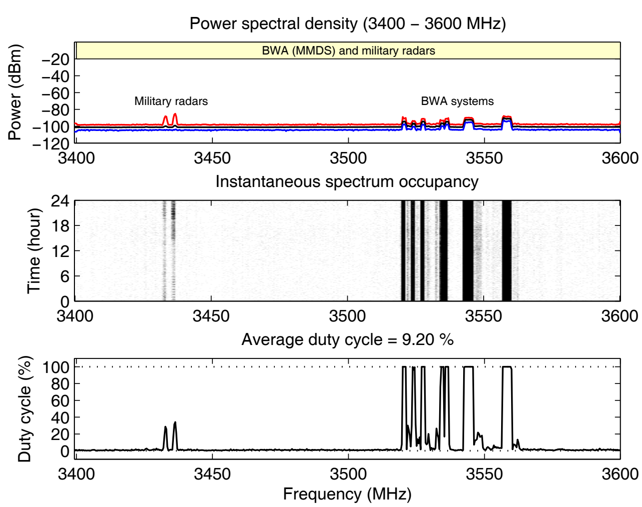

Figure 9. Spectrum occupancy for BWA (3400-3600 MHz).

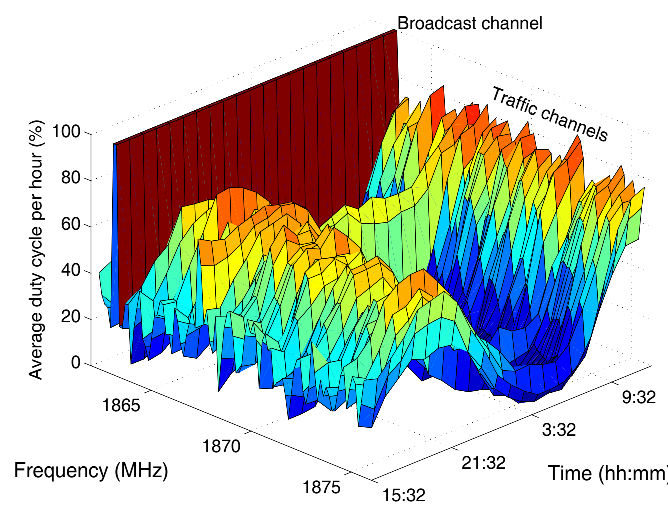

Figure 10. Average duty cycle per hour for DCS 1800 (1862.5-1875.5 MHz).

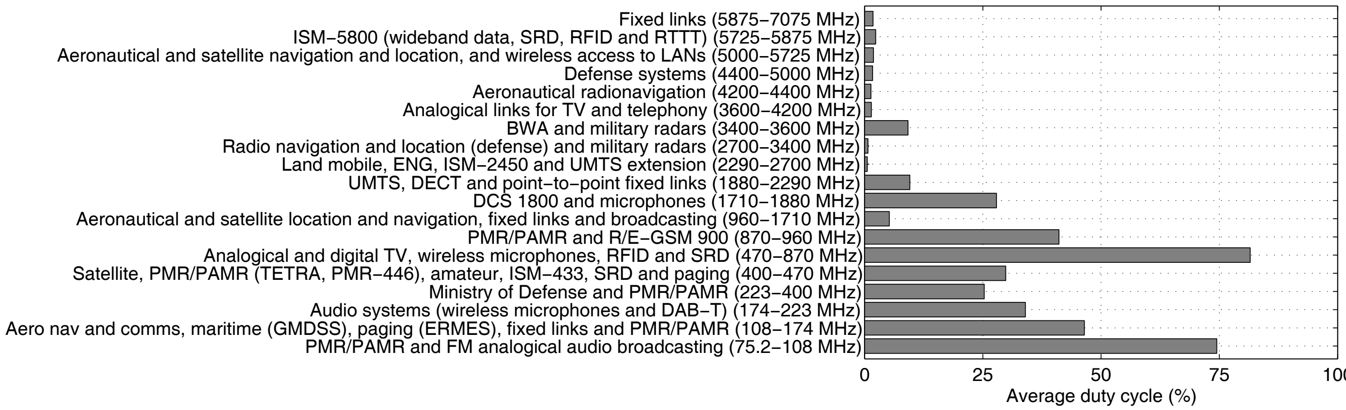

Figure 11. Band by band average duty cycle statistics for the whole measurement range (75-7075 MHz).

IV. Blind Standard Recognition Sensor

A. General Description

As it is described in figure 12, this sensor analyzes the received signal in three steps. The first step is an iterative process that decreases the signal bandwidth to be analyzed, so that the band of analysis is reduced to the only non-zero regions. During the second step an analysis is performed thanks to several sensors. Then during the third step, a fusion of all the information given by the analysis phase is performed in order to decide which standard is present.

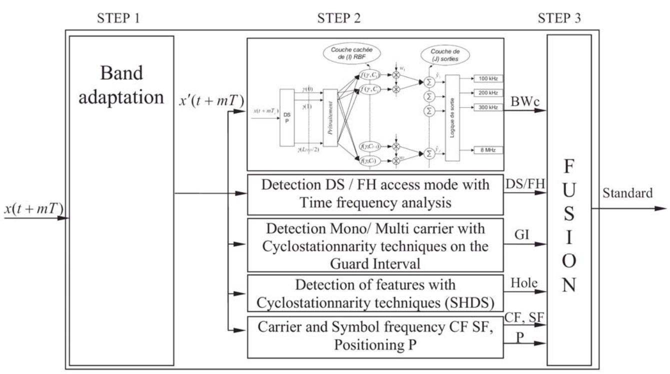

Figure 12. The blind standard recognition sensor (BSRS).

During the second step, different sensors analyze the bands selected in step one. Many sub-sensors could be used for the recognition of the standard in use such as positioning of the equipment, presence of the telecom signal, detection of the carrier frequency, recognition of the signal bandwidth, recognition of the Frequency Hopping/Direct Spread (FH/DS) signal, recognition of single/multi carrier, etc. In our implementation only three sub-sensors are used for standard recognition.

B. Step 1: Bandwidth Adaptation

The difficulty here relies in the fact that the ratio between the global bandwidth to be analyzed and the smallest bandwidth parameter to be recognized may be very high. Therefore an iterative adaptation of the bandwidth to be analyzed is performed to solve it. In each iteration the process analyzes energy in the band with a conventional periodogram, then filters and decimates the samples around the detected peak of energy.

C. Step 2: Analysis with Sensors

We chose three sub-sensors to analyze and identify the received signal according to a list of predetermined standards: the bandwidth recognition, single/multi-carrier detection and FH/DS signal detection. Other sensors could be used to identify other parameters.

The bandwidth recognition sensor has been fully described in [13], where it was claimed that, in the frequency domain, the channel bandwidth (BW_c) was a fully discriminating parameter. To find the bandwidth shape on the received signal a choice has been made to compute a PSD on this signal in order to obtain its BW_c shape. The empirical spectrum shape is compared with a reference spectrum shape.

Single/multi carrier detection sensor was also firstly presented in [13]. It is well known that a Guard Interval (GI) is inserted in multi-carrier systems in order to avoid Inter-Symbol Interference (ISI). There are several possibilities for creating this GI. The simplest and most usual way is to copy the end of the symbol in the GI. After the computation of the autocorrelation function, the cyclic frequency corresponding to the GI is derived.

Unfortunately, the results previously presented with the fusion of the two previous sensors are not sufficient yet. It fails in the discrimination of Bluetooth and IEEE 802.11b at 2.4 GHz in FH Spread Spectrum (FHSS) mode. In this situation, the two standards coexist at the same time in the same frequency band, so the resulting spectrum is the product of the original spectrums and consequently the previous sensor does not work properly. Therefore, we need to find another parameter. The detection between FH and DS modes should solve this difficulty. We describe this FH sensor in section V in more detail.

D. Step 3: Fusion

During the third step, a fusion of all the information given by the analysis phase is performed in order to decide which standard is present. At the end of the analysis step, three indicators are obtained. The simplest way to make the fusion is to apply some logical rules on these indicators. This method could be improved with neural networks (like Multilayer Perceptron). Moreover, as these indicators give information that could be weighted by a reliability factor, a future work will further explore solutions based on Bayesian networks.

V. FH/DS Signal Detection

Recently [14] addressed the FH/DS signal detection problem and proposed to use the Wigner-Ville Transform (WVT) in order to discriminate between Bluetooth and IEEE802.11b. The results are well adapted to our needs, because the system can discriminate between FH and DS signals. Figure 13 presents the WVT of a FH signal with noise. With an adequate threshold applied to this signal, a binary representation is extracted as shown in figure 14.

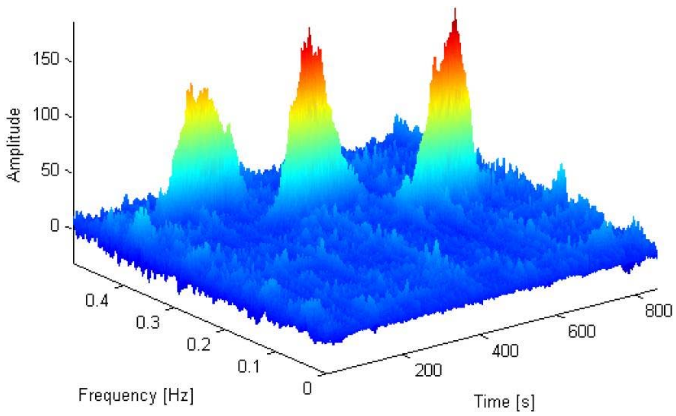

Figure 13. WVT of a FH signal with SNR = 5 dB.

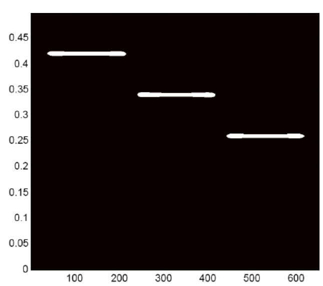

Figure 14. Time/frequency plane after the binarization threshold.

The threshold used in the proposed algorithm is based on the mean value of the WVT of the signal. Then, segmentation (both in time and frequency) offers the opportunity to extract the number of components in the time-frequency plane and to compute for each component *i* three features: time duration (tf-td), frequency deviation (ff-fd) and time period between two successive components (td_i-tf_{i-1}), as it is shown in figure 15. The obtained vectors of these three features are then compared to a decision threshold in order to decide if the signal is (or is not) a FH signal. The algorithm is shown in section V.A, and the obtained results are discussed in section V.B.

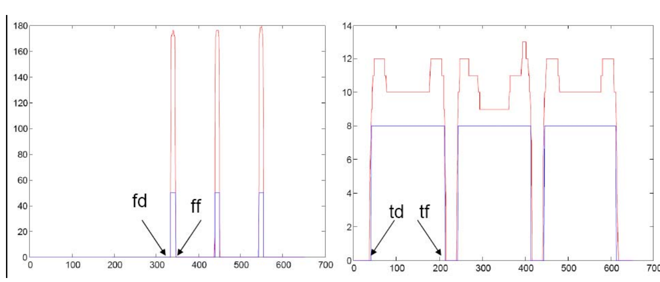

Figure 15. Features obtained after segmentation.

A. The FH Detection Algorithm

The algorithm employed to determine the presence of FH signals is described in the following scheme:

1. Bandwidth adaptation of $x(t)$
2. $tfr_x(t,\nu)$ = Time Frequency Representation of $x(t)$
3. $tfrb_x(t,\nu)$ = Threshold $tfr_x(t,\nu)$ by the mean value $\overline{tfr_x(t,\nu)}$
4. Histogram segmentation :
   - 4.1 Vertical (time segmentation)
   - 4.2 Horizontal (frequency segmentation)
5. Features extraction :
   - 5.1 Nb = number of signal components
   - 5.2 Ti = duration of the component i
   - 5.3 Bpi= bandwidth of the component i
   - 5.4 $Tm = \frac{1}{Nb}\sum_i T_i$
   - 5.5 $Bpm = \frac{1}{Nb}\sum_i Bp_i$
   - 5.6 $Delta = \sum_{i \neq j}(Ti - Tj)$
6. if(Nb = 1) than
   - 6.1 x(t) is not FHSS
   - 6.2 Go to the end.
7. else
   - 7.1 Metric calculation (vector of the tree features) :

   $M = [\sum_i^{Nb}|T_i - Tm|\ ,\ \sum_i^{Nb}|Bp_i - Bpm|\ ,\ Delta]$
   - 7.2 if ($M \leq Vs$) The signal is FHSS
   - 7.3 else The signal is not FHSS

B. Simulation Results

In this section two types of results are presented. First, good detection results with noisy synthetic signals are presented (Figure 16). Then, in order to be as close as possible to reality, we use real signals digitized as in [13] in order to obtain the false alarm vector presented in TABLE III.

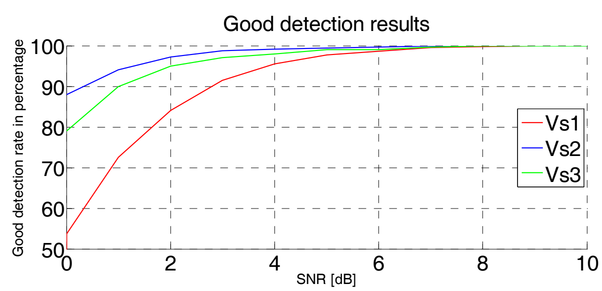

Figure 16. FH good detection versus SNR for 10,000 runs.

The synthetic signal of figure 16 is a Bluetooth FH signal. The three curves are obtained for different values for the threshold: Vs1, Vs2 and Vs3. Threshold Vs2 offers the best tradeoff between good detection rate (87% at 0 dB) and false alarm rate (0.09% at 0 dB).

In the realistic context of real signals, TABLE III presents the performance of the detector in the presence of several different non-FH standards. We can see that when only a GSM signal is present, the detector never detects FH for 100 measures, which confirms its correct behavior for single-carrier signals. However, for multi-carrier standards such as DAB and Digital Video Broadcasting (DVB), the detector fails because of the common feature of FH and OFDM signals, i.e. the use of several carriers.

TABLE III. DETECTION RESULTS WITH REAL DIGITIZED SIGNALS.

Standard	GSM	DAB	DVB
FH detection	0 %	6 %	4 %

This is the goal of combining this information with the bandwidth recognition sensor described in section IV.C, performed in the fusion step of section IV.D, to decrease this false detection and obtain a global good standard recognition sensor. This answer solves the issue presented in [15] to discriminate between Bluetooth and IEEE.802.11b.

VI. SUMMARY AND FUTURE WORK

The cognitive radio paradigm has recently emerged as a promising solution to conciliate the current spectrum demand growth and spectrum underutilization without changes to the existing legacy wireless systems. The cognitive radio concept implicitly relies on two basic premises: spectrum underutilization, which has been demonstrated in some previous spectrum measurements campaigns, and ability of unlicensed users to effectively detect and identify the presence of different licensed technologies. This paper has reported the joint work on these two areas that is currently being carried out in the framework of the FP7 Network of Excellence in Wireless COMmunications (NEWCOM++). Concretely, this paper presents spectrum occupancy measurements conducted in the frequency range from 75 MHz to 7075 MHz that demonstrate the low degree to which spectrum is currently used in an urban outdoor environment and also describes the blind standard recognition sensor concept, a sensor embedded in a cognitive radio equipment to enable the identification of many commercial wireless standards without the need to connect to any network. The joint research in these areas is a key step in promoting and validating the idea of dynamic spectrum usage and both research lines are expected to converge in the future within the framework of NEWCOM++.

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