Spectral Occupancy Measurements in Rural and Urban Environments: Analysis and Comparison

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Abstract— **In order to enable the coexistence of an ever-increasing number of communication systems in a limited amount of frequency, the traditional static frequency allocation is not the best solution any longer. Cognitive Radio (CR) technology, based on a dynamic spectrum access, is a possible solution for improving the efficiency of spectrum usage. A first step in order to identify the frequency bands that are more suitable for opportunistic usage is to evaluate the degree in which licensed bands are currently used. Although some measurement campaigns have already been carried out, most of them were done in urban environments and only a few in other locations. This paper presents results of two measurement campaigns conducted in Romania both in urban and rural environments, covering the frequency range from 25 MHz up to 3.4 GHz. The results are confronted with the frequency allocation table published by the national authority for radio communications and a comparison and analysis of the obtained data are being made.**

Keywords - spectral occupancy; cognitive radio; dynamic spectrum access; energy detection; measurement campaign.

I. INTRODUCTION

During the last decades, the demand for more radio spectrum increased with the development of wireless communications. With the deployment of more wireless communications systems, most of the available spectrum has been statically allocated. Therefore, many countries are facing the problem of spectrum insufficiency. Nevertheless, measurement studies have revealed that most of the allocated spectrum experiences low utilization efficiency. These two facts motivate the introduction of dynamic spectrum access, which allows secondary users to reuse/share the same radio spectrum originally allocated to the primary (licensed) users.

Cognitive radio (CR) technology is the key technology that enables a system to use spectrum in a dynamic manner. The CR term was coined by J. Mitola III in [1], defining a wireless communication system that allows spectrum sharing over a wide frequency range and that is able to handle multiple radio access technologies. In order to avoid any interference to the primary system, the CR equipment should include the following functionalities: frequency-agility and re-configuration of radios, spectrum sensing, and spectrum management.

Prior to developing standards for CR applications, there is a need for a thorough investigation of potential spectral regions to be used. Therefore, it is important to gather spectral investigation results from as many as possible different geographical regions and scenarios. These results will facilitate the CR standards development, to make the CR devices work under several circumstances, with different spectral regulations.

Several measurement campaigns concerning spectrum occupancy were conducted worldwide [2]-[10], most of them were carried out the in the USA [2]-[3] and only a few in other locations worldwide, including Singapore [5], Germany [6], New Zeeland [7], Spain [8] and Italy [9], 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 [2]. Studies were also targeted at narrower frequency bands, like the public safety ones, and the benefits of cooperative sensing were highlighted [3]. The difference between indoor and outdoor locations was discussed in [5] based on measurements performed in Aachen, Germany. The study in [9], based on measurements performed in Spain and Italy, focuses on determining the hidden noise margin in order to find out if cognitive devices are able to detect and distinguish between empty and occupied TV channels. Recently, after a thorough investigation of real radio communications systems, accurate statistical models for the time-domain spectral occupancy were proposed in [10].

The paper is organized as follows. Section II contains a description of the equipments used to perform our measurements. The methodology and the obtained results of the measurements are presented in Section III. In Section IV, the measurement results are analyzed from a CR perspective. Finally, in Section V, the conclusions are drawn and future work aspects are presented.

II. MEASUREMENT LOCATION, SETUP AND EQUIPMENT

The measurements for an urban environment were performed in Bucharest from the top of the main building of

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our Department (GPS location: latitude 44°26'01" N, longitude 26°03'27" E, MSL altitude 150 m, relative altitude 30 m). The location is excellent for such a measurement campaign, having direct line of sight with several FM transmitters, Analog and DVB-T TV transmitters, GSM and UMTS base stations and several other stations The headquarters of the governmental agency for special telecommunications is also located just a few hundreds of meters away from the measurement location.

The small village of Maneciu (GPS location: latitude 45°18'49" N, longitude 25°59'38" E, MSL altitude 584 m, relative altitude 10 m) was chosen for the measurements in a rural environment. The village is located in a hilly region approximately 100 km away from Bucharest and at least 40 km away from any other big city. A map of the southeastern part of Romania, having highlighted the measurement locations is given in Figure 1.

The antenna used for collecting the measurement data is a wideband discone antenna (Sirio SD3000N), 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). Images showing the equipment that was used during the measurement campaigns can be found in [11].

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

The measurement data was collected from the spectrum analyzer using a remote mode, the necessary commands were generated using a notebook connected through the network interface. Data was acquired for each of the 14 spectrum sub-bands at intervals of around 70 seconds, resulting more than 1000 samples for each of the sub-bands for each day.

A list containing values of the parameters used to configure the equipment in order to perform the measurements is given in Table I.

TABLE I. SPECTRUM ANALYZER CONFIGURATION

Parameter	Value	
Frequency 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 9.1710-1880 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 (bands 2, 3, 5, 6, 8, 9, 11, 12, 13) 1 MHz / 1MHz (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 MathWorks MATLAB software environment was used for collecting, processing and analyzing the data obtained during the measurement campaign.

III. MEASUREMENT RESULTS

Several sensing methods can be used in order to decide if a certain frequency band is available for opportunistic access: energy detection, matched filtering, cyclostationary feature detection, eigenvalue detection, wavelet detection [12]-[15]. In order to evaluate the spectral occupancy in the several frequency bands presented in Table I using the data collected during the measurement campaigns we chose the energy detection method.

The energy detection method provides an optimal detection in cases where the primary user signal is unknown, as it does not require any a priori knowledge about it. Some other advantages offered by this method are low computational costs and a short necessary sensing time. The main drawbacks of this method are that the results obtained are highly susceptible to changes in the background noise and interference level and that it cannot distinguish primary users from secondary ones. However, research has been done, like the one described in [12] in order to improve the detection performance of such a method by dynamically adjusting the threshold value.

One of the main challenges when using the method is a proper selection of 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. 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 order to estimate the noise level, several methods are available. Although the most simple one would imply a measurement using a matched load (of 50 Ω in case of our configuration) instead of the measurement antenna, this would imply that the evaluation of the noise level would be made at a different moment of time from the one when the measurements are being made. In this case, the accuracy of the measurement would not be acceptable, and moreover the values obtained could not be dynamically adjusted to reflect possible changes in the radio environment. To overcome these disadvantages we determined the noise level using a sliding window in the frequency domain, having an adaptive width. An algorithm was used to determine the most wide frequency interval without any active signal for each of the 14 frequency bands described in Table I, and a mean of the values for this interval would indicate the current noise level for the corresponding band.

To mitigate the effects of high-power noise samples in order to decrease the false alarm probability, a second sliding window with a calculated width of 100 kHz was used in order to mean out such samples.

In Table II, an example calculation was made for the 470 to 766 MHz frequency band by choosing several different values for the false alarm probability.

TABLE II. INFLUENCE OF THRESHOLD VALUE OVER MEASURED OCCUPANCY FOR THE 470-766 MHZ FREQUENCY BAND (URBAN ENVIRONMENT, HOUR INTERVAL 14-22, WORKDAY)

False alarm probability (%)	Spectral occupancy (%)	Threshold level (dBm)	Threshold above noise level (dB)
1	34,21	-84.82	4,80
3	38,52	-85.67	3,95
5	40,43	-85.95	3,67
7	42,03	-86.13	3,49
10	**44,24**	**-86.33**	**3,29**
15	47,56	-86.55	3,07
20	48,92	-86.64	2,98

The threshold value was chosen in order to respect a chosen false alarm probability of 10% for all the frequency bands that were considered during the measurement campaigns. As expected, when the value chosen for the false alarm probability is increased, the value of the necessary threshold will decrease. As a result, the measured spectral occupancy will have higher values, as signals having levels close to the noise level will be taken into account.

As it can be noticed, having a 19 % variation in the false alarm probability implies also almost a 15% variation in the determined occupancy. The value of 10% for the false alarm probability was highlighted, as it is the value that was used during the measurement campaigns.

Table III contains the measured spectrum occupancies for both the urban and rural environments for the 25 MHz to 3.4 GHz frequency band. The listed results were obtained by using a value of 10% for the false alarm probability for the threshold for each of the 14 different frequency sub-bands.

Occupancy results were calculated for both the urban and the rural areas using data collected over intervals of 48 hours, one working day and one week-end day.

IV. MEASUREMENT ANALYSIS

Figures 2 and 3 contain spectrum occupancy results for some of the 14 frequency sub-bands analyzed during the urban environment measurement campaign. In case of sub-band 470-766 MHz (Figure 2) different metrics are used in order to express the degree of spectral occupancy. A first sub-figure contains the maximum, minimum and mean power spectral density value for an 8-hour observation interval. In a second sub-figure the occupancy duty cycle is represented, expressing the amount of time (in %) in with each of the frequencies from the respective frequency band was occupied or not. A third sub-figure is a histogram showing a map of the instantaneous spectral occupancy for the whole 8-hour interval. In case of Figure 4 the maximum, minimum and mean power spectral density value are given for four different sub-bands.

The frequency spectrum below 1 GHz shows the highest occupancy values from the whole frequency domain that was covered during our measurement campaigns, both in the urban and rural environments. Nevertheless, in both cases the calculated values are below 50% (37.23% in the urban area, 19.19% in the rural area), which means that even in this frequency range there are bands with some potential for cognitive radio applications. Another aspect worth being noticed is that for this frequency interval the difference between the two environments is the most significant one, the occupancy being almost double in case of the urban area. The reason for this difference is the lower density of broadcast radio and TV stations and a lower number of frequency channels used in case of the GSM mobile networks in the rural area.

TABLE III. SPECTRUM OCCUPANCY IN BOTH URBAN AND RURAL ENVIRONMENTS FOR THE 25-3400 MHZ FREQUENCY RANGE

<table>
<tr><th rowspan="2">Frequency range (MHz)</th><th rowspan="2">Possible applications according to TNABF [16]</th><th colspan="2">Measured Occupancy (%)</th><th colspan="4">Mean Occupancy (%)</th></tr>
<tr><th>Urban environment</th><th>Rural environment</th><th>Urban environment</th><th>Rural environment</th><th>Urban environment</th><th>Rural environment</th></tr>
<tr><td>25 - 230</td><td>FM radio, Aero/Marine, Fixed/Mobile, Military, other applications</td><td>48.64</td><td>28.67</td><td rowspan="6">37.23</td><td rowspan="6">19.19</td><td rowspan="14">21.00</td><td rowspan="14">14.19</td></tr>
<tr><td>230 - 400</td><td>Military, Mobile</td><td>17.82</td><td>13.25</td></tr>
<tr><td>400 - 470</td><td>Analogue/Digital Terrestrial Mobile, Meteorology, other applications</td><td>42.83</td><td>23.43</td></tr>
<tr><td>470 - 766</td><td>Analogue TV, DVB-T</td><td>43.06</td><td>11.42</td></tr>
<tr><td>766 - 880</td><td>Military, TV, DVB-T, Cordless, Military, other applications</td><td>17.63</td><td>11.10</td></tr>
<tr><td>880 - 960</td><td>Mobile communication systems :GSM, E-GSM, Military</td><td>50.85</td><td>44.19</td></tr>
<tr><td>960 - 1525</td><td>Aero/Naval, Navigation, Radar, Military, Radio astronomy</td><td>10.89</td><td>10.11</td><td rowspan="4">15.89</td><td rowspan="4">11.15</td></tr>
<tr><td>1525 - 1710</td><td>Satellite Mobile, Military, Meteorology</td><td>10.91</td><td>10.83</td></tr>
<tr><td>1710 - 1880</td><td>Mobile communication systems :GSM 1800, other applications</td><td>28.58</td><td>14.64</td></tr>
<tr><td>1880 - 2200</td><td>Mobile communication systems :UMTS/IMT 2000, DECT, other applications</td><td>20.87</td><td>11.34</td></tr>
<tr><td>2200 - 2400</td><td>SAP/SAB, Military</td><td>17.26</td><td>17.04</td><td rowspan="4">13.64</td><td rowspan="4">13.44</td></tr>
<tr><td>2400 - 2500</td><td>ISM, RFID, RLAN, other applications</td><td>17.66</td><td>15.90</td></tr>
<tr><td>2500 - 2690</td><td>Mobile communication systems :UMTS/IMT 2000, Military</td><td>21.13</td><td>21.01</td></tr>
<tr><td>2690 - 3400</td><td>Military, Radar, Navigation, Meteorology, other applications</td><td>10.05</td><td>10.06</td></tr>
</table>

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The frequency band 25 to 230 MHz exhibits a quite high occupancy degree especially in the urban environment, mainly because of (Figure 3a). The occupancy results in case of this particular frequency band during the whole measurement period, divided in 6 time intervals, are given in Table IV.

The frequency band 470-766 MHz (Figure 2) is licensed for analog and digital TV broadcasting. Although due to European regulations analog TV broadcasting in Romania was initially intending to be completely replaced by digital one beginning with the 1st of January 2012, things are not quite there yet. In Figure 2 several analog TV broadcasting stations can be noticed in the urban area (the level for the station located on 506 MHz is higher than average, as the broadcast antenna is located on the same building from where the measurements were performed). This is also the frequency band where the biggest difference between the occupancy measured in the two environments was noticed (43.06% in the urban area compared to 11.42% in the rural one). The reason is mainly the DVB-T broadcasting that is for the moment performed only in the area surrounding Bucharest. The corresponding signals can be found in Figure 2 on the 546 MHz carrier frequency (channel 30) and on the 738 MHz carrier frequency (channel 54). Considering the fact that the spectral efficiency of the digital TV broadcasting is much higher than in case of the analog one, once the analog TV stations will cease broadcasting a drop in the spectral occupancy in this frequency band is to be expected. The Romanian National Authority for Management and Regulation in Communications (ANCOM) established 2013 as a new term for ceasing the analog TV broadcasting, so new measurements will have to be conducted in order to evaluate spectral occupancy in this frequency band afterwards. This frequency band is also targeted by several new standards based on dynamic spectrum access (including 802.22 and 802.11af).

The lowest spectral occupancy below 1 GHz was obtained in the 766 to 880 MHz band (Figure 3b), however most of this band is for the moment licensed for military applications. In this frequency band, only a test DVB-T broadcast station (carrier frequency 778 MHz, channel 59) was detected in the urban area during the measurement campaign, although other possible applications are allowed according to the National Table for Frequency Allocation in Romania [16].

The 880-960 MHz (Figure 3c) and 1710-1880 MHz are licensed for the GSM 900 and 1800 mobile communication system. In the frequency bands corresponding to the downlink direction (925-960 MHz for GSM 900 and 1805-1880 MHz for GSM 1800) a higher power level was measured, as the transmit power employed is considerably higher than the one used in case of mobile stations. In case of the rural environment, a significant difference in the degrees of occupancy was obtained in this frequency band depending on the time interval, as described in Table V.

In order to prove the reason for such a big difference in the degree of occupancy, in Figure 1 are pictured the histograms for the three 8-hour intervals listed in Table V.

As it can be clearly seen, a certain number of frequency channels used during the day (05:00 to 18:00) are turned off during nighttime, probably because of lack of traffic during off-work hours. Although in frequency bands corresponding to the uplink (880-915 MHz and 1710-1785 MHz) the measured occupancy was extremely low in both environments, it should be noted the measurement locations and the low transmit power of mobile stations might cause an underestimation of the real occupancy. CR equipment that are designed to function in these frequency 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 for the frequency bands above 1 GHz was extremely low for both environments (mean occupancies of less than 20% in both cases). As it can be noticed from Table III, the differences between the values obtained in the two areas are very small, excepting two bands: the 1710-1880 MHz band licensed for GSM 1800 and the 1880-2200 MHz band (Figure 3d) licensed for UMTS. In both cases because of the lower population density from the rural area the network operators use less frequency channels, this being the reason for the lower occupancy measured in the rural environment. Considering the very low spectrum occupancy degree, most of these frequency bands are potential candidates for CR applications.

TABLE IV. INFLUENCE OF DAY PERIOD OVER MEASURED OCCUPANCY FOR THE FREQUENCY BAND 25-230 MHZ (URBAN ENVIRONMENT)

Observation interval (hours : minutes)	**Measured occupancy (%)**
06:00 – 14:00 (workday)	47,68
14:00 – 22:00 (workday)	47,39
22:00 – 06:00 (workday)	47,27
06:00 – 14:00 (weekend)	51,06
14:00 – 22:00 (weekend)	50,22
22:00 – 06:00 (weekend)	48,25

TABLE V. INFLUENCE OF DAY PERIOD OVER MEASURED OCCUPANCY FOR THE FREQUENCY BAND 880-960 MHZ (RURAL ENVIRONMENT)

Time interval (hours : minutes)	Measured spectral occupancy (%)
06:00 – 14:00 (week-end day)	47,22
14:00 – 22:00 (week-end day)	43,98
22:00 – 06:00 (week-end day)	40,60

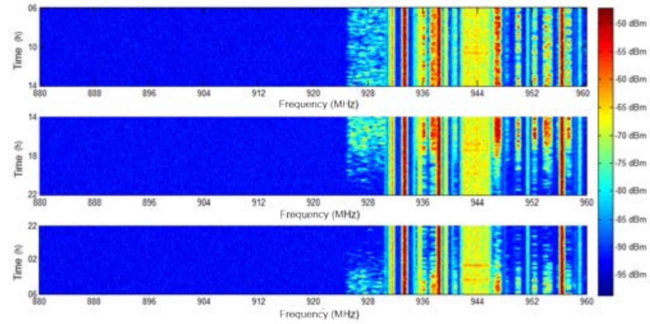

Figure 1. Histograms for the frequency band 880-960 MHz for three intervals of eight hours each (rural environment).

The ISM band 2400 to 2500 MHz is a very good opportunity for testing CR prototype devices, as the measured occupancy is quite low in both cases (17.66% in the urban environment and 15.90% in the rural area) and there are multitudes of commercially available hardware devices that are able to operate in this frequency range.

V. CONCLUSION AND FUTURE WORK

Results obtained during the measurement campaign conducted in both urban (Bucharest) and rural (Maneciu) environments in Romania clearly indicate that several frequency bands allow opportunistic access for future CR applications, especially in the rural environment and for the frequency bands above 1 GHz. The analyzed frequency range was 25 MHz to 3.4 GHz, and the mean occupancy ratio over the whole band was as low as 21.00% in the urban environment and 14.19% in the rural environment.

It is difficult to make a direct comparison between the results obtained during the different measurements campaigns mentioned in Section I and the measurement campaigns performed in Romania. The main reasons are the differences that can be found in the measurement setup (frequency intervals, spectrum analyzer bandwidth) and in the signal processing section (imposed false alarm probability). However, a common conclusion that can be drawn from the measurements is that the spectral occupancy degree that can be obtained by using a 'classical' static allocation approach is far from being optimal. The dynamic spectrum access proposed by technologies such as cognitive radio promises to bring substantial improvements in terms of efficiency of spectrum usage.

Despite the fact that the calculated occupancy for some frequency bands is quite low (e.g., the GSM 900 and 1800 uplink bands), CR devices intended to operate in these frequency areas should be properly designed in order to avoid interference with licensed systems.

In order to increase the relevance of the obtained data, measurements in wider frequency bands (up to 6 GHz) are intended in the near future.

Further measurements will be necessary in case of the 470-766 MHz frequency band once the analog TV broadcasting will be completely replaced by the digital one.

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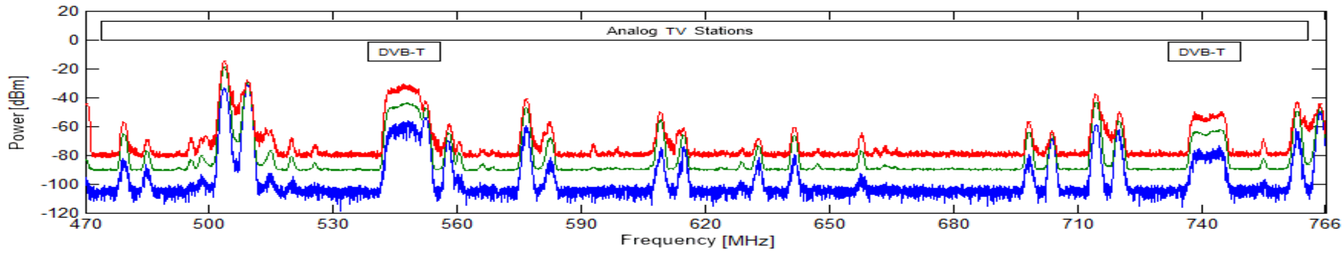

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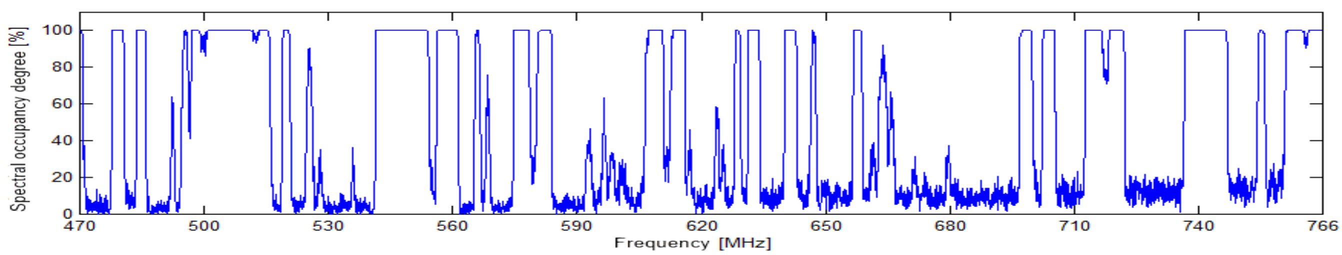

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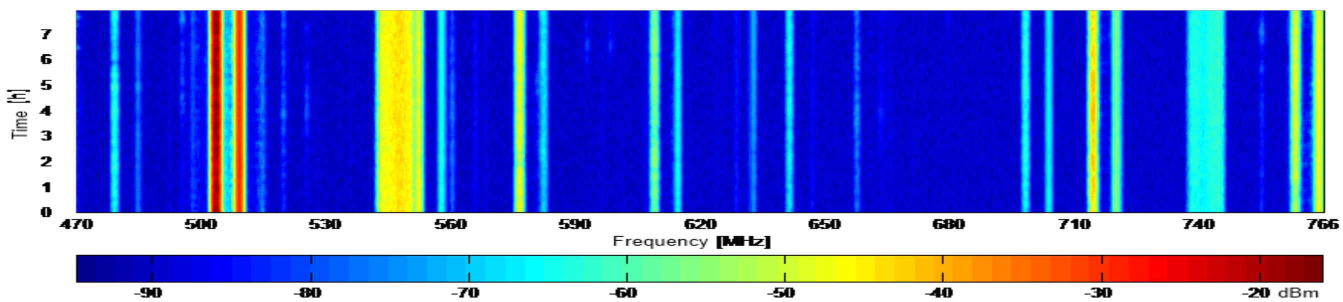
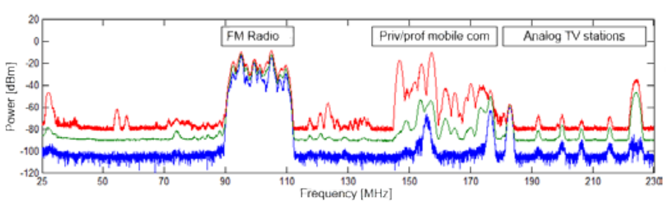


(c)

Figure 2. Spectral occupancy for the 470 MHz - 766 MHz frequency band using different metrics (urban environment, 14:00-22:00, working day) (a) Mean, minimum and maximum signal values (b) Occupancy duty cycle (c) 8 hour histogram



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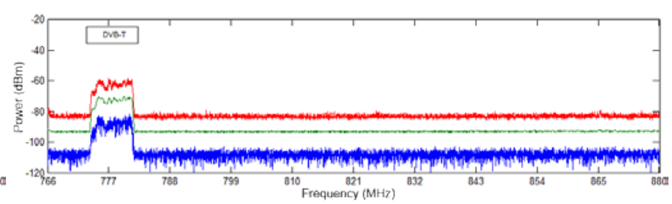

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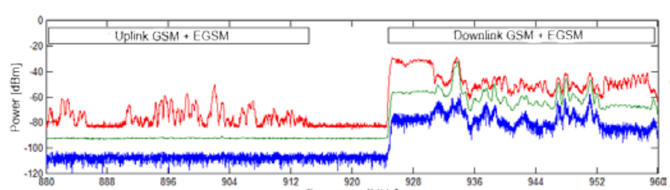

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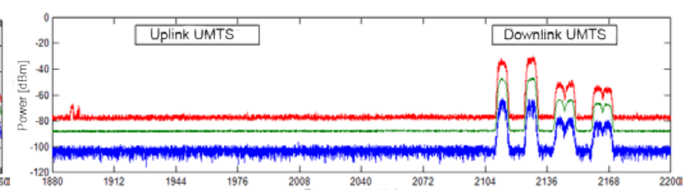

(d)

Figure 3. Mean, minimum and maximum signal (urban environment, 14:00-22:00, working day) for the frequency bands (a) 25-230 MHz (b) 766-880 MHz (c) 880-960 MHz (d) 1880-2200 MHz