Evaluation of Spectrum Occupancy in an Urban Environment in a Cognitive Radio Context

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Abstract — **Lack of frequency spectrum is becoming one of the major problems in the telecommunication field with the introduction of several new radio communication technologies. Cognitive Radio (CR) technology promises to be one possible solution to this problem, by allowing access of unlicensed users in licensed bands, based on an opportunistic approach and without interfering with the licensed (primary) user. In order to identify which frequency bands are more suitable for such purposes, it is necessary to evaluate the degree in which licensed bands are actually used. Although some measurement campaigns have already been carried out, most of them were done in the USA and only a few in other locations worldwide. This paper presents results of a measurement campaign conducted in Bucharest, Romania, covering the frequency range from 25 MHz up to 3.4 GHz. An overview of the various spectrum sensing methods available for evaluating the spectral occupancy is presented. The measurement results are confronted with the frequency allocation table published by the national authority for communications and an analysis of the obtained data is being made.**

Keywords - spectrum occupancy; spectrum sensing; cognitive radio; measurement campaign.

I. Introduction

Radio frequency spectrum is a resource of fundamental importance in wireless communication systems. During recent years a multitude of wireless applications and services were developed, and as a result, the need for new frequency bands increased. As most of the available spectrum has already been allocated, the lack of spectrum resources has become a serious problem.

In order to address this problem, one possible approach is to create user equipment devices that are able to dynamically detect free spectrum resources and use them in order to improve overall spectrum usage. A first step in this direction was the introduction of Software Defined Radio (SDR), devices where components that have been usually implemented in hardware (e.g. filters, amplifiers, modulators/demodulators, etc.) are instead implemented by means of software. Such an approach allows the equipment to be easily reconfigured in order to receive and transmit different radio protocols by selecting which part of the software is to be used.

J. Mitola III introduced in 1999 the cognitive radio (CR) term, which can be defined as a wireless communication system that allows spectrum sharing over a wide frequency range and that is able to handle multiple radio access technologies [2].

An application of CR that would greatly contribute to an increased spectral efficiency is to allow unlicensed users access to licensed bands. In order to avoid any harmful interference to the primary (licensed) system, CR equipment should include the following functionality:

- Frequency-agility and re-configuration of radios;
- Spectrum sensing, in order to be aware of the surrounding radio environment;
- Capability of discerning between secondary and primary systems and avoidance of interference to the primary system;
- Spectrum management, in order to achieve effective co-existence and radio resource sharing with primary systems.

The spectrum sensing functionality is a key element of any CR equipment, allowing it to detect accurately the spectrum holes.

Although there are several ways in which cognitive radio spectrum sensing can be performed, a first classification can be made according to how the information is shared between CR devices in the following two categories:

- Non-cooperative spectrum sensing: This form of spectrum sensing occurs when a CR acts on its own. The CR device configures itself according to the signals it can detect.
- Cooperative spectrum sensing: Within a cooperative CR spectrum sensing system, sensing is performed by a number of different radios within the CR network. Typically, a central station will receive information from a variety of radios in the network, process it and adjust the overall CR network accordingly.

The current work represents an extension of a paper presented at the AICT 2010 conference [1]. The paper presents the results of a measurement campaign regarding spectrum occupancy conducted in Bucharest, Romania. These results represent just a preliminary work as the collected data is just instantaneous. Further measurements including long time measurements and data collected from other rural locations have been done and the results have been published in [3].

The paper is organized as follows. At first, results obtained during several other measurement campaigns are commented. Section II contains a description of the equipment used for performing the measurements. An overview of the various conventional spectrum sensing methods is given in Section III. The methodology and results of the measurements are presented in Section IV. During Section V, the measurement results are being analyzed from the cognitive radio perspective. Finally, in Section VI, the conclusion is being drawn and aspects concerning the future work are presented.

A. Related Work

Several measurement campaigns concerning spectrum occupancy were conducted worldwide [4]-[11], most of them were carried out the in the USA [4]-[5] and only a few in other locations worldwide, including Singapore [6], Germany [7]-[9], New Zeeland [10] and Spain [11], in urban or suburban scenarios. Results of a measurement campaign conducted in Chicago, USA showed a mean occupancy as low as 17.4% in the frequency band 30 to 3000 MHz [4]. Studies were also targeted at narrower frequency bands, like the public safety ones, and the benefits of cooperative sensing were highlighted [5]. During spectrum measurements taken over 12 weekday periods for a wider frequency band up to 5850 MHz in Singapore a mean occupancy value of only 4.54% was obtained [6]. The difference between indoor and outdoor locations was discussed in [7] based on measurements performed in Aachen, Germany.

Spectrum power measurements during a large public event (the 2006 Football World Cup in Germany) are presented in [8] and [9]. The campaign was conducted in 2 different cities, Dortmund and Kaiserslautern, and the measurements were taken in the proximity of football stadiums during match days. The obtained results clearly indicated a strong interdependency between spectrum occupancy values and different stages of the football match. Data collected throughout the measurement campaign was analyzed in order to find suitable methods for evaluating the vacancy of spectrum bands due to time-dependent statistics, including average channel allocation, average run length and amount of runs.

The measurement campaign conducted in urban Barcelona goes as high as 7075 MHz, using 2 different discone antennas, a low-noise amplifier and a high performance spectrum analyzer [10]. Three different metrics were used for evaluating the spectrum occupancy: power spectral density, instantaneous evolution of the temporal spectrum occupancy and duty cycle as a function of frequency. For the entire frequency band between 75MHz and 7075MHz the measured spectrum occupancy was quite low 17.78%, but if for the frequency area below 1 GHz the spectrum usage was moderate, for the are above 2 GHz the spectrum remained mostly underutilized.

However, as frequency spectrum regulations differ considerably between regions and even countries, it is important to obtain results from as many different scenarios as possible, in order to analyze the possible situations that a CR user equipment might encounter.

II. Spectrum Sensing Methods

Several spectrum sensing methods can be used in order to decide if a certain frequency band is available for opportunistic access [12]-[15]. For each of the described methods, a short description of the principle used is given, and the strengths and weaknesses of the method are underlined.

A. Energy Detection

The energy detection method provides an optimal detection in cases where the primary user signal is unknown [13]. The received radio frequency energy or the received signal strength indicator is measured and compared to a precomputed threshold to determine whether the spectrum is occupied or not.

The energy can be measured in several ways. When using an analogue implementation, a pre-filter with fixed bandwidth is required. However, this solution is not suitable for simultaneous sensing of narrowband and wideband signals, situation that is very often expected considering modern communication systems. More flexibility can be obtained when using a digital implementation, because of FFT-based spectral estimates. In this case, various bandwidth types are supported, which will allow simultaneous sensing of multiple signals.

The advantages of the energy-detection methods are universal applicability, relative low computational complexity and reduced amount of prior signal knowledge required.

The most serious drawbacks of the energy detection method are that it is highly susceptible to changes in the background noise spectral density and to the presence of in-band interference. Another major disadvantage, specific to cognitive radio scenarios, is that the energy detection method cannot distinguish the primary systems from the secondary ones sharing the same channel. This becomes a critical challenge when multiple primary systems are present in the same area where cognitive radio equipment operates.

B. Matched Filtering

A filter matched to a received signal has an impulse response equal to a conjugated and time-reversed version of the received signal [15]. This matched filter represents an optimal detection method as it provides a maximum signal-to-noise ratio (SNR) output in the presence of additive white Gaussian noise (AWGN). The output of the matched filter is compared to a threshold in order to decide if the signal corresponding to a primary system is present or not. The binary decision that has to be made is

$$\begin{aligned} &\bullet H_0, if \sum_{n=1}^{N} y[n]x[n]^* \le \lambda \\ &\bullet H_1, otherwise \end{aligned} \quad (1.1)$$

where λ represents the threshold, $y[n]$ represents the unknown signal and $x[n]^*$ represents a time-reversed version of the assumed signal.

In order to apply this matched filtering method, a priori knowledge is required about the signal that is to be detected, at both physical and medium access control layers. Fortunately, for most of the actual communication systems there is enough information available (e.g., pilot subcarrier synchronization sequence in OFDM systems, midamble sequence in GSM systems) in order to allow signal detection using this method.

Between the advantages offered by the matched filtering method can be mentioned optimality for AWGN channels, relative low computational complexity needed and the possibility to be applied to most licensed systems.

The most important disadvantages of this method are sensitivity to imperfect synchronization and poor performance in non-AWGN channels. A further drawback of the matched filtering method is that a CR equipment that operates in an area where multiple possible primary systems could be present will need a dedicated receiver for every kind of primary system. This will generate an increase of the complexity and will make the implementation of such equipment a significant challenge, even in case of programmable realization.

A variant of matched-filtering detection is tone detection. In this particular case, the presence of a tone of finite strength is detected, and this presence implies the presence of a particular signal associated with that tone’s frequency. Matched filtering or Fourier analysis of a narrow frequency band around the expected tone frequency can be used in order to detect the presence of this tone.

C. Cyclostationary Feature Detection

Spectral correlation is a statistical property that is characteristic for cyclostationary signals [15]. One or several probabilistic parameters (e.g., mean, autocorrelation, probability density function, nth-order moment, or nth-order cumulant) of cyclostationary signals are periodic functions in time domain. An example of how the cyclostationary detection can be performed is the following. First, the cyclic autocorrelation function $R_x^{\alpha}(\tau)$ of the observed signal $x(t)$ is computed as

$$R_x^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t+\tau/2)x^*(t-\tau/2)e^{-j2\pi\alpha t} dt \quad (1.2)$$

where α denotes a cyclic frequency. Further on, the spectral correlation function (SCF) $S_x^{\alpha}(f)$ is calculated as the discrete Fourier transformation of the cyclic autocorrelation function:

$$S_x^{\alpha}(f) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau) e^{-j2\pi f \tau} d\tau \quad (1.3)$$

It can be proved that

$$\begin{aligned} &S_x^{\alpha}(f) = \\ &= \lim_{T\to\infty}\lim_{Z\to\infty} \frac{1}{TZ} \int_{-Z/2}^{Z/2} X_T(t, f+\frac{\alpha}{2}\tau) X_T^*(t, f-\frac{\alpha}{2}\tau) dt \end{aligned} \quad (1.4)$$

where

$$X_T(t, f) = \int_{t-T/2}^{t+T/2} x(u) e^{-j2\pi f u} du \quad (1.5)$$

Finally, the detection is concluded by looking for the unique cyclic frequency corresponding to a maximum value in the SCF plane.

The most important advantage of the cyclostationary detection method consists in its insensitivity to noise and co-channel insensitivity. The reason for that is that noise has no spectral correlation, and the SCF can reflect only the spectral correlation properties of a single signal if the cyclic frequency is unique to that signal. A further advantage of the cyclostationary detection method is applicable to nearly all the modern communication signals. This method can work also with lower SNR than the energy detection method, as it exploits the information embedded in the received signal.

The main disadvantage of the cyclostationary detection method is that the cyclic frequency has to be be known by the secondary user. It also requires a more complex implementation and a longer observation time than in case of the energy detection method. This may cause the cyclostationary detector to be inefficient in case of spectrum holes of short time duration.

D. Wavelet Detection

The wavelet detection method is particularly suitable in case of wideband signals, as it presents advantages in terms of implementation and flexibility compared to the conventional approach of using multiple narrowband bandpass filters [15].

The entire frequency band of a wideband signal is modeled as a series of consecutive frequency sub-bands, in order to identify spectrum holes. The power spectral characteristic is smooth within each sub-band, but changes abruptly on the border of two neighboring sub-bands. By using a wavelet transform of the power spectral density of the observed signal $x[n]$, the singularities of the power spectral density $S(f)$ can be located and the available frequency bands can be identified.

The main weakness of the wavelet detection method is related to the high sampling rates needed when building a wavelet detector for large bandwidth signals.

E. *Delay-and-Multiply Detection*

Another sensing technique is the delay-and-multiply signal detector, which multiplies the collected data block with a delayed and conjugated version of itself in order to generate an additive sine-wave component the presence of which can be detected by using Fourier methods [14]. The presence of the tone implies the presence of the signal, and the exact frequency of the tone provides a parameter estimate for the signal, usually equal to the symbol rate (chip rate for direct sequence spread spectrum signals).

The delay-and-multiply detector is a simple exploitation of cyclostationarity in that it employs a quadratic transformation to generate a spectral line. This is only possible for CS signals.

The strengths of the delay-and-multiply detector are that it can provide superior sensitivity relative to the energy detectors, is robust to uncertainties in the noise power and interference parameters, and is computationally less expensive than more thorough methods that exploit the cyclostationarity property. Its main weaknesses are that it is not applicable to a large number of signals and that optimum performance requires knowledge of the optimum delay, which in turn requires knowledge of the transmitter filtering applied to the signal to be detected. That is, the optimum delay for rectangular-pulse signals is half the symbol interval, but for signals that have been filtered with a square-root raised-cosine filter, the optimum delay is zero.

F. *Swiss Army Knife Solutions*

In order to improve the overall sensing performance it would be possible to implement a spectrum-sensing device that contains a highly specialized detector for each type of signal that has to be detected: a matched filter for DVB-T, a delay-and-multiply detector for DSSS, an energy detector for GSM, etc. This kind of sensing strategy is called a Swiss Army knife (SAK) solution because of the disparate nature, computational requirements, and achievable performance of the various signal-specific sensors [14]. A possible approach would be to make a choice between the various available detectors depending of the frequency band that is scanned, which could provide information about what type of licensed signals are expected in the respective frequency area.

III. MEASUREMENT EQUIPMENT

The measurement campaign has been carried out from the top of the main building of our Department, which proves to be an excellent location for such a purpose. The terrace has direct line of sight with several FM transmitters, Analog and DVB-T TV transmitters, GSM and UMTS base stations and several other stations (GPS location: latitude 44°26'01" N, longitude 26°03'27" E, MSL altitude 150m, relative altitude 30m). The headquarters of the governmental agency for special telecommunications is also located just a few hundreds of meters away from the measurement location. A bird's eye view of the surrounding area is presented in Figure 1.

Figure 1. Bird's eye view of the measurement location (Copyright (c) 2009 Microsoft Corporation and/or its suppliers, One Microsoft Way, Redmond, Washington 98052-6399 U.S.A.).

For the frequency bands below 1 GHz a wideband discone antenna (Sirio SD1300N, specified from 25 to 1300 MHz) was used, mounted on the building terrace. The antenna has an omnidirectional pattern in the horizontal plane and was connected using a low-loss RF cable to a high performance signal analyzer (Anritsu MS2690A - 50 Hz to 6 GHz, average noise level -155 dBm/Hz at 2 GHz), located in a laboratory on the last floor of the building. Although the length of the cable was approximately 20m, the cable attenuation was less than 5 dB. For the frequency bands above 1 GHz a directional antenna (Aaronia Hyperlog 4060, 400 MHz to 6 GHz) was used. In this case, a short cable of 1.5 m (SUCOFLEX 104PEA) was used and the insertion loss was lower than -1dB. During the measurements, the spectrum analyzer was configured as described in Table I.

TABLE I. SPECTRUM ANALYZER CONFIGURATION

Parameter	Value
Frequency sub-bands	**1.** 25-230 MHz **2.** 230-400 MHz **3.** 400-470 MHz **4.** 470-766 MHz **5.** 766-880 MHz **6.** 880-960 MHz **7.** 960-1525 MHz **8.** 1525-1710 MHz **9.** 1719-1880 MHz **10.** 1880-2200 MHz **11.** 2200-2400 MHz **12.** 2400-2500 MHz **13.** 2500-2690 MHz **14.** 2690-3400 MHz
Resolution/video bandwidth (RBW/VBW)	300 kHz / 300 kHz (sub-bands **2, 3, 5, 6, 8, 9, 11, 12, 13**) 1 MHz / 1MHz (sub-bands **1, 4, 7, 10, 14**)
Sweep time	5 ms
Reference level	0 dBm
Attenuation	10 dB
Detection type	Pos & Neg
Trace points	10001

The performed measurements covered the frequency range from 25 MHz to 3400 MHz, the whole band being further divided into 14 sub-bands according to the type of service and the bandwidth of the allocated signal.

The measurement equipment is shown in Figures 2 and 3.

(a) (b)

Figure 2. Antennas used during the measurements: (a) Sirio SD1300N and (b) Aaronia Hyperlog 4060.

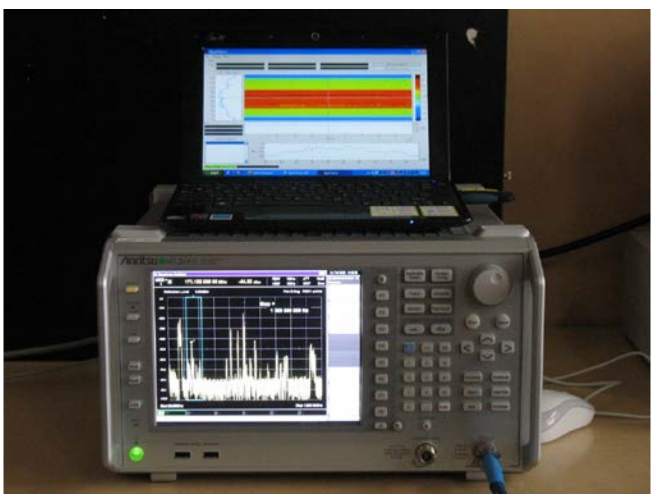


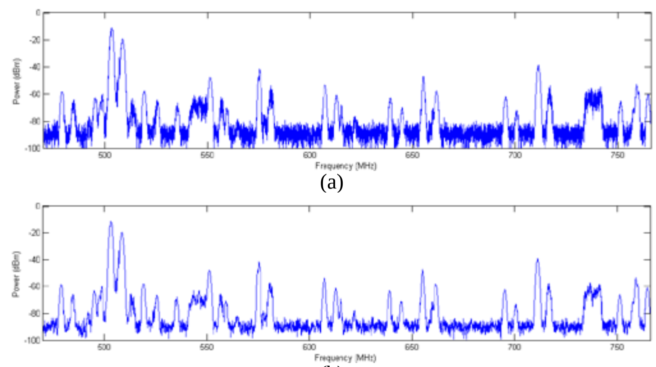
Figure 3. Signal analyzer as used during measurements.

The MathWorks MATLAB environment and the Anritsu Signal Viewer application were the software tools used for processing and analyzing the data obtained during the measurement campaign.

IV. MEASUREMENT RESULTS

As it was already described in Section II, the energy detection method is the only method that does not require any a priori knowledge about the evaluated signals, and this is the method that was used in order to evaluate the occupancy in the several frequency bands presented in Table I.

In order to estimate correctly the noise floor, a sliding window of 1000 samples was used for each of the frequency bands. A mean value of the samples contained in the sliding window was calculated and the lowest mean value, corresponding to an unoccupied frequency area, was chosen as the noise floor of the corresponding frequency band. To mitigate the effects of high-power noise samples in false activity detection, a second sliding window with a calculated width of 100 KHz was used in order to mean out such samples and to minimize the false alarm probability. To illustrate the effect of this second window, an example is presented in Figure 4 for the frequency band from 470 to 766 MHz.



(a)

(b)

Figure 4. Spectral occupancy for the 470-766 MHz frequency band (a) before and (b) after applying the 100 kHz sliding window.

In Figure 4 (a) the original captured signal can be seen, and in Figure 4 (b) can be noticed the signal obtained after processing. In case of this frequency band, the width of 100 kHz chosen for the window results in a number 3 consecutive samples to be taken into account when processing the signal.

A parameter of great importance when using the energy detection method for taking decision about the availability of a certain frequency band is the value chosen for the energy threshold.

If the value used for the threshold is too high weak signals will be treated as noise and this would result in an underestimation of the actual occupancy. In Figure 5 (a), an example is presented for the frequency band from 470 to 766 MHz. The mean noise value is represented with the red line, and the value chosen for the threshold is represented with a green line. It can be noticed that when choosing a value of 11dB for the threshold, several low-power signals are below the threshold level.

On the other hand, choosing a too low value for the threshold will increase the false alarm probability caused by high-power noise samples and this would cause an overestimation of the actual occupancy. In Figure 5 (b), for the same frequency band a value of 3dB is chosen for the threshold, and several noise samples raise above the threshold level.

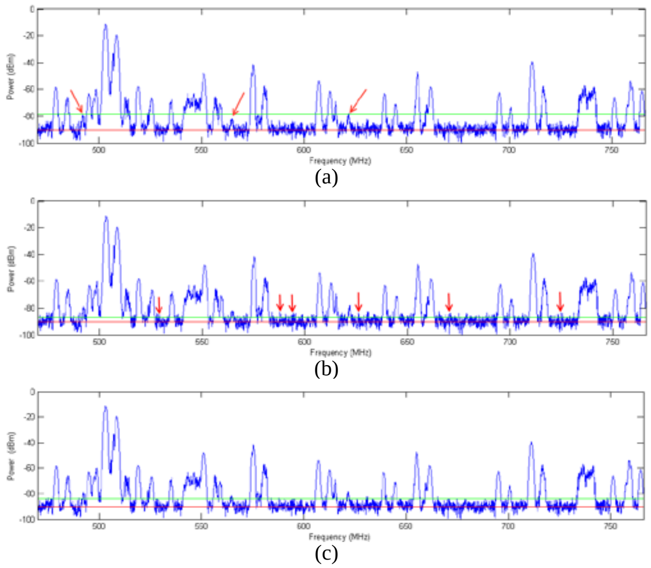


Figure 5. Spectral occupancy for the 470-766 MHz frequency band for 3 different values of the threshold: (a) 11dB (b) 3dB and (c) 5dB.

By analyzing the signals measured during the campaign, a value of 5 dB for the threshold was chosen, as it allows detection of the weakest measured signal and in the same time is high enough to avoid false detections. This situation is illustrated in Figure 5 (c).

The results listed in Table II were obtained by using this threshold value of 5dB for all the 14 different frequency sub-bands.

TABLE II. SPECTRUM OCCUPANCY IN THE 25-3400 MHZ FREQUENCY RANGE

Frequency range (MHz)	Possible applications according to TNABF [8]	Measured Occupancy (%)	Mean Occupancy (%)	
25 - 230	FM radio, Aero/Marine, Fixed/Mobile, Military, other	28.44	27.79	12.19
230 - 400	Military, Mobile	11.09		
400 - 470	Analogue/Digital Terrestrial Mobile, Meteorology, other	18.37		
470 - 766	Analogue TV, DVB-T	40.02		
766 - 880	Military, TV, DVB-T, Cordless, Military, other	12.30		
880 - 960	GSM, E-GSM, Military	46.80		
960 - 1525	Aero/Naval, Navigation, Radar, Military, Radio astronomy	2.36	8.56	
1525 - 1710	Satellite Mobile, Military, Meteorology	4.08		
1710 - 1880	GSM 1800, other	22.86		
1880 - 2200	UMTS/IMT 2000, DECT, other	14.50		
2200 - 2400	SAP/SAB, Military	2.89	3.80	
2400 - 2500	ISM, RFID, RLAN, other	9.42		
2500 - 2690	UMTS/IMT 2000, Military	2.21		
2690 - 3400	Military, Radar, Navigation, Meteorology, other	3.7		

Table II lists the effect of choosing different values for the threshold on the occupancy measured in the 25 to 230 MHz frequency band.

TABLE III. INFLUENCE OF THRESHOLD VALUE OVER MEASURED OCCUPANCY

Energy detection threshold (dB)	Measured occupancy (%)
3	41.53
5	28.44
7	22.32
9	19.60
11	18.18

As it can be noticed, the measured occupancy decreases when raising the value of the threshold, because the low-energy signals visible in Figure 4 are being ignored.

All the measurements have been carried out during daytime in weekdays, when higher values for spectral occupancy are expected, comparing to nighttime or weekends.

V. MEASUREMENT ANALYSIS

Although most of the frequency range between 25 MHz and 1GHz shows a relative high occupancy, there are bands with some potential for cognitive radio applications. The lowest occupancy percent was measured in the 230 to 400 MHz band (Figure 7), however most of this band is for the moment licensed for military applications.

The frequency band 470-766 MHz is currently used mostly for analog TV broadcasting. Several analog TV broadcasting stations can be noticed in Figure 9 (the level for the station located on 506 MHz is higher then average, as the broadcast antenna is located on the same building from where the measurements were performed). However, although for the moment the occupancy is quite high at 40.02%, this might change in the near future, with the introduction of DVB-T. Test broadcasting for DVB-T is already being performed in the Bucharest area, corresponding signals can be noticed in Figure 9 on 546 MHz (channel 30) and 738 MHz (channel 54). New measurements will have to be conducted in order to evaluate spectral occupancy in this frequency range, once the digital TV broadcasting technology will completely replace the analog one (analog TV broadcasting in Romania is only allowed until 1 January 2012, due to European regulations). Furthermore, the broadcast area for both DVB-T and analog TV stations is limited around big cities, which will result in a lower occupancy for this band in rural environment.

In the frequency band 766 to 880 MHz (Figure 10) only a test DVB-T broadcast station (778 MHz, channel 59) was detected during the measurements, although other possible applications are allowed conforming to the governmental agency responsible for frequency allocation in Romania [16].

The 880-960 MHz and 1710-1880 MHz (Figures 11 and 12) are licensed for the GSM 900 and 1800 systems. In the frequency bands corresponding to the downlink communication direction (925-960 MHz for GSM 900 and 1805-1880 MHz for GSM 1800) a high power level was measured during the whole band, as the locations of base station antennas was close to the measurement location and the transmit power employed is considerably higher than the one used in case of mobile stations. Although in frequency bands corresponding to the uplink communication direction (880-915 MHz and 1710-1785 MHz) the measured occupancy was extremely low, it should be noted the measurement location and the low transmit power of mobile stations might cause an underestimation of the actual occupancy. CR equipment activating in these bands should have a detection mechanism capable of recognizing low-power signals with energy close to the noise floor, in order to avoid interference to primary users active in the area.

The overall spectrum occupancy measured in frequency bands located above 1 GHz was extremely low (mean occupancies of less than 10%), which make most of this frequency bands potential candidates for CR applications. Occupancies higher than 10% were obtained for sub-bands 9, where the GSM 1800 systems are licensed, and 10, licensed for UMTS/IMT 2000 systems. In both cases, it is again to be noticed that the measured occupancy is much higher for the downlink direction compared to the uplink direction, especially for the UMTS systems where spread spectrum signals are used.

The ISM band 2400 to 2500 MHz is a very good opportunity for testing CR prototype devices, as the measured occupancy is quite low (9.42%) and there are a multitude of commercially available hardware devices operating in this frequency range.

VI. Conclusion and Future Work

Results obtained during the measurement campaign conducted in an urban environment in Bucharest, Romania clearly indicate that there are several frequency bands that allow opportunistic access for future CR applications. The frequency range analyzed was 25 MHz to 3.4 GHz, and the mean occupancy ratio over the whole band was as low as 12.19%.

Although the values for spectrum occupancy were higher than the ones obtained for the frequency sub-bands above 1GHz, there were two sub-bands, 2 (230-400 MHz) and 5 (766-880 MHz), where the measured occupancy was lower, close to 10%.

In case of the frequency sub-bands above 1 GHz, there are several sub-bands where spectrum occupancy values lower than 5% were obtained (960 – 1525 MHz, 1525 – 1710 MHz, 2200 – 2400 MHz, 2500 – 2690 MHz, 2690 – 3400 MHz). All these bands offer good opportunities for testing of CR prototypes and development of CR networks.

In order to increase the relevance of the obtained data, measurements over longer periods of time and in wider frequency bands (up to 6 GHz) will be performed.

Related to the methodology used for choosing the threshold in case of the energy detection method, another fact that should be taken into account for future analysis is the mean sensitivity of the licensed user equipment that operates in the corresponding frequency band.

Although the results obtained up to now were collected exclusively in an urban environment, further measurement campaigns targeted at suburban and rural environments are intended, in order to obtain a complete picture of the perspectives for future CR applications.

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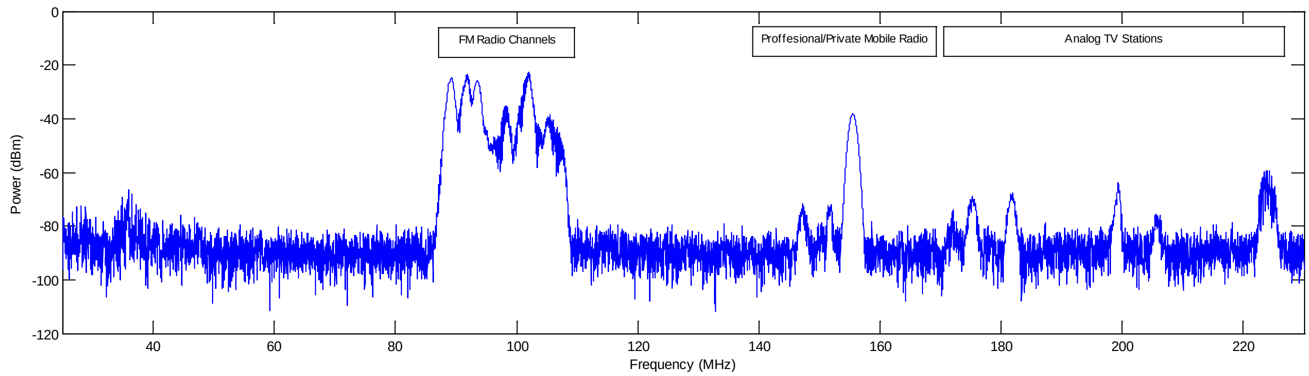

Figure 6. Instantaneous Spectrum Occupancy results: 25 to 230 MHz.

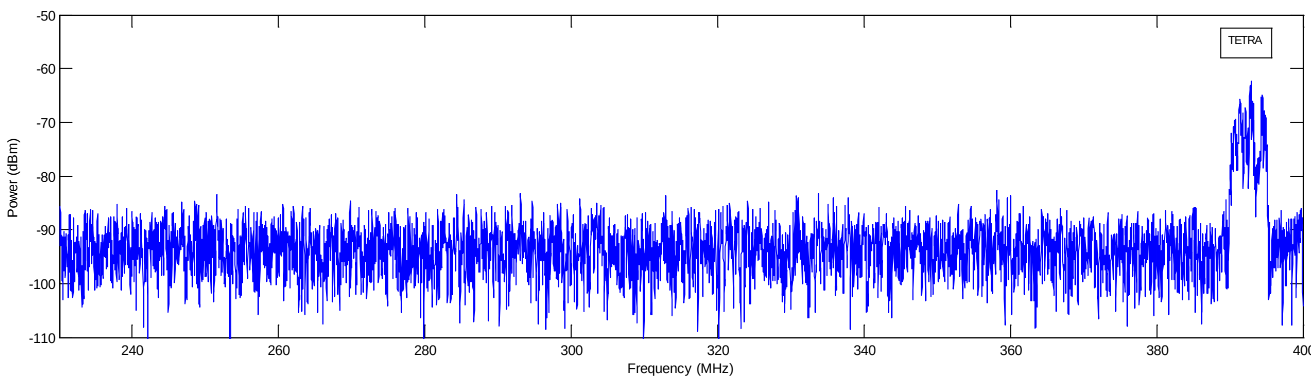

Figure 7. Instantaneous Spectrum Occupancy results: 230 to 400 MHz.

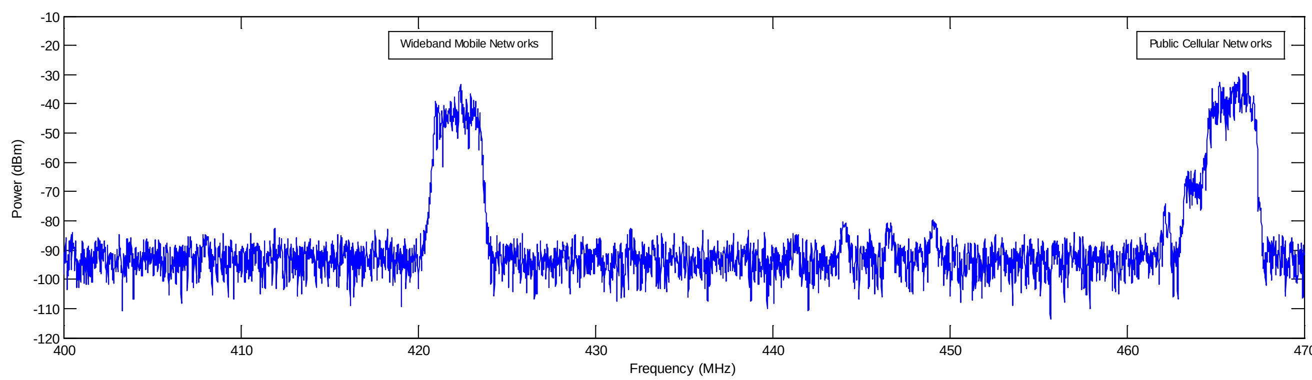

Figure 8. Instantaneous Spectrum Occupancy results: 400 to 470 MHz.

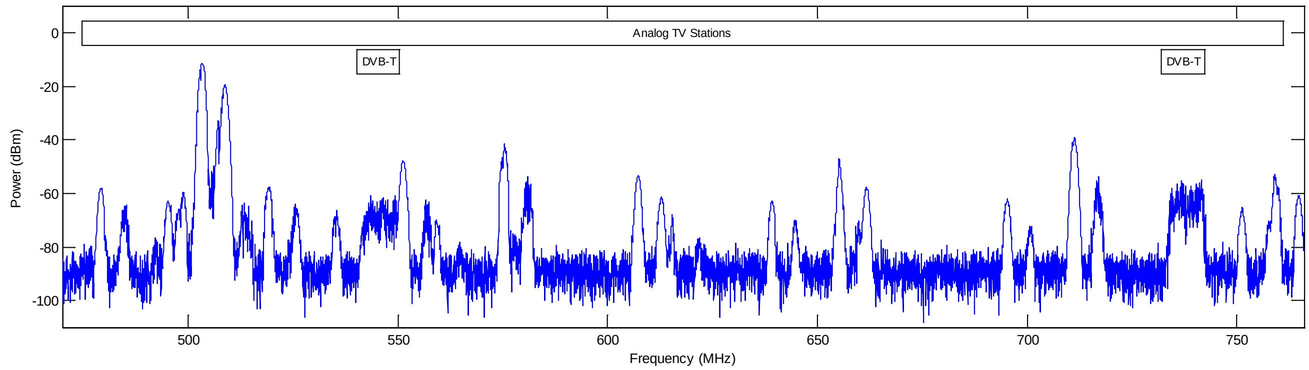

Figure 9. Instantaneous Spectrum Occupancy results: 470 to 766 MHz.

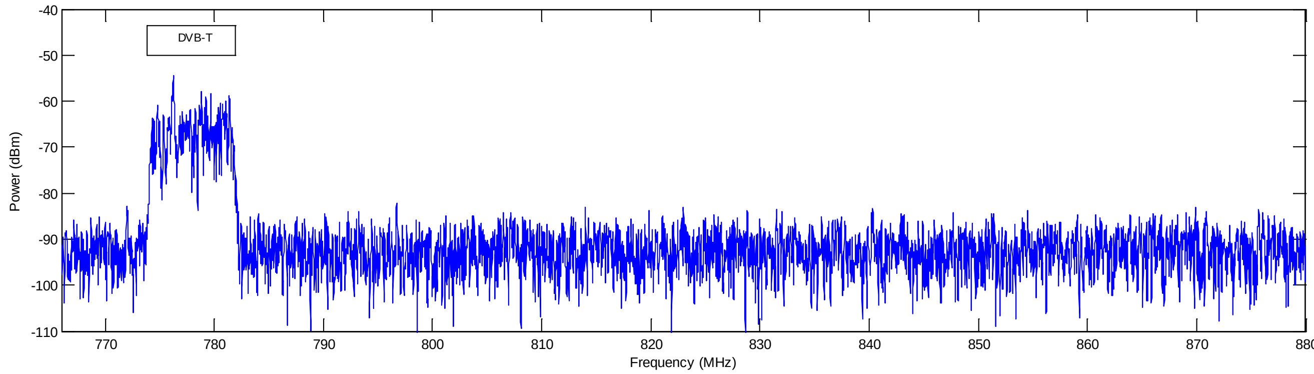

Figure 10. Instantaneous Spectrum Occupancy results: 766 to 880 MHz.

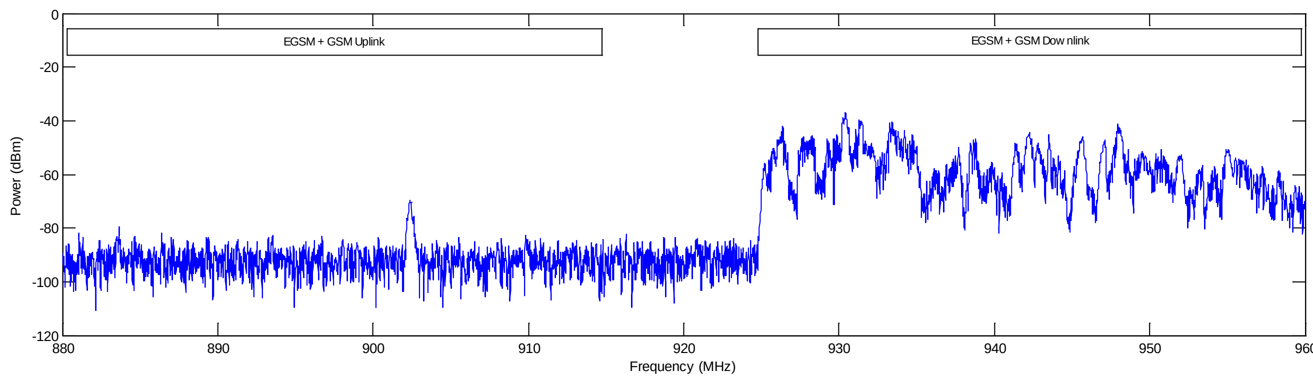

Figure 11. Instantaneous Spectrum Occupancy results: 880 to 960 MHz.

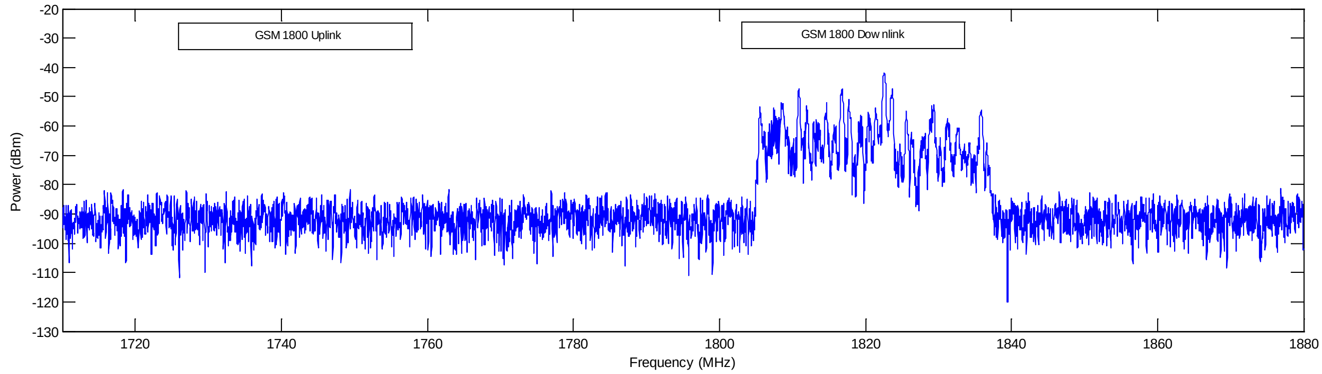

Figure 12. Instantaneous Spectrum Occupancy results: 1710 to 1880 MHz.

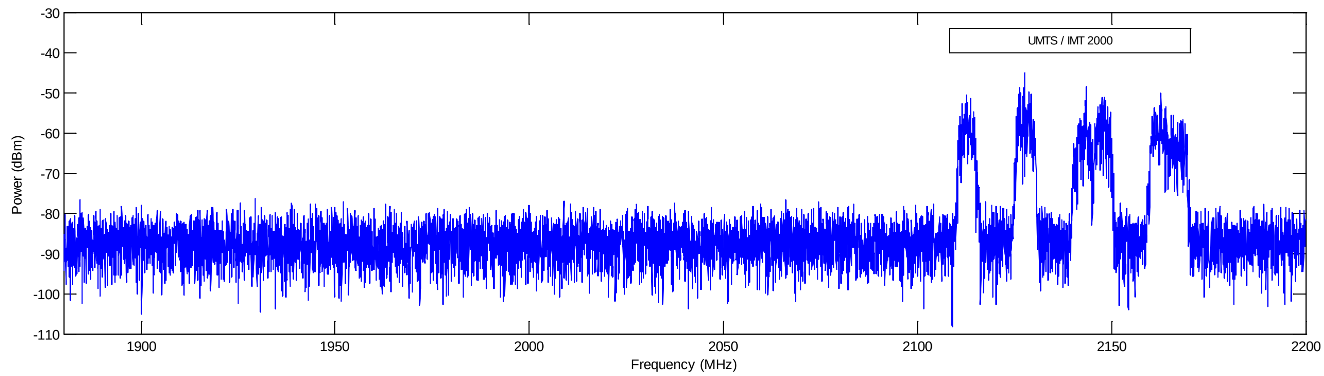

Figure 13. Instantaneous Spectrum Occupancy results: 1880 to 2200 MHz.