Universitat Autònoma de Barcelona

Treball Fi de Grau

Grau d'Enginyeria en Sistemes de Telecomunicació

Spectrum Survey in Sub-Urban Environment: Campus of Universitat Autònoma de Barcelona

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UAB

El tribunal d'avaluació d'aquest Treball Fi de Grau, reunit el dia *4 de Juliol de 2014*, ha acordat concedir la següent qualificació:

President: ________________________________

Vocal: ________________________________

Secretari: ________________________________

UAB

Els sotasignant, Dr. Pedro de Paco Sánchez, Professor de l'Escola d'Enginyeria de la Universitat Autònoma de Barcelona (UAB),

CERTIFICA:

Que el projecte presentat en aquesta memòria de Trebal Fi de Grau ha estat realitzat sota la seva direcció per l'alumne Óscar Muñoz Montero.

I, perquè consti a tots els efectes, signa el present certificat.

Bellaterra, 4 de Juliol de 2014.

Signatura: Dr. Pedro de Paco Sánchez

Resum:

En aquest document es descriu l'estudi dels diferents patrons d'ocupació de l'espectre en una zona sub-urbana, al campus universitari de la Universitat Autònoma de Barcelona, ja que aquest lloc mostra diverses característiques que el fan atractiu per dur a terme l'estudi sobre l'ocupació de l'espectre. Les bandes freqüencials sota estudi van entre els 75 MHz i els 5 GHz. Els objectius són trobar les taxes d'ocupació de cadascuna de les bandes objecte d'estudi i la comparació dels resultats obtinguts amb altres estudis realitzats en zones urbanes, l'extracció de les similituds i diferències, així com la discussió de les oportunitats per al desplegament de polítiques d'accés dinàmic a l'espectre. El llindar de decisió implementat en aquest estudi ha estat millorat amb la finalitat de rebutjar el soroll extern capturat per l'antena, així com la correcció de les variacions de soroll intern.

Resumen:

En este documento se describe el estudio de los diferentes patrones de ocupación del espectro en una zona sub-urbana, en el campus universitario de la Universidad Autónoma de Barcelona, ya que este lugar muestra varias características que lo hacen atractivo para llevar a cabo el estudio sobre la ocupación del espectro. Las bandas frecuenciales bajo estudio se extienden entre los 75 MHz y los 5 GHz. Los objetivos son encontrar las tasas de ocupación de cada una de las bandas objeto de estudio y la comparación de los resultados obtenidos con otros estudios realizados en zonas urbanas, la extracción de las similitudes y las diferencias, así como la discusión de las oportunidades para el despliegue de políticas de acceso dinámico al espectro. El umbral de decisión implementado en este estudio ha sido mejorado con el fin de rechazar el ruido externo capturado por la antena, así como la corrección de las variaciones de ruido interno.

Summary:

This document describes the study of the different spectrum occupancy patterns in a sub-urban area near the Autonomous University of Barcelona, as this location shows several characteristics that make it attractive to carry out the spectrum survey. The frequecy bands under study ranges from 75 MHz to 5 GHz. The objectives are to find the occupancy rates on each one of the bands under study and compare the obtained results with other studies performed on urban areas, extracting the similiarities and differences, as well as discussing the opportunities for the deployment of Dynamic Spectrum Acces (DSA) policies. The decision threshold implemented on this study has been improved in order to reject the external noise captured by the antenna, as well as correcting the internal noise variations.

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1 Introduction

This document describes the study of the different spectrum usage patterns near Universitat Autonoma de Barcelona (UAB) Bellaterra Campus, in the frequency bands ranging from 75 MHz to 5 GHz. This emplacement show some characteristics which make it attractive to develop the Spectrum Survey:

- The Autonomous University of Barcelona has its central campus in Bellaterra (Cerdanyola del Vallès), located at 20 km from Barcelona, between Sabadell and Sant Cugat del Vallès. This location cannot be considered as an urban area, as the campus is not located inside an urban core, but neither as a rural area, as it is surrounded by several cities. This scenario leads us to categorize the location as a sub-urban area, where the spectrum usage patterns can differ from both urban and rural areas, which make this location attractive to carry out the study.
- Another characteristic that makes this location special is that the campus is surrounded by two highly transited highways (C-58 and AP-7), which can have an impact on the survey results, or, even more important, the results obtained can be exploited to offer support to the existing traffic services.
- Although we are situated in a sub-urban area, the population density is very high during the day resulting on high spectrum occupancy rates, while it is almost null at night or in the weekends, which in turn results on low spectrum occupancy rates. These two different behaviors makes again this campus very suitable to perform the spectrum survey, as different spectrum activity will be recorded depending on the activity on the campus.
- Since the campus is situated only 20 km away from Barcelona, we have direct Line of Sight with some of the most important telecommunications towers, like Collserola's tower, which is the most important telecommunications base station in that area, as well as some repeater towers, which extend the coverage area of several services.
- Furthermore, the air-space activity is also very high, due to the proximity of Sabadell Airport, and of course, the international airport of Barcelona - El Prat, which attracts a high airspace activity to our geographical area.

All these characteristics make this study different from others studies that have been carried out in this field, since most of them are carried out in urban areas, as in Barcelona [1], Singapore [4], Chicago [5] or San Francisco [8], where the environmental radio conditions are similar, while our location shows very different conditions that encourage us to carry out this study.

1.1 Background

Traditionally, the telecommunications regulatory bodies that manage the spectrum allocation, have been applying policies which granted a fixed spectrum band to a licensed user for exclusive access. Only a few, small, unlicensed bands were left open for anyone to use as long as they followed certain power regulations. While these polices have worked well in past decades, the emergence of new technologies and the extraordinary growth of wireless communication services have increased the demand for the radio frequency spectrum. As a result, the radio frequency spectrum has become overcrowded; the licensed bands are granted to the users who own them, and the unlicensed bands are crowded with everything from wireless networks to digital cordless phones.

On the other hand, regulatory bodies in the world (including the Federal Communications Commission in the United States and Ofcom in the United Kingdom) as well as different independent measurement campaigns found that most radio frequency spectrum was inefficiently utilized. For example, cellular network bands are overloaded in most parts of the world, but other frequency bands (such as military, amateur radio and paging frequencies) are insufficiently underutilized. These unused spectrum bands, called spectrum holes or white spaces, offer a great opportunity for wireless communications. Figure 1 shows an example of the whitespaces present on the TV band in our geographical area.

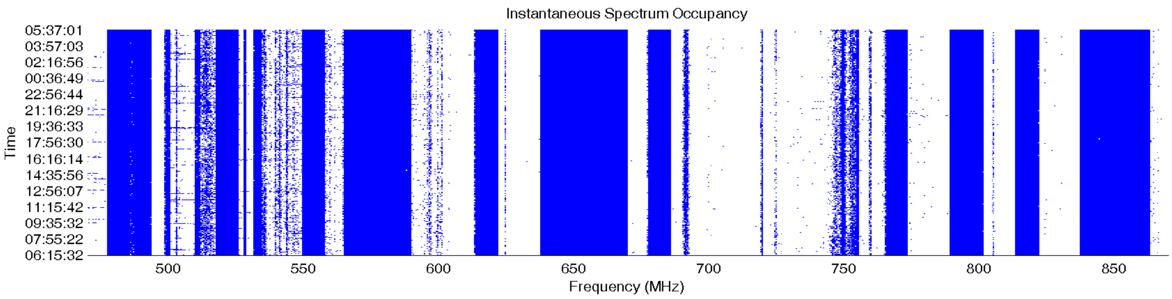

Figure 1: Example of TV Whitespaces.

These spectrum holes or whitespaces have motivated the appearance of new Dynamic Spectrum Access (DSA) policies, which are supported on three main guidelines: Maximize flexibility of spectrum use, Account all dimensions of spectrum use and Promote efficient use of spectrum. The radio spectrum is a multidimensional entity; space, time, frequency and polarization are some of the key dimensions. There are some new technologies that are trying to exploit this new vision of spectrum utilization, these technologies are known by different names: terms such as reconfigurable networks, adaptive radio, cognitive radio and Cognitive Radio Networks (CRNs) have become common and often used interchangeably.

One of the most important components of this new concept is the ability to measure, sense, learn, and be aware of the parameters related to the radio channel characteristics, like the availability of spectrum and power, radio's operating environment, user requirements and applications, available networks (infrastructures) and nodes, local policies and other operating restrictions.

This new vision of spectrum utilization is going to change the design of some telecommunication systems, in order to exploit more efficiently the spectrum, what will force the new devices to be able to sense the spectrum in order to detect the spectrum holes and take advantage of them. For that reason, some spectrum surveys are being carried out around the world to check the utilization rate of the different bands, studying the feasibility of that new concept, obtaining results that are showing the low occupation rates of spectrum through different cities around the world.

1.2 Objectives

The main objective of this work is to make a first approach to the spectrum characterization, to see how the different dimensions of the spectrum are exploited. Aspects like modulation scheme, power received, protocol used, system infrastructure or coding have not been of interest for us in this first approach. The main purpose is to measure the occupancy of the different bands under test, obtaining different measurements that allow us to extract useful information to characterize the spectrum and radio environment. To achieve this goal, a measurement system have to be implemented accordingly to the needs of this particular application. Those needs are the ability to cover a large range of frequencies, the ability to detect all the signals presents on the radio environment or the ability to differentiate between weak signals and noise. Those specifications mean that we are going to deal with wideband instruments, so we must take care of aspects that this specification entails, like the noise filtering or the prevention of saturation of active instruments like power amplifiers. Low noise figures will be desirable, in order to keep the SNR as high as possible to detect as weak signals as we can.

Besides the hardware detection system, a software engine has to be implemented in order to set the configuration of the hardware during the measurement, being able to correct the deviations or variances of the system. Additionally, a post-processing algorithm has to be developed to obtain useful results that make it easy to extract conclusions from the measurement. Once the whole system is assembled, the spectrum survey will be carried out, obtaining the spectrum occupancy results, leading to an analysis of the occupation on the different spectrum bands.

1.3 Methodology

To implement our measurement system, first we have to decide what sensing technique is going to be implemented, to design the measurement system accordingly to it. For that reason, a review of the different spectrum sensing techniques are shown on section 2, discussing the pros and cons of each one. Once the sensing technique is chosen, the detection system is designed by choosing the RF elements that best fit our specifications. On section 3 the different elements selected are presented, showing its characteristics, as well as the selected configuration for the system. After having assembled the measurement equipment, the software engine is designed to perform the measurement automatically, with the desired configuration for each one of the bands and all the related parameters to it. Also a post-processing algorithm is implemented to obtain useful and representative results. Sections 4 and 5 shows the different proceedings followed to design the software engine. Finally, the results obtained are shown on section 6 and a discussion of the spectrum occupancy is presented.

2 Spectral Sensing Methods

One of the key features of that new vision of spectrum occupancy is the knowledge of the RF environment, allowing the wireless devices to detect the activity around them, giving them the capacity to see what is happening outside its system, enabling a new feature that the classical wireless devices don't have: the ability of "Sensing".

Spectrum sensing is the task of obtaining awareness about the spectrum usage and existence of primary users in a geographical area. This awareness can be obtained by using geolocation and database, by using beacons, or by local spectrum sensing at cognitive radios. Several studies have shown the problems of local sensing, like the hidden primary user problem, noise uncertainty, fading or shadowing. To solve this problem, a cooperative sensing technique is proposed, where a number of sensing nodes can interact with each other or a master node to efficiently carry out the spectrum sensing, obtaining the set of unused bands in the different points of a geographical area, generating a georeferenciated database that can be updated automatically. Providing an open access to the database would enable any device with internet access to search for the available whitespaces in its geographical area, in order to exploit the unused channels in an opportunistic way. The scheme is very simple, only by checking the database and asking for a temporal allocation, the requested channel would be allocated to its applicant accordingly to a certain DSA policy, and the database would get updated in order to set the requested channel as busy until the grant expires.

This idea is being exploited by Google in the United States, where a cooperative spectrum sensing is being carried out in the television band, due to the attractive whitespaces present on it. The Google Spectrum Database Project has deployed a spectrum sensing network in the USA that covers the whole territory, creating a database which allows anyone to know where and when are the spectrum whitespaces, and thus, the occupancy opportunities. Figure 2 shows the spectrum availability in the United States.

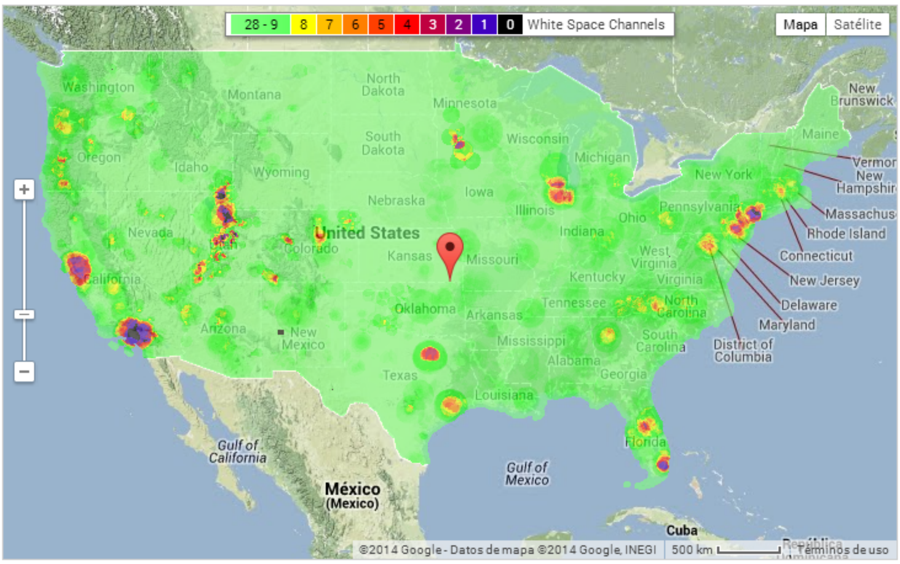

Figure 2: Available TV Whitespaces on the USA.

Moreover, Google has developed an API that allows device manufacturers, researchers and anyone interested to query white space availability based on time and location. In that new context, it will be very important to detect unused spectrum, to have a set of unused bands in which the new systems can operate on an opportunistic way. The different spectrum-sensing techniques may be grouped into different categories:

2.1 Energy Detection Based Sensing

The Energy Detection Sensing Method is the most generic sensing method, as the receiver doesn't need to know any knowledge of the primary user signals. To decide if a band is used, the output of the energy detector is compared against a previous-defined threshold, which is usually set some dB's over the noise floor.

The more challenging aspects of this method are the threshold selection, the detection of low SNR signals, the detection of spread-spectrum signals and the uncertainty about the origin of the spectral peaks, in order to differentiate a real signal from an interference, spurious emission or peak noise.

2.2 Ciclostationarity Based Sensing

This sensing method is based on the recognition of repeated patterns on the received signals, exploiting its cyclostationary features. This sensing technique is supported on the fact that the noise is wide-sense stationary (WSS), what means that it is uncorrelated, while the modulated signals are cyclostationary, as its correlation present peaks, due to the periodicity of the signal.

This method neither needs knowledge of the primary user signal, what makes it easy to implement. From the correlation of the signal, the spectral density can be calculated applying the Fourier transform to it, and this method can be used in combination with the Energy Detector Method in order to improve the performance of the sensing.

2.3 Matched Filtering

The Matched-Filtering Method is known to be the most effective sensing technique, as the receiver knows exactly what is the signal that the primary user is transmitting, allowing the receiver to differentiate on an effective way the presence of the primary user on a frequency band. This method has a good performance on low SNR scenarios, and has the capacity to detect any type of primary user signal, as it is known on the receiver.

The main disadvantage is the complexity of these types of receivers, as they have to be prepared to detect all signal types, what results on a difficult implementation and bad power consumption efficiency due to the execution of various receiving algorithms, as well as the previous knowledge of the signals present on the radio environment, which is very difficult in practice.

2.4 Waveform Based Sensing

The Waveform-Based Sensing technique is a hybrid between the Matched Filtering technique and the Cyclostationarity-Based technique, as the receiver uses known patterns as preambles, synchronization frames, regularly transmitted pilot patterns or spreading sequences to correlate them with the received signal, and then detect the presence of the primary user.

It has been demonstrated that this technique outperforms the Energy Detection Based Method in reliability due to the knowledge of some patterns of the signal. The main disadvantage of this method is that is only applicable to systems with known signal patterns.

2.5 Other Sensing Methods

There are another types of sensing methods like Radio Identification, Multitaper Spectral Estimation, Wavelet Transform based estimation, or Hough transform based estimation.

Radio Identification is based on the extraction of features of a signal in order to classify it and identify what type of signal is, to exploit their spectrum opportunities or other characteristics of the identified system.

The Multitaper Spectral Estimation is based on the average of different and independent estimations called "tapers", extracted from the signal received in order to get a spectral estimation the most similar to the real one.

The Hough and Wavelet Transforms are widely used on digital image processing; the Hough Transform is used to find known shapes of an object on an image, but in our context of signal detection can be used to find known periodically repeated patterns on the received signal.

The Wavelet Transform, is used to detect edges on the Power Spectral Density of a wideband channel. This edges represent the transition between an occupied band and an unused band, and vice versa. With that information, the spectrum can be divided into the different occupied and empty bands, on a binary fashion, obtaining directly the occupation pattern of the spectrum.

3 Measurement System

After having taken a look at the different sensing techniques, the selected sensing method for our application is the Energy Detector Based Sensing Method, due to its low complexity and the needless of primary user information. Although it is not the most accurate method, it is enough to make a first approach of the spectrum characterization and see what is going on in the radio environment. Therefore, the system implemented won't demodulate the received signals, only the RF signal power will be detected and then compared against a threshold, to determine if the channel is free or not.

3.1 Measurement Equipment

The equipment used for the measurement in this study relies on an ultra-wideband discone antenna, which will enable our system to see the RF activity over a wide range of frequencies. The antenna is connected to a FM Band Stop Filter, in order to avoid a possible saturation of the amplifier, due to the high power level received on the FM Band. Once the FM band is attenuated, the received signal is guided to a Low Noise Amplifier (LNA) that will improve the sensitivity of our measurement system, allowing the system to detect weak signals without worsening the system noise level too much. The output of the LNA is connected to the Agilent's spectrum analyzer model E4407B which has an operating frequency range of 9 KHz to 26.5 GHz, measurement range from -150 dBm to 30 dBm, ±0.4 dB overall amplitude accuracy and a maximum sensitivity of -150 dBm. The spectrum analyzer is connected to a desktop computer by general purpose interface bus (GPIB). The MatLab Software, installed on the desktop computer is used for automatically setting the equipment for measurement and store the extracted data. A Single Pole Double Throw Switch has been used to swap between the antenna and a matched load, for noise calibration reasons. A block diagram of the measurement system is shown on Figure 3.

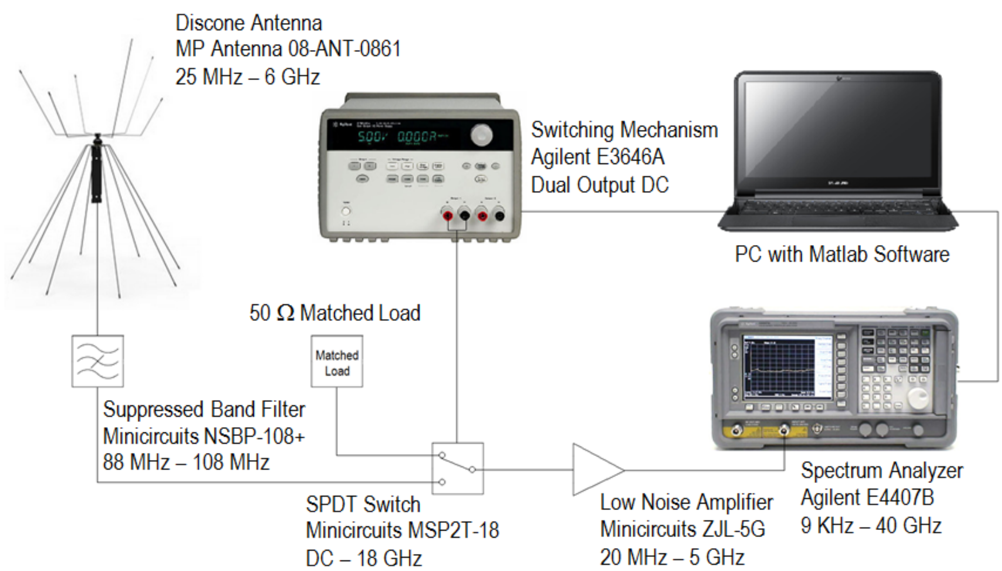

Figure 3: Measurement System Diagram Block.

3.1.1 The Discone Antenna

To perform the measurement, a discone antenna (MP Antenna, Model 08-ANT-0861) has been selected for several reasons that make it suitable for our application. In terms of frequency, its cone-shaped structure gives it an ultra-wideband performance, covering the frequency range from 25 MHz to 6 GHz in reception mode, allowing us to study a wide range of frequencies. In spatial terms, the antenna presents an omnidirectional pattern, which allows us to detect incoming signals with different angles of arrival, what will be useful, as the signals from the different systems can arrive from any direction. The antenna is also Multi-Polarized, which enables the system to receive horizontal, vertical and oblique polarized signals. This is an important feature, as there are several systems that only transmit one polarization, and with a single-polarized antenna its reception would be weak if the antenna is not well positioned. In terms of power, the radiation efficiency and the impedance matching are the key features of interest. In Figure 4, the Gain and the SWR of the antenna are plotted in function of frequency:

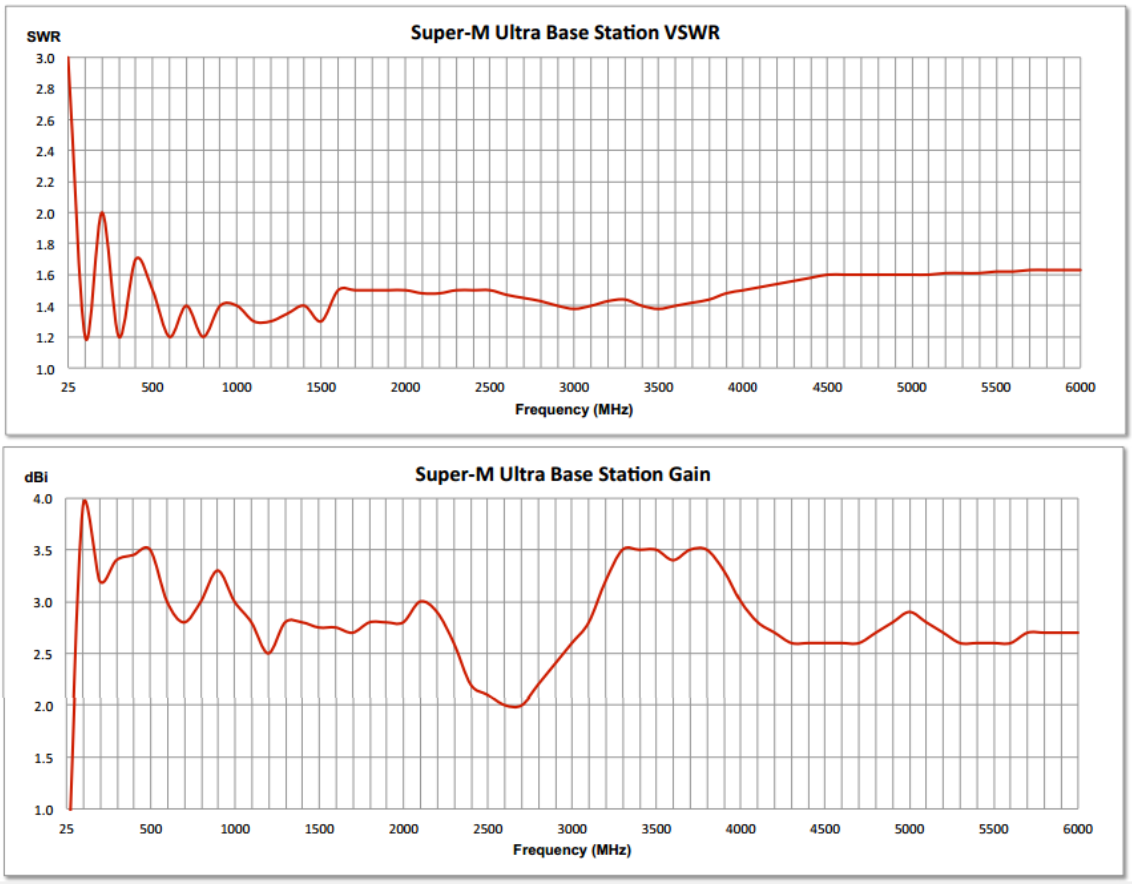

Figure 4: Antenna Gain & VSWR.

3.1.2 FM Band Rejection Filter

Directly connected to the antenna, the system has a FM Band Stop Filter (Minicircuits NSBP-108+), in order to decrease the high power received on the FM Band, avoiding a possible saturation of the amplifier, which would cause the generation of spurious signals on different frequencies, inducing the energy detector to an error, detecting a primary user where possibly it is not present. The main features of the filter are the insertion losses on the suppressed band and the impedance matching out of the rejected band. In terms of Insertion Losses, it is desirable to have an attenuation on the stop band highly enough to avoid the amplifier saturation and an attenuation the nearer as 0 as possible out of the suppressed band. In terms of matching, it is desirable to have values of VSWR out of the suppressed band the nearer as 1 as possible. On Figure 5 these characteristics are shown:

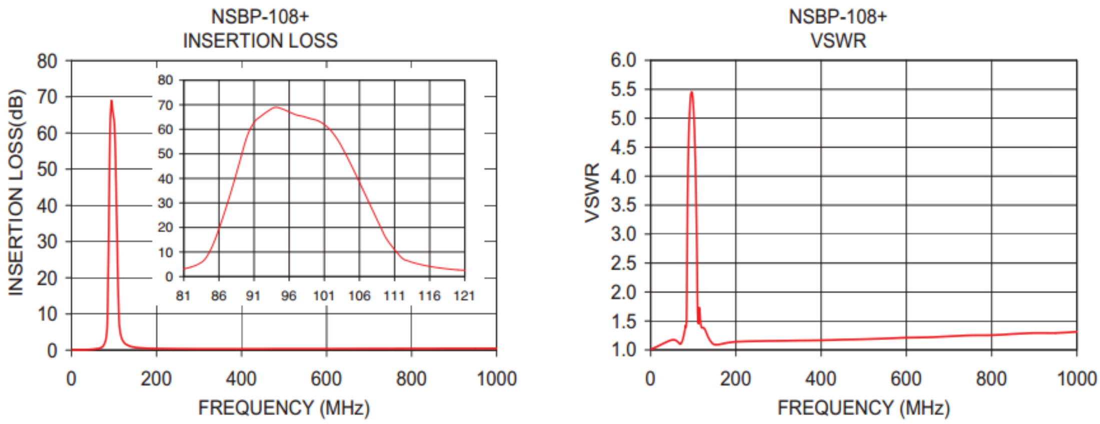

Figure 5: Filter Insertion Loss & VSWR.

3.1.3 Switch & Matched Load

A Single Pole Double Throw Switch (Minicircutis MSP2T-18) has been used to swap between the antenna and a matched load, for noise calibration reasons. The Switch works on a frequency range from DC to 18 GHz. The key features of the switch are the Insertion Loss, which is below 0.15 dB in the range of frequencies of our measurements, the Isolation between its inputs, which is high enough, around 100 dB on our frequency range, and the VSWR, which is below 1.2 in our frequency range. The 50 Ω Matched Load is used to calibrate the noise of the system, in order to set the threshold of the measurement correctly. The key feature of the load is the VSWR, which is low enough on the range of frequencies of our study.

3.1.4 Low Noise Amplifier

The last element on the RF chain just before the detector is the Low Noise Amplifier (MiniCircuits ZJL – 5G), which allow us to rise the power level of the received signals, increasing the ability to detect the weak ones, improving the sensitivity. This LNA is ultra-wideband, as it works from 20 to 5000 MHz. This specification forces us to be very careful to the power that we are injecting to it, in order to avoid intermodulation products, which would turn into false detections of primary users at different frequencies. The IP3 of the LNA has a typical value of +32 dBm typ. and a Noise Figure typical value of 8.5 dB. Another important specification of the power amplifier is its gain, which has a typical value of 9 dB, with a typical ripple of ±0.55 dB. Its VSWR has a value of 1.6 for input and 1.3 for output. On Figure 6 those different specifications are shown.

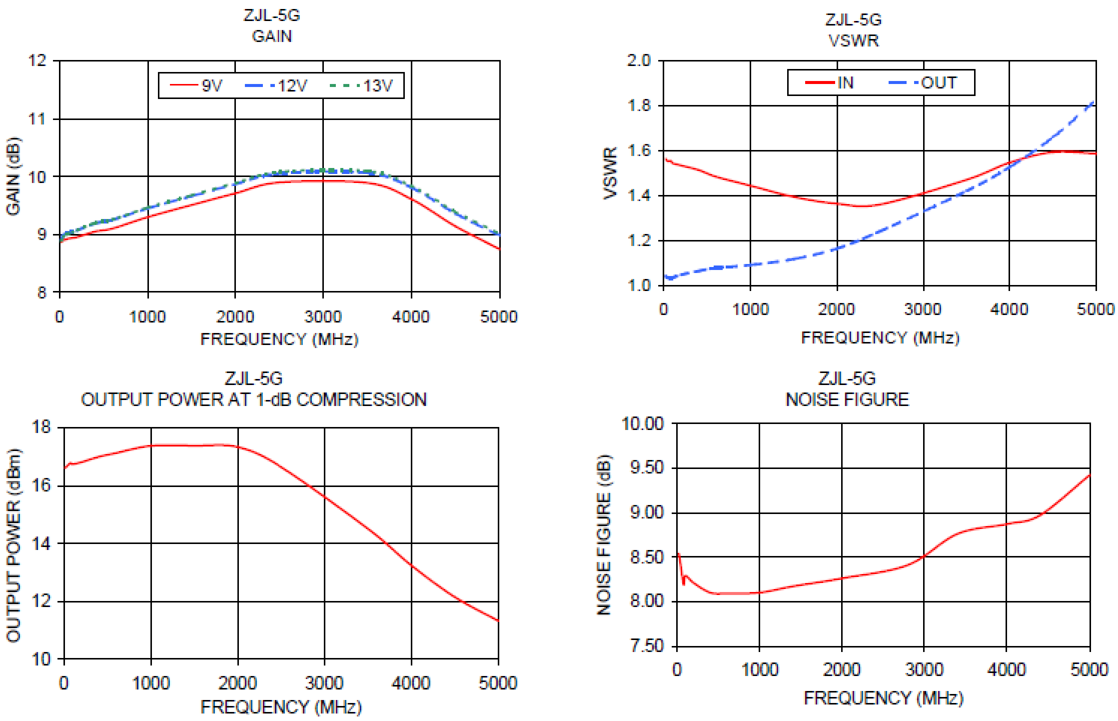

Figure 6: Amplifier Specifications.

3.1.5 Spectrum Analizer

The output of the LNA is connected to the Agilent's spectrum analyzer model E4407B which has an operating frequency range of 9 KHz to 26.5 GHz, measurement range from -150 dBm to +30 dBm, variable sweep points from 101 to 8192 points, ±0.4 dB overall amplitude accuracy and a maximum sensitivity of -150 dBm for a RBW of 1 Hz and internal RF preamplifier on. The spectrum analyzer is connected to a desktop computer by general purpose interface bus (GPIB).

3.2 Measurement Settings

Setting the measurement parameters is a crucial factor to obtain a reliable and precise characterization of the spectrum, as the different programmable parameters of the spectrum analyzer can affect directly to our results. The most important parameters of the measure are the sensibility and frequency resolution of the spectrum analyzer, directly related with the Resolution Bandwidth, and the Sweep Time employed to measure the whole spectrum. It will be desirable to have a low Resolution Bandwidth, in order to increase the sensibility and frequency resolution of the measure, and a short Sweeping Time, in order to increase the temporal resolution, detecting sporadic signals.

These specifications are inversely related to each other, since a low Resolution Bandwidth results in long Sweeping Times, because more frequency points are needed to cover the whole spectrum. Inversely, short Sweeping Times require fewer steps, increasing the Resolution Bandwidth, and as a result worsening the sensibility and resolution.

Therefore, all these parameters have to be chosen in order to reach a trade-off between them. The measurement parameters have been chosen according to the basic principles of spectrum analysis as well as some particular considerations specific to Cognitive Radio. The following tables show the selected settings to perform the spectrum characterization; Table 1 shows the different bands in which the spectrum has been divided and the spectral resolution selected on each one accordingly to the service deployed on it.

	Start Frequency	Stop Frequency	Span	Points	Frequency Bin
Band 1	75 MHz	470 MHz	395 MHz	3160	125 KHz
Band 2	470 MHz	870 MHz	400 MHz	800	500 KHz
Band 3	870 MHz	960 MHz	90 MHz	900	100 KHz
Band 4	960 MHz	1710 MHz	750 MHz	2500	300 KHz
Band 5	1710 MHz	1880 MHz	170 MHz	1700	100 KHz
Band 6	1880 MHz	2290 MHz	410 MHz	1312	312.5 KHz
Band 7	2290 MHz	3600 MHz	1310 MHz	2620	500 KHz
Band 8	3600 MHz	5000 MHz	1400 MHz	2800	500 KHz

Table 1: Spectrum Sub-Bands.

The division of the spectrum under study into sub-bands has the objective to adapt the measurement parameters to the service deployed in each of the bands. For example, in the GSM Band, where the channels have a bandwidth of 200 KHz, selecting a Frequency Bin higher than 200 KHz would lead to an undersampled measurement on this band, as some channels wouldn't be measured. Following this criteria, the Frequency Bin has been selected in order to obtain enough resolution to cover all the possible channels while keeping a Sweeping Time as lower as possible. Table 2 shows the different parameters set up on the spectrum analyzer to take the measures.

	Parameter	Value
Frequency	Frequency Range	75 MHz - 5 GHz
	Frequency Span	Refer to Table 1
	Points Per Span	Refer to Table 1
	Frequency Bin	Refer to Table 1
	Resolution Bandwidth	100 KHz
	Video Bandwidth	100 KHz
Time	Measurement Period	24 Hours
	Sweep Time	5.01 Seconds
Amplitude	Built-In Pre-Amplifier	On
	Reference Level	-40 dBm
	Reference Level Offset	0 dB
	Scale	10 dB/div
	Input Attenuation	0 dB
	Averaging	Off

Table 2: Spectrum Analizer Settings.

3.3 Data Storage

When a measurement campaign of these characteristics is set up, the volume of data obtained will be very large, forcing us to make a previous study of the memory required to store the measurement data. The volume of data obtained will be directly proportional to measurement time, the number of points taken on each sweep, and the precision (number of bits) chosen to save each point. The size of the obtained data can be easily calculated according to Formula 1:

$$\text{Total Data Size} = \text{Measurement Time} * \frac{\text{1 Measure}}{\text{X Sweep Time}} * \frac{\text{X Points}}{\text{1 Measure}} * \frac{\text{X Bits}}{\text{1 Point}} \quad (1)$$

In this study, the total measurement time is about 24 Hours, the whole spectrum measurement has a sweep time of 5.01 seconds, obtaining 15792 points which are saved with a double-precision floating-point format, occupying 8 bytes (64 bits). With those metrics, the Data Storage estimation is shown on Formula 2:

$$24Hours * \frac{3600Sec}{1Hour} * \frac{1Measure}{5.01Sec} * \frac{15792Points}{1Measure} * \frac{8Bytes}{1Point} = \text{2.178.728.623 Bytes (2,03 GB)} \quad (2)$$

It can be seen that the volume of data produced in only 24 hours is about 2 GB of information. This fact helps us to realize that we must implement an efficient post-processing algorithm to help us organize the data in order to present the required information in an orderly and representative manner. It is also important to say that the real data size will be slightly smaller, due to the compression techniques applied by Matlab® when saving the obtained data.

4 Software Engine

After having taken a look at the different hardwdare devices that make up the measurement equipment, the software engine will be introduced in this section. The development of an efficient algorithm is crucial for the optimization of the system in terms of time or computational load, leading to the production of measures as fast as possible, keeping a high sampling frequency.

The procedure used to obtain the measures, it's structure or the post-processing, are introduced on the following subsections. The programming environment chosen to develop the algorithm is Matlab®, due to its low complexity high-level programming language and its versatility.

4.1 Measurement Structure

In this subsection, the measurement structure is presented, studying it first from its finest granularity, as a detailed, exhaustive and low-level model of it, up to its coarsest granularity, showing how the structure builds up from small blocks, creating larger ones.

4.1.1 Single Sweep Block

The first step is to obtain a single sweep of the spectrum under test, accordingly to the parameters set on Tables 1 and 2. The bands to be evaluated can be selected by the user, if only some bands are of interest. Furthermore, the bands can be redefined if a detailed study of a band is desired, as well as the spectral resolution.

As discussed above, the resolution taken on each one of the bands of the spectrum is different, which means that the obtained points won't be linearly spaced, what force us to create a vector with the different spectral resolutions selected on each one of the bands.

Figure 7 shows a decimated version of the distribution of the spectral points. The decimation factor taken is 188, what means that every sample of the figure correspond to 188 real samples. This decimation has been performed in order to see visually the sampling in each band.

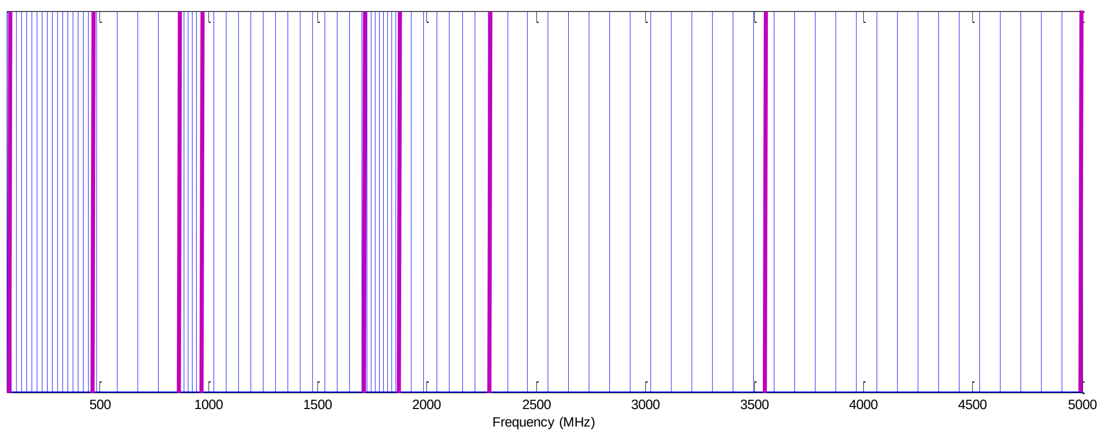

Figure 7: Spectral Point Density on each Sub-Band.

4.1.2 Noise Calibration Block

Once the Single Sweep Block has the desired resolution on each one of the bands, the Noise Calibration can be performed. To do that, the algorithm sends the ON command to the power supply through the GPIB, which enables the output voltage on the power supply, which in turn sets the switch to connect the system to the 50 Ω Matched Load. Figure 8 shows the block diagram of the process.

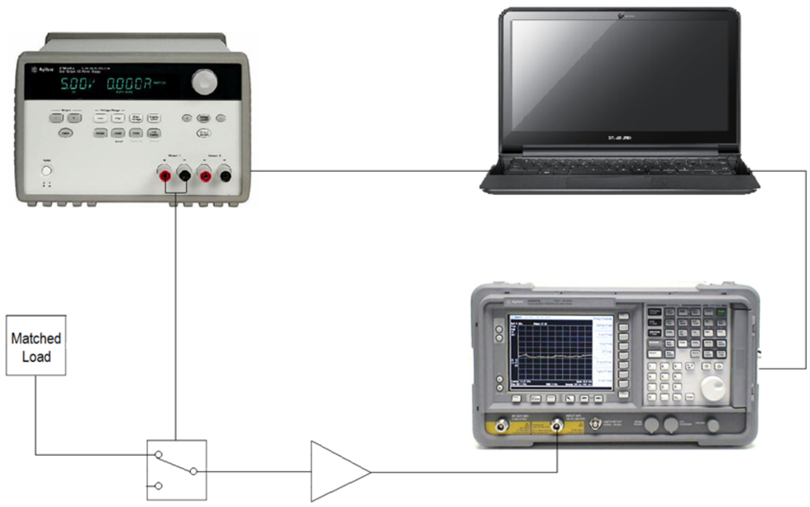

Figure 8: Noise Calibration SubSystem.

Once this action is carried out, the measurement of the Internal Noise of the system is performed in order to calibrate the Threshold Level. The Noise Calibration Block is formed by a few single sweeps, usually between 2 and 5 Sweeps, in order to minimize the calibration time, leaving more time to the spectrum measurement. Figure 9 shows the structure of the Noise Calibration Block.

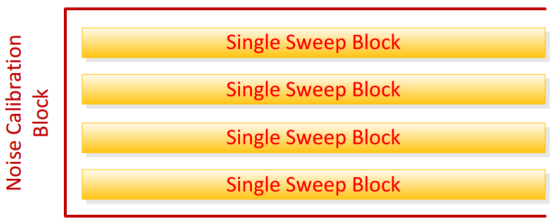

Figure 9: Noise Calibration Block Diagram.

4.1.3 Spectrum Measurement Block

Once the the Noise Calibration Block is obtained, the threshold is generated accordingly to the internal noise of the system. In Section 5 the procedure followed to obtain the threshold will be shown. After the generation of the threshold, the Spectrum Measurement Block is obtained measuring the different signals captured by the antenna. To do that, the algorithm sends the OFF command to the power supply through the GPIB, which disables the output voltage on the power supply, which in turn sets the switch to connect the system to the antenna branch. Figure 10 shows the block diagram of the process.

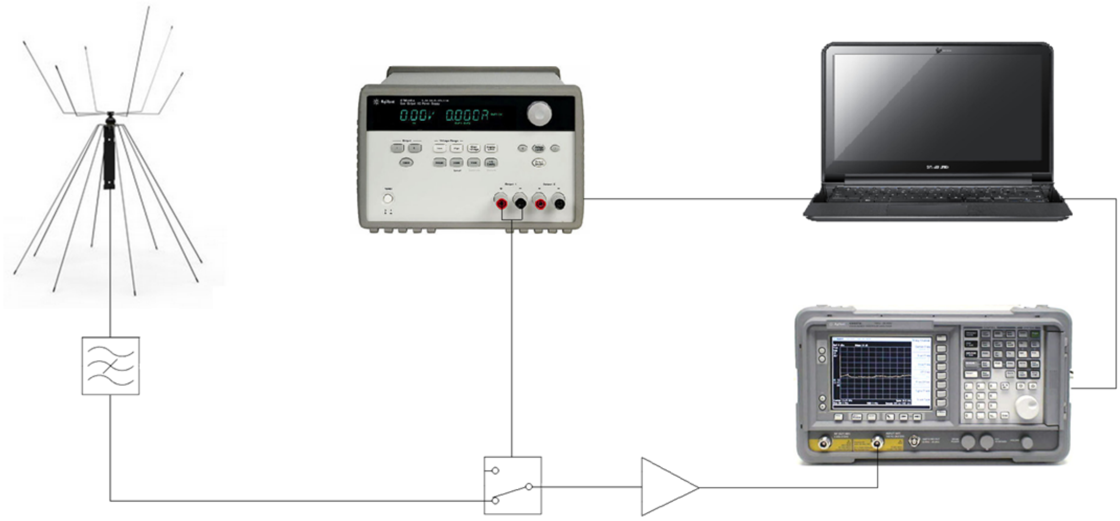

Figure 10: Spectrum Measurement SubSystem.

With this action carried out, the system is ready to start the survey of the spectrum, performing as many sweeps as desired, obtaining a large block of spectrum sweeps, which are the effective data and the main objective of all the process carried out. Figure 11 shows the schema of the Spectrum Measurement Block.

Figure 11: Spectrum Measurement Block Diagram.

4.1.4 Cycle Block

Usually, it would be desirable to set a very large number of sweeps in the Spectrum Measurement Block, in order to keep the spectrum monitoring as long as desired, but this criteria would end on a biased characterization of the occupancy of the spectrum, as the Measurement System Characteristics can change over time.

Like any electronic device, the continuous operation of our Measurement System leads to its heating, which affects directly on the internal noise produced by the system itself. Moreover, environmental conditions like air temperature or the variations on the power supplies also contribute to the variation of the internal noise of the system. For this reason, it is necessary to repeat the process of obtaining the Noise Calibration Block, and then, rebuild the threshold accordingly to the new characteristics of the system and continue taking spectrum measurements.

This repeating dynamic prompts us to group the Noise Calibration Block and the Spectrum Measurement Block, as this is the structure that gets repeated along the global measure, setting up a new block that groups calibration and measurement: The Cycle. Figure 12 shows the structure of the Cycle Block, formed by both calibration and measurement blocks.

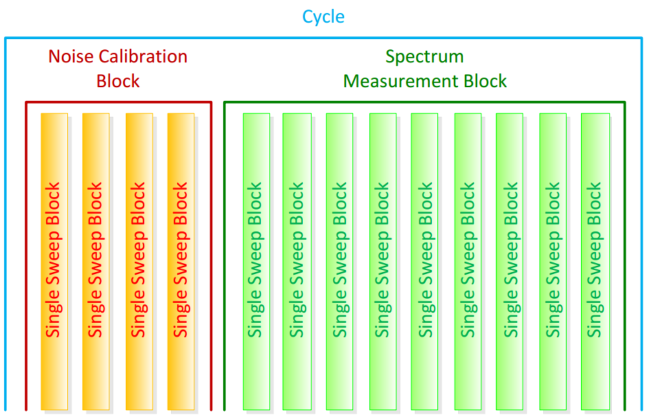

Figure 12: Cycle Block Diagram.

4.1.5 Global Measurement Structure

When a new Spectrum Survey is set up, all previous blocks can be configured, giving total freedom to the designer. Usually, the sweeps carried out to calibrate the system are much less than the measurement ones. Depending on the hardware equipment that the algorithm is managing, the measurement sweeps can be larger if the system is stable in terms of internal noise, or conversely, lower if the system has fast noise variations.

Once the calibration and measurement blocks are set, the global measure gets defined by the number of cycles that are carried out. Figure 13 shows the structure of a measure formed by 2 Cycles consisting on 4 Calibration Sweeps and 9 Measurement Sweeps.

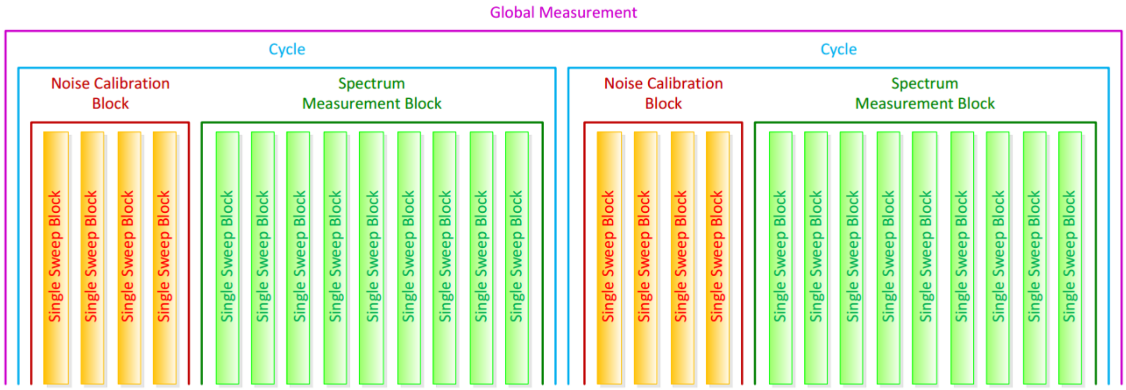

Figure 13: Global Measurement Block Diagram.

4.2 Post-Processing Algorithm

Once the total measurement is obtained, the post-processing algorithm is launched, to process the acquired data in an organized way, obtaining representative graphics and tables that provide useful information about the spectrum occupancy. In this section, the different programmable options of the outputs are presented, showing the system flexibility.

4.2.1 Customizable Output Period

As mentioned above, the overall measurement is composed of different cycle blocks containing the spectral sweeps of a certain period of time. When setting up the measurement post-processing parameters, the data processed in every one of the outputs can be configured, obtaining the different outputs for every period of time previously configured. Figure 14 shows a measurement composed of 3 cycles, and the three posible outputs that can be set:

Option A 1 Cycle per Output, leading to a Result Set per cycle.

Option B 2 Cycles per Output, leading to a Result Set for the 2 first cycles and a second Result Set for the remaining cycle.

Option C 3 Cycles per Output, leading to a single Result Set comprising the whole measurement.

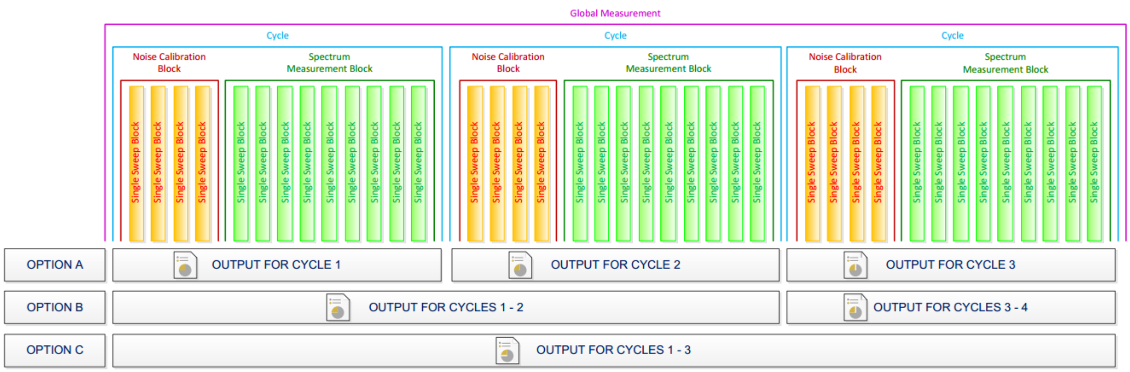

Figure 14: Customizable Output Example.

4.2.2 Post-Processing Outputs

To evaluate the spectrum occupancy, the first output is a figure composed by three different occupancy metrics, which give us information about the maximum, minimum and mean power registered, the temporal behaviour of the spectrum and its duty cycle.

1. The first occupancy metric used is the Power Spectral Density (PSD), showing the maximum, mean and minimum values registered during the previously specified period. From these metrics, the temporal behaviour of every frequency band can be evaluated. For example, if the three PSD metrics are very similar, it can be thought that the band is continuously occupied, and the reception of this band experiences low fadings. On the other hand, if the difference between the PSD values is higher, it can be thougth that the spectrum is used sporadically, or maybe the transmitter is moving, and the fading is varying during the measurement period. Figure 15 shows an example of these metrics.

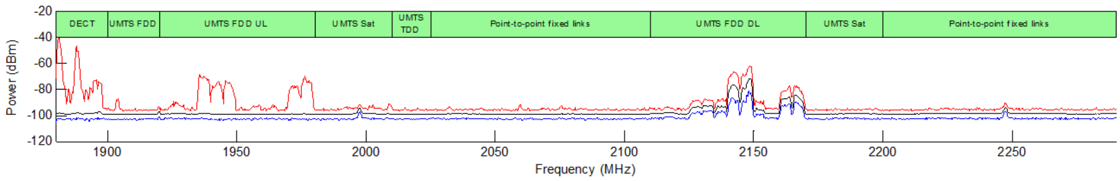

Figure 15: Example of PSD Metrics.

2. The second occupancy metric obtained is a time-frequency waterfall in which the temporal evolution of the different spectrum bands is plotted. This output can be configured in order to obtain the evolution of the spectrum occupancy, where the blue points show the occupied frequencies, while the white ones show the idle frequencies, but it can be also set to obtain the evolution of the power recevied on each frequency, which can be used to obtain information about the fading variation over time and the possible motion of the transmitter. Figure 16 shows both occupancy and power waterfalls that can be obtained.

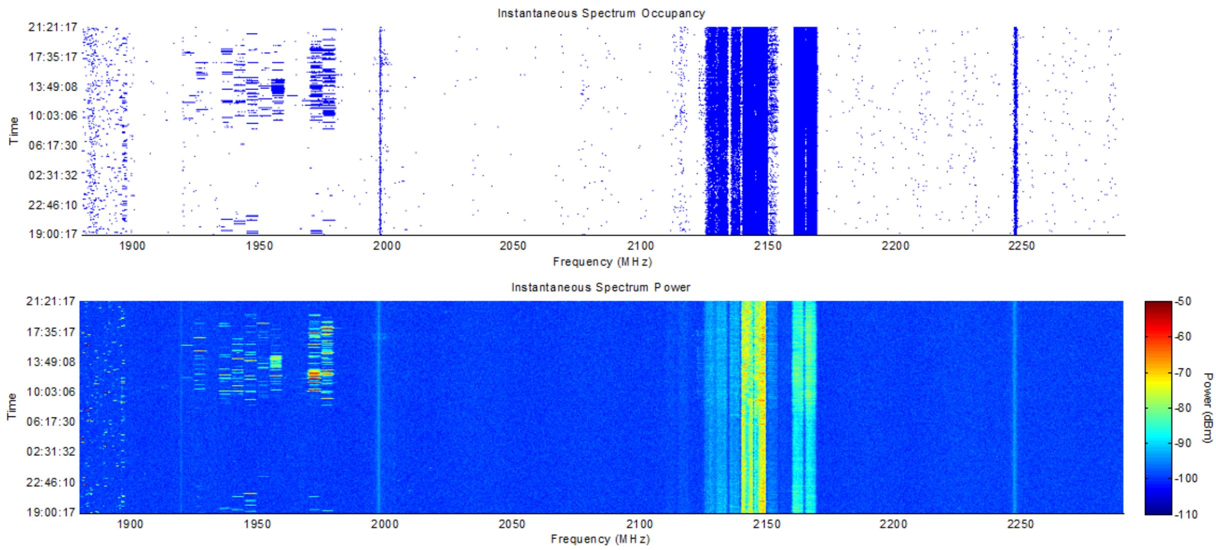

Figure 16: Example of Occupancy and Power Waterfalls.

3. The third occupancy metric obtained is the Duty Cycle of every band, which gives us the information about the time (in percentage) that the band has been occupied. The combination of the three occupancy metrics leads to an accurate spectrum characterization. Figure 17 shows an example of this metric.

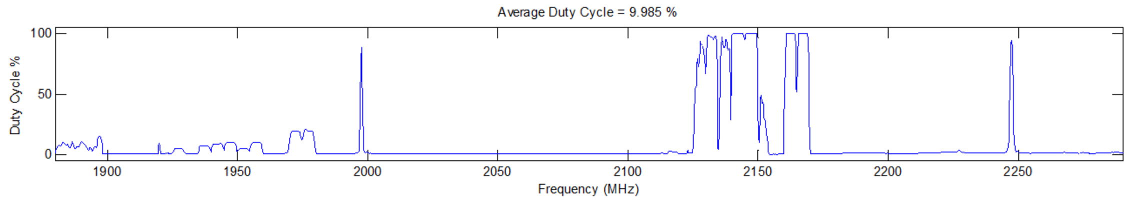

Figure 17: Example of Duty Cycle Metric.

The second output is a figure showing the average duty cycle on every one of the bands configured, revealing which bands are the the busiest ones, and which bands are the more inactive. To obtain a more accurate characterization, the same figure is processed for every different service. Figure 18 shows an example of this output.

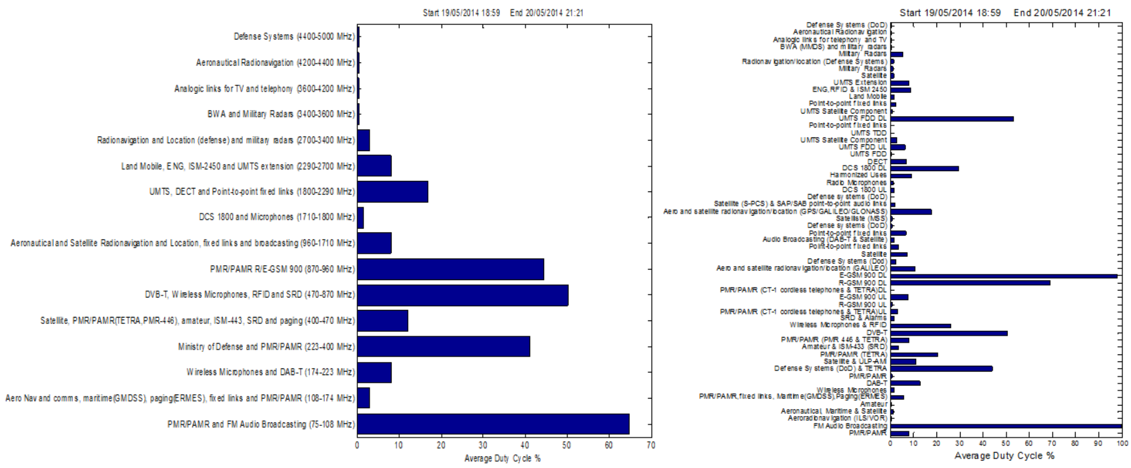

Figure 18: Example of Average Duty Cycle Metric on each Band and Service.

The third output is a table showing the occupation of every service. The Start Frequency, the stop Frequency, and the bandwidth allocated for each service is presented. The numerical value of the average duty cycle of the service is shown, as well as the effective occupied bandwidth.

All these results are generated automatically by the developed algorithm, which make it very easy to make the spectrum survey. By setting up the different parameters of the measurement and the post-processing, the desired results are generated by the Software Engine without the need of any action from the user.

5 Decision Threshold Definition

As we have discussed above, choosing the threshold level is one of the most challenging aspects of the Energy based Sensing Method. To define the threshold level, the system needs to calibrate the resulting noise at the end of the RF chain, and then place the threshold above noise level, according to a selected algorithm.

5.1 Internal Noise Calibration. Matched Load Method

Internal Noise Calibration is performed by switching the input of the measurement system from the antenna to a 50 Ω Matched Load, in order to detect on the spectrum analyzer only the internal noise generated by the measurement equipment, avoiding the presence of external signals on the calibration. To select a proper threshold level, the implemented algorithm has to be able to couple the threshold to the noise spectral density. The spectrum analyzer used in this study has different filter banks and reception chains, depending on which frequency we are working. Due to this fact, the total noise figure of the system will change over the range of frequencies of the study, obtaining a non-planar noise spectral density.

On many studies, the threshold level is set some dB above the measured noise level; one of the ITU recommendations suggests setting the threshold 10 dB above the ambient noise. In this study, the threshold will be set to obtain a certain probability of alarm, where the probability of alarm is defined as the probability of detecting a primary user when it is not really present, due to a peak of noise reaching the threshold. To set the threshold, the internal noise of the system is measured during a certain period of time. The maximum levels of noise are recorded, being the input of the algorithm. The next step is to understand the noise spectral density as a time-domain signal which is composed by fast variations (due to the stochastic characteristic of noise) and slow variations (due to the change of the noise figure of our measurement system). Those different variations are shown on Figure 19.

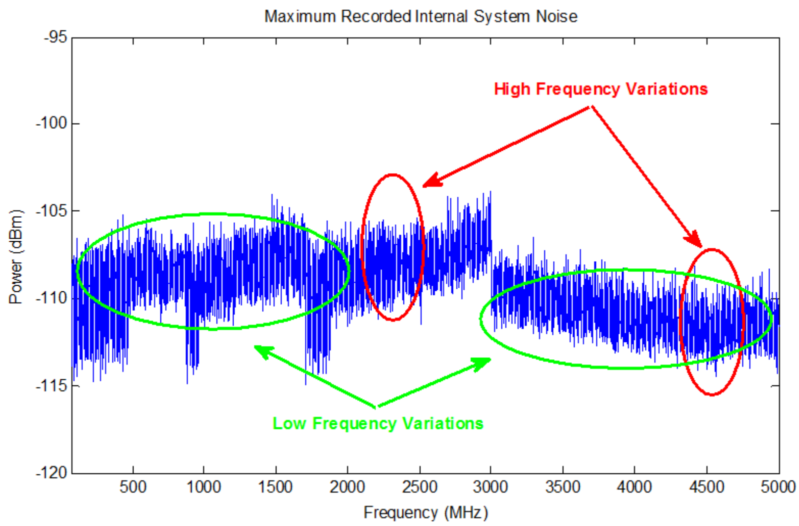

Figure 19: Maximum Recorded Internal System Noise.

This signal is low-pass filtered, removing the fast variations in order to get a smooth threshold, while maintaining the slow ones, in order to give to our threshold the same shape as the spectral noise density of our system. Once we have the desired threshold shape, the total spectrum is divided into sub-bands, and every sub-band is placed above the noise level in order to obtain a maximum probability of alarm. The total spectrum probability of alarm will be equal or less to the probability of alarm set for every sub-band.

The convergence time of the algorithm is proportional to the number of sub-bands in which the spectrum is divided, and the increment step of the threshold to reach the specified probability of alarm. A little increment step allows the threshold to approach very well the false alarm specification, with the penalization of increasing the convergence time. On the other side, a big increment step decreases the convergence time, but the threshold can be set too high, worsening the ability of the system to detect weak signals.

Partitioning the spectrum in too much bands, allow the threshold to couple very well to the spectral noise density, but it penalizes the convergence time of the algorithm. On the other hand, partitioning the spectrum in fewer bands can penalize the shape of the threshold, as a peak of noise would result on a threshold too high in the range of frequencies of the sub-band in which the noise peak is present. A tradeoff between all these factors has to be reached, to obtain an effective threshold level in the shortest time possible. Figure 20 shows an example of threshold definition.

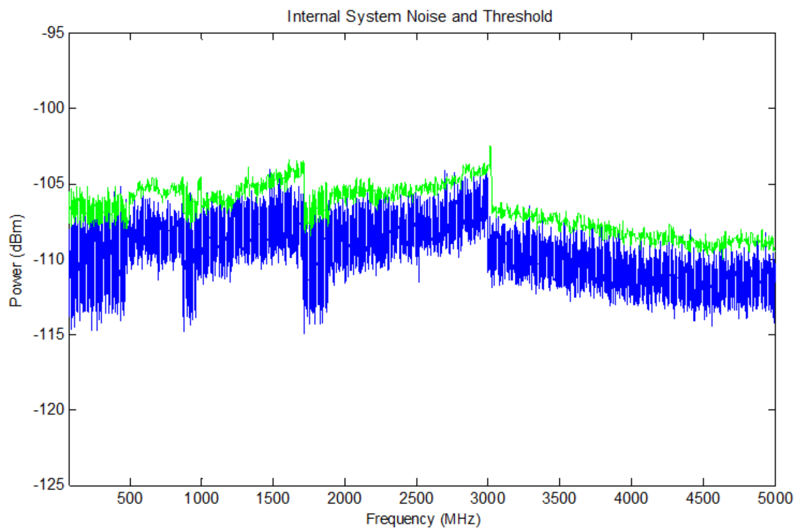

Figure 20: Internal Threshold.

It can be seen how the noise is not flat in the range of frequencies presented, due to the different RF chains of the Spectrum Analizer depending on the band that it is working. Note that there are some bands like GSM or UMTS bands in which the noise has a lower effect than in other bands. Notice also the step on 3 GHz, due to the change from one filter bank to another one. Once the threshold has been defined, a test is performed in order to see how effective is the previously defined threshold and to check if it is matchig well the spectral shape of the noise captured by our antenna. On Figure 21 the results are shown.

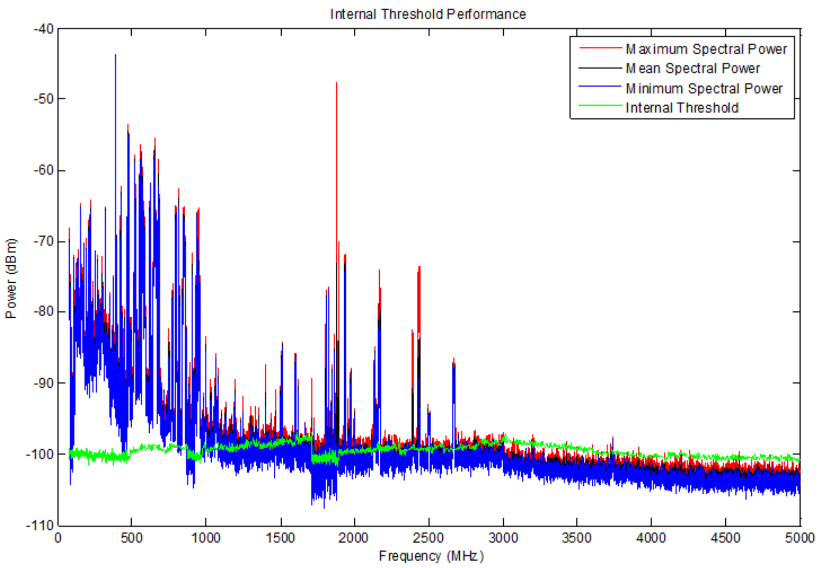

Figure 21: Internal Threshold Performance.

It can be seen that the threshold is not well defined in the range of VHF and UHF frequencies, as the noise level in those frequencies is higher than the measured on the calibration. To fix this problem, another type of technique has to be applied in order to obtain an adequate threshold level on these frequencies.

5.2 Matched Load Calibration Method Mismatch Troubleshooting

At this point, an alternative calibration techinque has to be applied to couple our threshold to the global noise floor of the system. Two different hypothesis are handled to find the cause of the noise floor behavior on these VHF and UHF frequencies. The following sections show the proceedings followed to check the proposed hypothesis.

5.2.1 Hypothesis 1. Amplifier Saturation

The first hypothesis takes into account the possibility that the total power taken up by the antenna is high enough to be saturating the amplifier, and, due to the high density of signals in the range of VHF and UHF frequencies, the spurious generated in that band are so many that they are too close to each other, and when integrating on the RBW of 100 KHz the resultant power is too high, giving that shape to the spectrum measured. To check if this hypothesis is true, a study of the power managed by the measurement system has been performed.

The first test carried out aims to measure what is the noise level at the output of the amplifier, allowing us to compute which is the dynamic range of input powers free of intermodulation products and harmonics. To make this test, the 3^{rd} Order Intermodulation Distortion and the 2^{nd} Order Harmonic Distortion are taken into account, since these distortions are the first that show up. Figure 22 shows the results obtained.

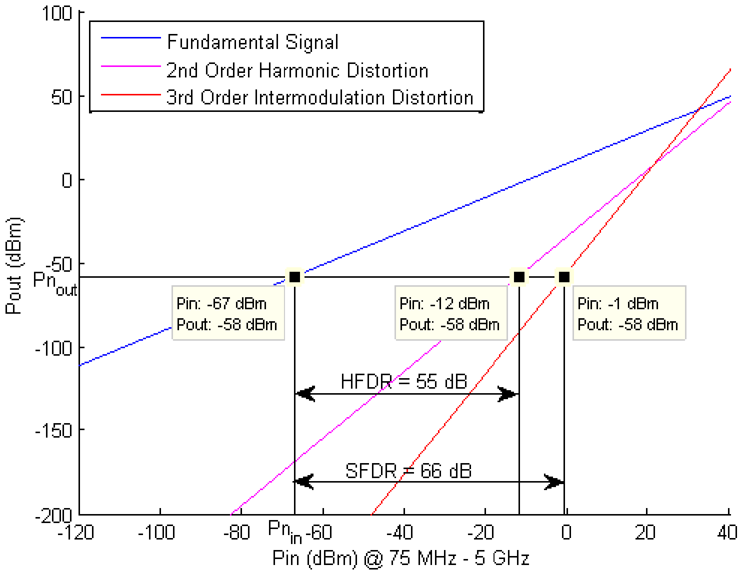

Figure 22: Dynamic Range Characterization

It can be seen that the output noise level is about -58 dBm for the measured input noise power, which is of -67 dBm. This output noise level defines a 55 dB dynamic range free of harmonic distortions, and a 66 dB dynamic range free of spurious. That means that the Harmonic Distortions will be below the noise level for total input powers less or equal than -12 dBm, and Intermodulation Distortions will be below the noise level for total input powers less or equal than -1 dBm. For input powers higher than -1 dBm, both Harmonic and Intermodulation Distortion will be present.

The second test carried out aims to measure the total power level captured by the antenna, in order to check if this power is saturating the amplifier. Figure 23 shows the results obtained.

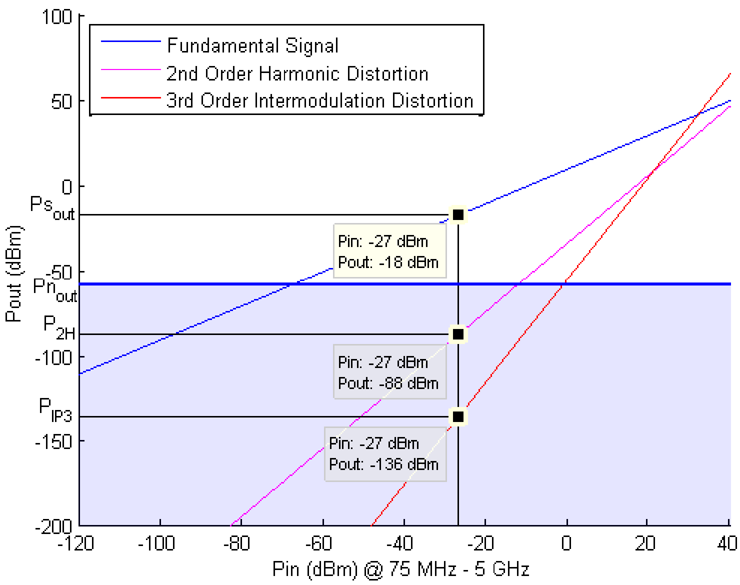

Figure 23: Output Rejection Levels for 2^{nd} and 3^{rd} Order Distortions

The total input power injected to the amplifier when the antenna is connected to the system was measured, obtaining a value of -27 dBm, what generates an output power of -18 dBm. It can be shown that the output power of the 2^{nd} Order Harmonic is about -88 dBm, obtaining an output rejection level for the 2^{nd} Order Harmonic of 70 dB. Moreover, it can be seen that this power level is below the noise level, what means that noise will mask this harmonic distortion.

In terms of intermodulation distortion, it can be shown that the power of the 3^{rd} Order Intermodulation is about -136 dBm, obtaining an output rejection level of the 3^{rd} Order Intermodulation Product of 118 dB. Note that the output power of this distortion is also masked by noise.

Once the study of the power managed by the amplifier has been done, it has been demonstrated that the fist hypothesis is false, showing that the amplifier is not being saturated. At that point, the following step is to take into account a different hypothesis, in order to find a cause that could explain the unexpected behaviour of the spectrum on VHF and UHF frequencies.

5.2.2 Hypothesis 2. External Noise Reception

The second hypothesis supposes that the antenna is capturing external noise, which has a significant importance on those VHF and UHF frequencies, and that could explain why the noise is increasing on this range of frequencies.

The measurement setup on Figure 3 shows that when the switch is selecting the 50 Ω matched load, the only devices that are left out of the system are the FM Band rejection filter and the antenna. Leaving aside the filter, the only device that can be introducing this noise to our system is the antenna. To check this hypothesis, our measurements are compared against the measurements taken by ITU in its Radio Noise Recommendation. The procedure is described below.

Generally, in order to manage the external noise captured by the antenna, a temperature “Ta” different from the physical temperature is attributed to the antenna, replacing the real scenario by a theoretical scenario in which no external noise is captured by the antenna, and the noise contribution is translated to the antenna, adding to it a certain temperature which generates the same level of power as the received external noise power.

Several studies have been performed on the field of Radio Noise and we will take support on the ITU Recommendation *“ITU-R P.372-11 (09/2013)”*, in which different radio noises are measured over a wide range of frequencies. In this study, only the range of frequencies between 75 MHz and 5 GHz will be evaluated. On Figure 24 the radio noise measurements performed by the ITU organization are presented on the range of frequencies of interest.

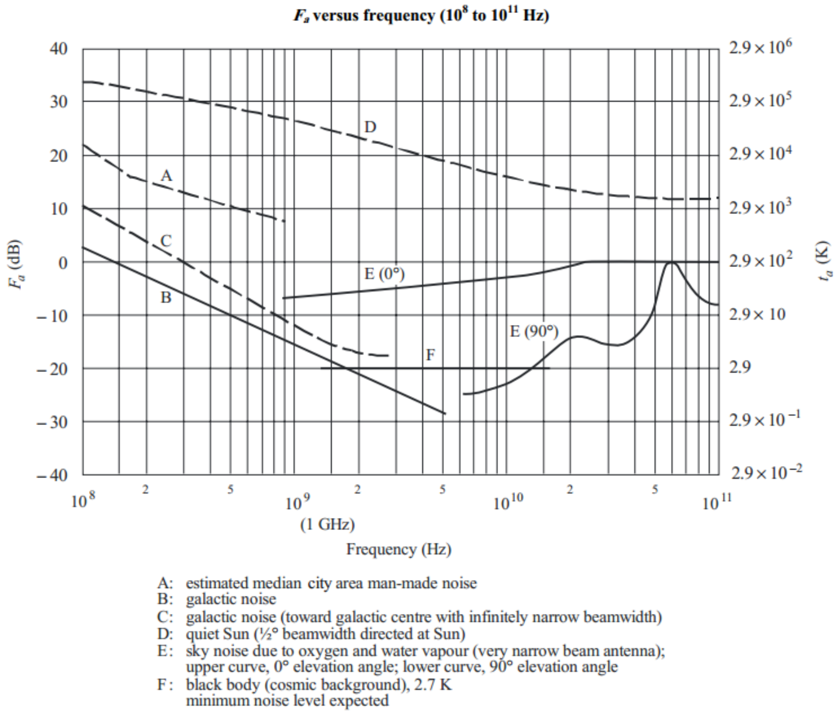

Figure 24: ITU Radio Noise Measurements.

Since our calibration is not adequate on the frequency range of VHF and UHF frequencies, only A, B, C and D types of radio noise are evaluated. To compare these different sources of noise with our measurement, their "Ta" values are introduced to Matlab, generating the different curves for each type of radio noise. On figure 25 the noise curves are plotted against our spectrum measure:

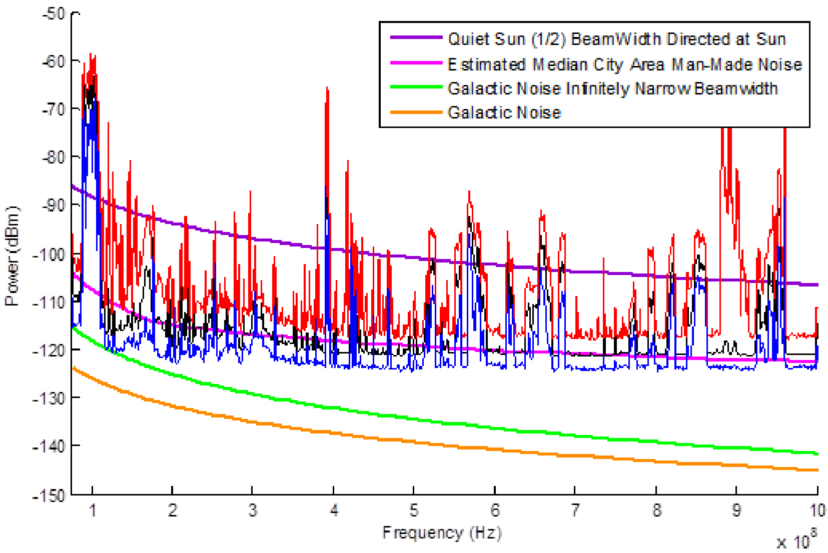

Figure 25: Noise Curves vs Spectrum Measurements.

It can be seen how the measured spectrum matches fairly good the Estimated Median Area City Man-Made Noise, which hints us that the behavior of the noise floor on those frequencies is largely due to the external Man-Made Noise captured by the antenna. Man-Made Noise is an artificial type of noise that can be produced by different sources; vehicle ignition circuits, computers, impulses on electrical switches, motors, power lines, microwaves or thermal industrial processes. This external noise has to be taken into account when sensing the spectrum. On [6] and [9], ambient, natural and man-made noises are taken into account on cognitive radio scenarios.

5.3 Global Threshold Definition. Internal & External Methods

Once the Internal and External noise calibrations are done, the two decision thresholds are combined, selecting one or another in function of the band in which we are. In the low frequencies, the external noise captured by the antenna predominates over the internal noise, while in higher frequencies the external noise became lower, being masked by the internal system noise. The global computed threshold will be the maximum between them.

As the internal system noise can be calibrated and it can change over time, the transition frequency between thresholds can change during the measurement, adapting to the system characteristics. The external noise is a statistically fixed parameter, and it won't be changed during the measure. On figure 26, internal, external and resultant thresholds are shown, and a test against a spectrum measurement is plotted in order to see the performance of the global threshold.

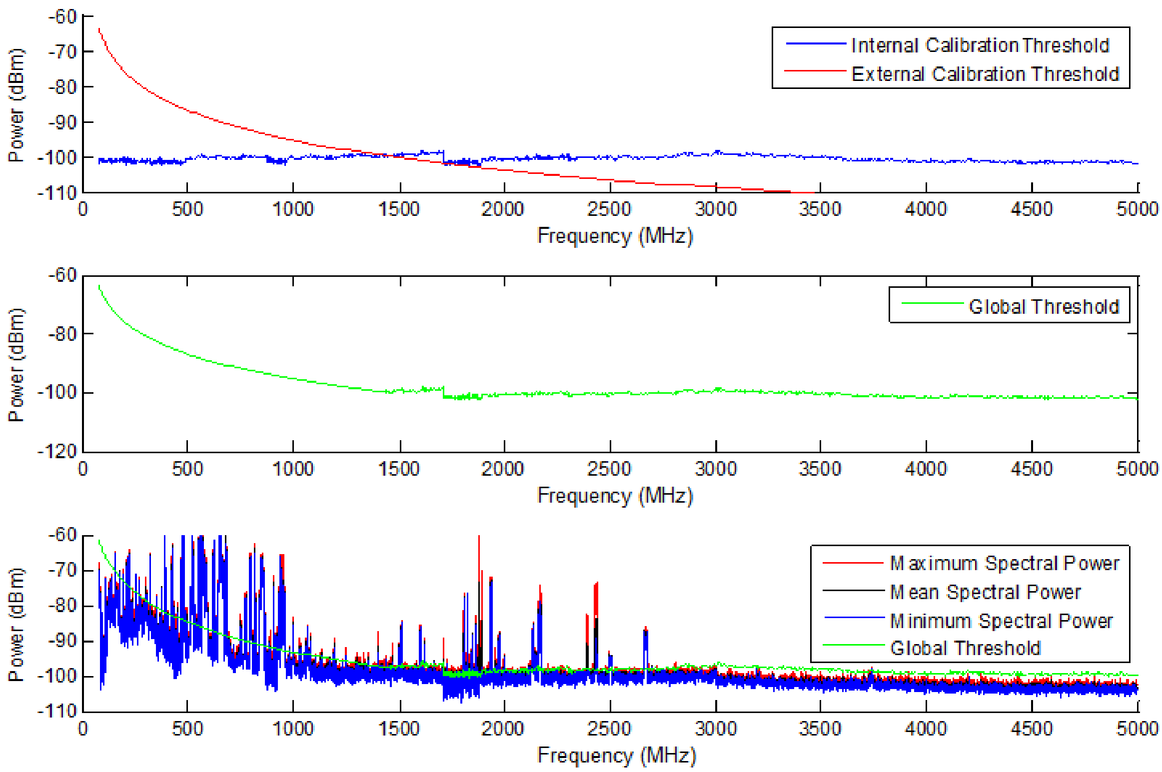

Figure 26: Global System Threshold.

6 Measurement Results

In this section, the band by band spectrum occupancy results are presented. The measurement is composed of 24 cycles of 1 hour, whose duty cycle is of 99.72% for calibration reasons. This settings lead to a total measurement period of 24 hours. The spectrum survey has been launched on Thursday June 12, 2014 at 00.00 hours.

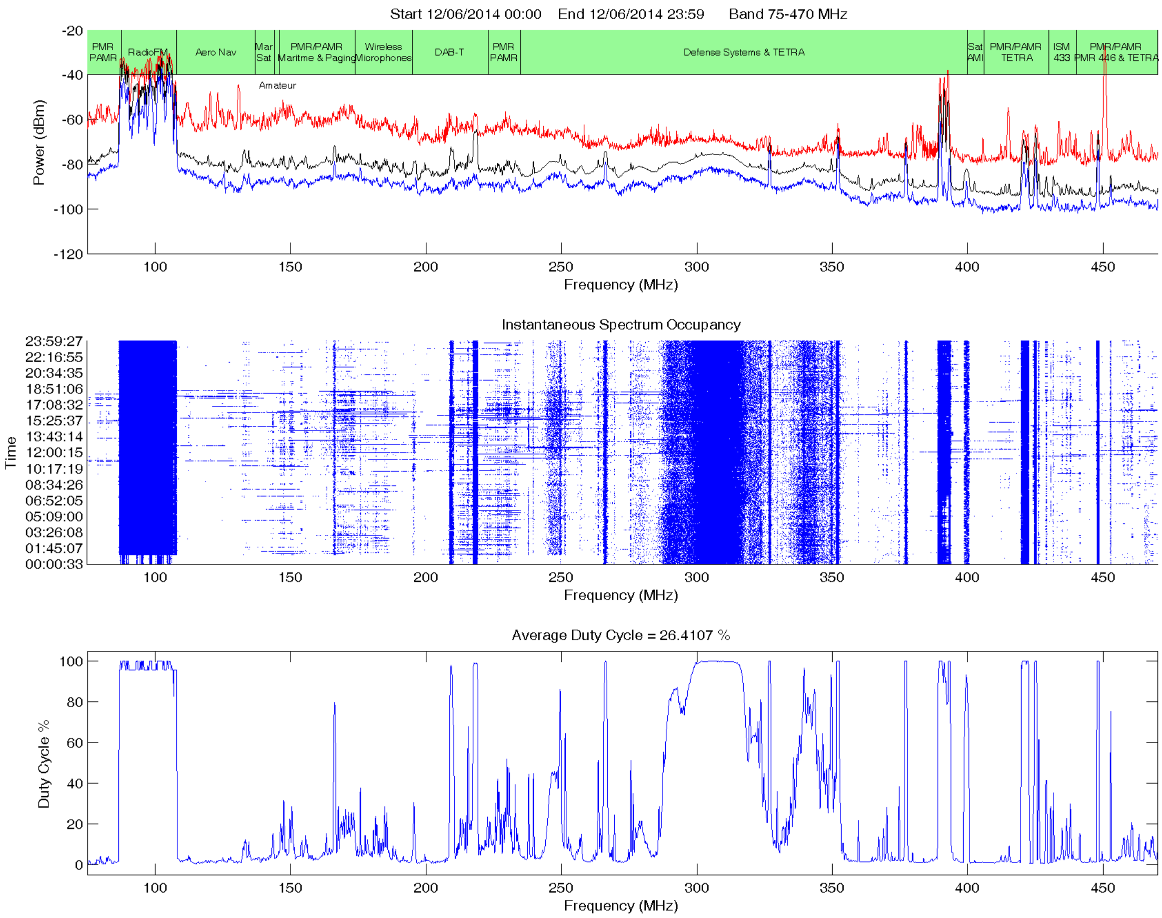

Figure 27: Band 1 (75 - 470 MHz).

Figure 27 shows the different spectrum occupancy metrics on Band 1 (75 - 470 MHz). In this band are present some Audio Broadcasting Services, like the FM Radio (88 - 108 MHz) or the Terrestrial Digital Audio Broadcasting (195 - 223 MHz), it can be shown how these broadcasting services have a duty cycle of 100%, as they are always active. There are also some bands for private mobile radio purposes, as well as TETRA. It can be observed the moderate use of PMR/PAMR bands, with medium to low duty cycles. The 108 - 137 MHz band is assigned to Aero RadioNavigation Services, and it is also sporadically utilized. The 235 - 400 MHz band is assigned mainly for the Spanish Ministry of Defense, for defense purposes. Inside this band, the 380 - 395 MHz band is assigned to the European TETRA Security Services, and it can be shown the high duty cycle of this band. Other services like Amateur, ISM-433 or wireless microphones are also present on this band. The average duty cycle of this band is 26.41%.

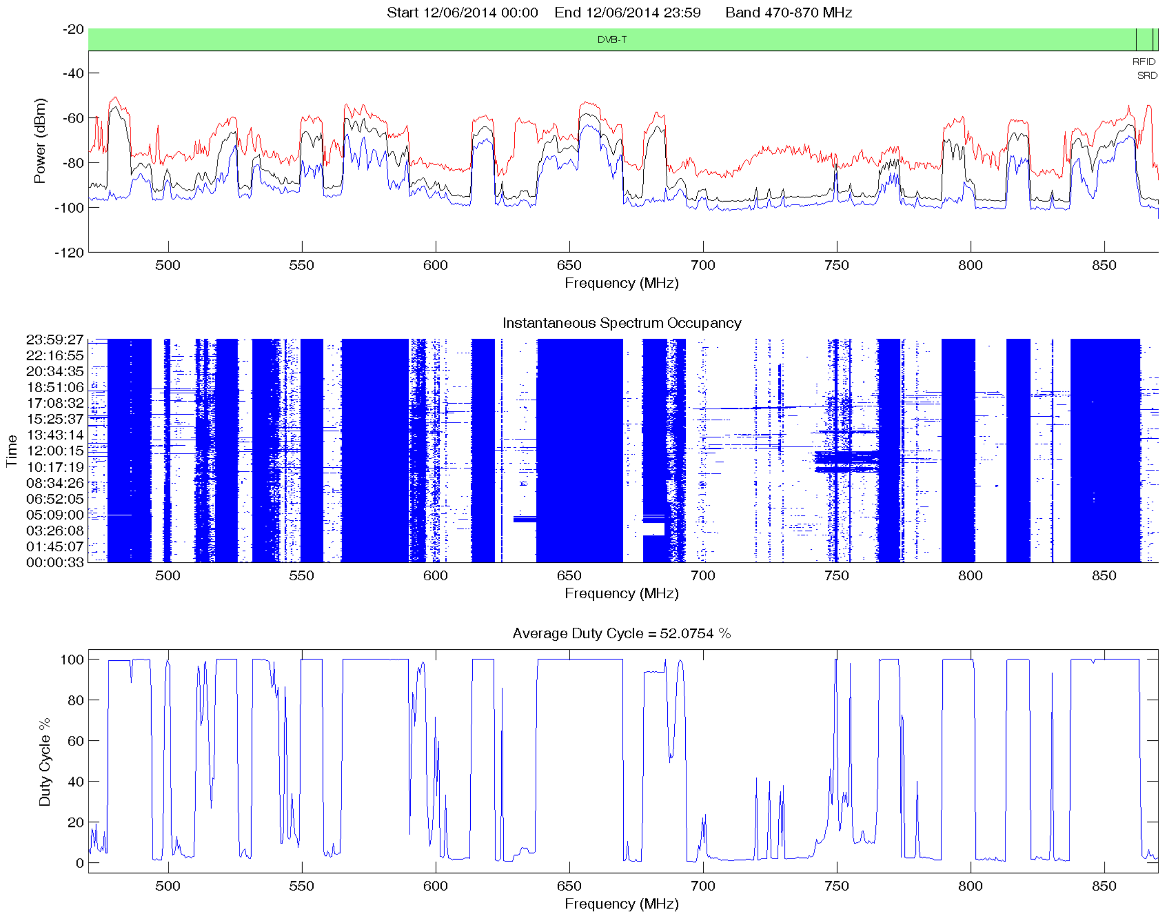

Figure 28: Band 2 (470 - 870 MHz).

Figure 28 shows the different spectrum occupancy metrics on Band 2 (470 - 870 MHz). This band is manly allocated to the Terrestrial Digital Video Broadcasting Service, which is typically known as the Digital Terrestrial Television. The TDT system is quite new, as it was fully implanted in Spain in April 2010, in order to make a more efficient use of spectrum, as the television band was overcrowded due to the high spectrum requirements of analogical television. The implementation of the DVB-T standard resulted on an extraordinary reduction of spectrum occupancy, which left many whitespaces on this band. The 8 MHz radioelectric channels are known as Multiplex or Mux, because more than one television channel is multiplexed in that bandwidth due to the MPEG-2 digital compression. Usually, 4 television channels are multiplexed on a multiplex, but the number of channels can change depending on the type of transmission. For example, to retransmit a football match, the MPEG-2 compression algorithm can double the bitrate of this transmission, assigning 2 multiplexed virtual channels to the match, obtaining a High Definition TV transmission.

The whitespaces present on this band make it attractive for opportunistic occupation purposes. It is also important to say that the allocation on this band is going to experience some changes due to the digital divide that will be carried out in 2015, which will force some TV channels on the 800 MHz band to reallocate their transmission frequencies, giving way to the 4^{th} Generation LTE cellular services. Note also that the 862 - 868 MHz band is allocated for RFID systems, and the 868 - 870 MHz band is allocated for Short Range Devices systems. The average duty cycle of this band is 52.07%.

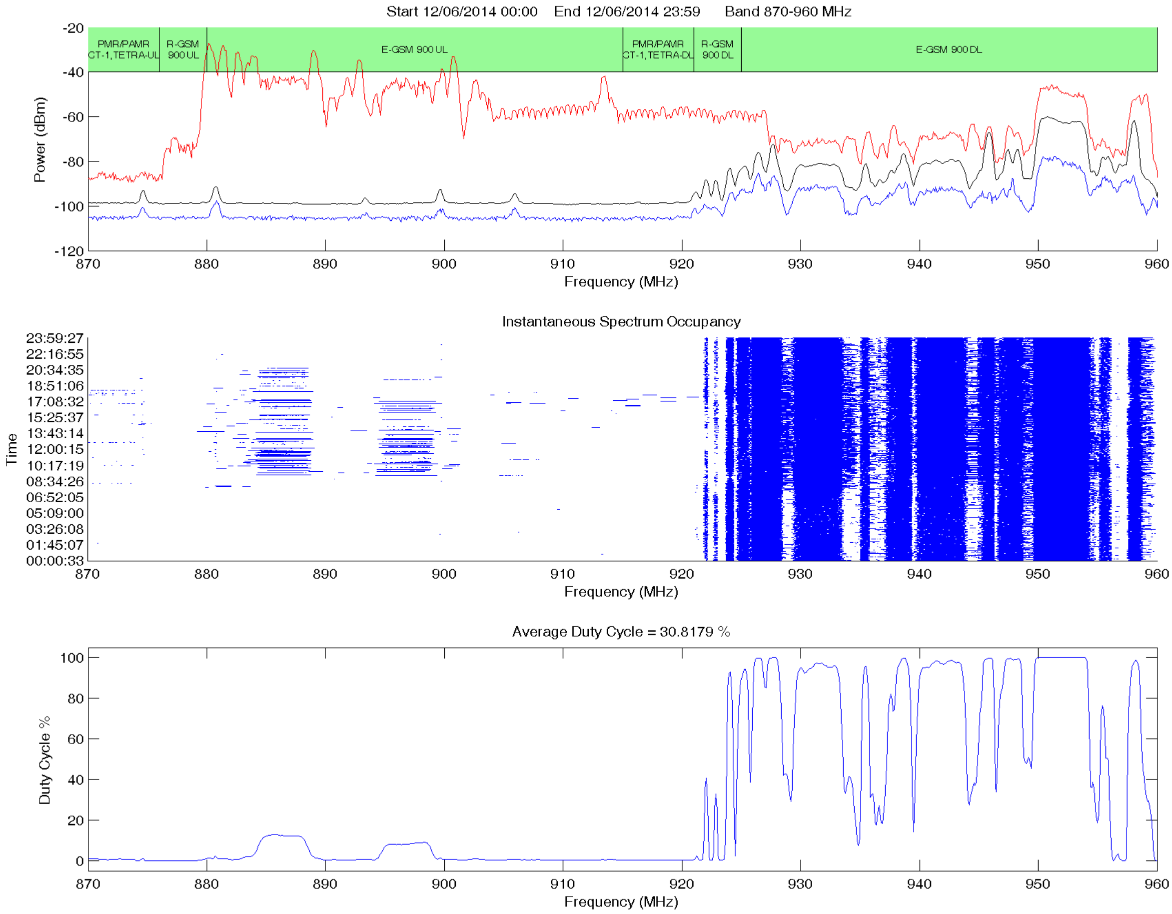

Figure 29: Band 3 (870 - 960 MHz).

Figure 29 shows the different spectrum occupancy metrics on Band 3 (870 - 960 MHz). This band is mainly allocated for the GSM900 cellular services, the 876 - 915 MHz band is the Uplink and the 921 - 960 MHz is the Downlink. It can be seen how the Downlink band has almost a 100% Duty Cycle, completely discarding it for opportunistic communications. On the other hand, it can be seen that the Uplink band is heavily utilized during the day, while at night its utilization is almost zero, which can be utilized for opportunistic purposes.

The 870 - 876 MHz and 915 - 921 MHz bands are allocated for private mobile radios, as well as the TETRA system or the CT-1 Cordless Telephone systems, and present very low duty cycles. The average duty cycle of this band is 30.81%.

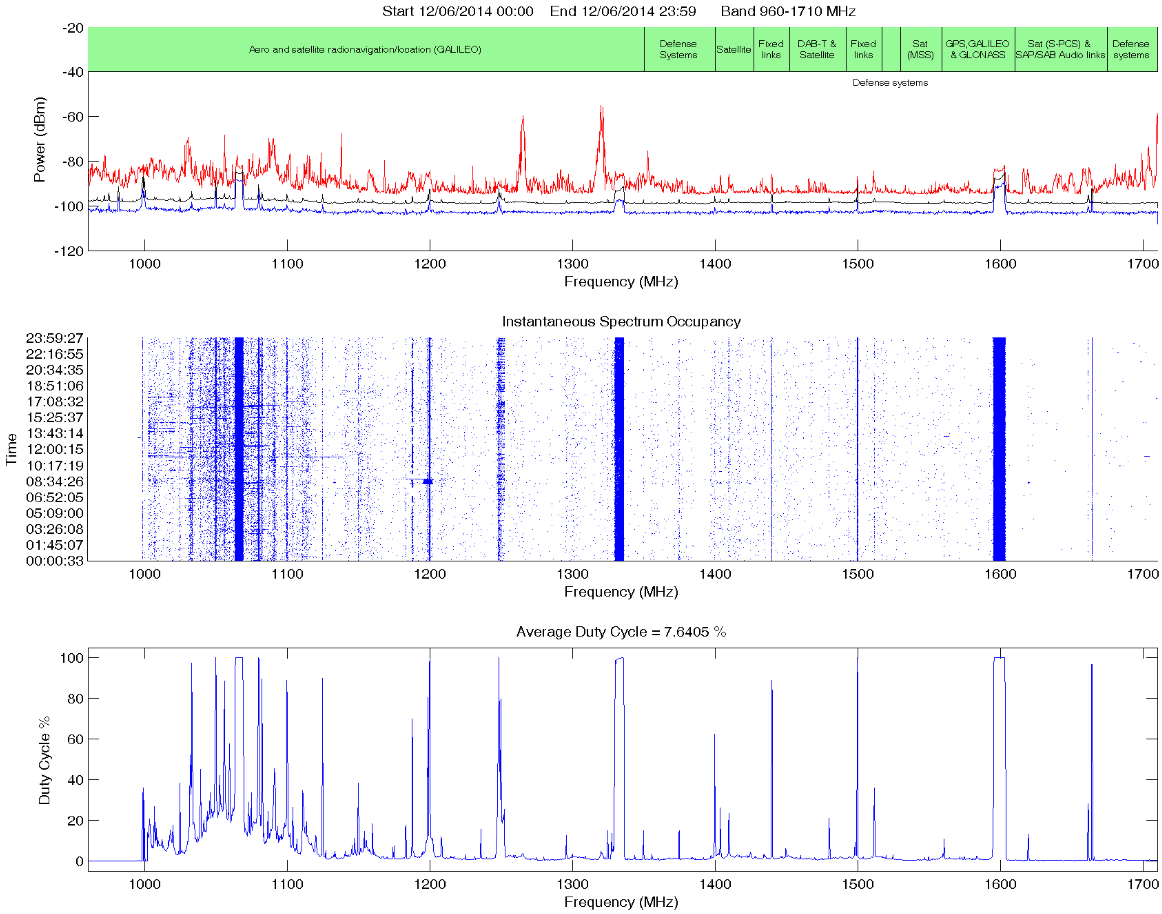

Figure 30: Band 4 (960 - 1710 MHz).

Figure 30 shows the different spectrum occupancy metrics on Band 4 (960 - 1710 MHz). The 960 - 1350 MHz and the 1559 - 1610 MHz bands are allocated for Aero and Satellite Radionavigation & Location Services. The European Global Navigation Satellite System (GNSS), GALILEO, use these bands for both Space-Earth and Earth-Space communications. The rest of frequencies are assigned for different services like Defense Systems, another Satellite Communications or Fixed Links. The average duty cycle of this band is 7.64%.

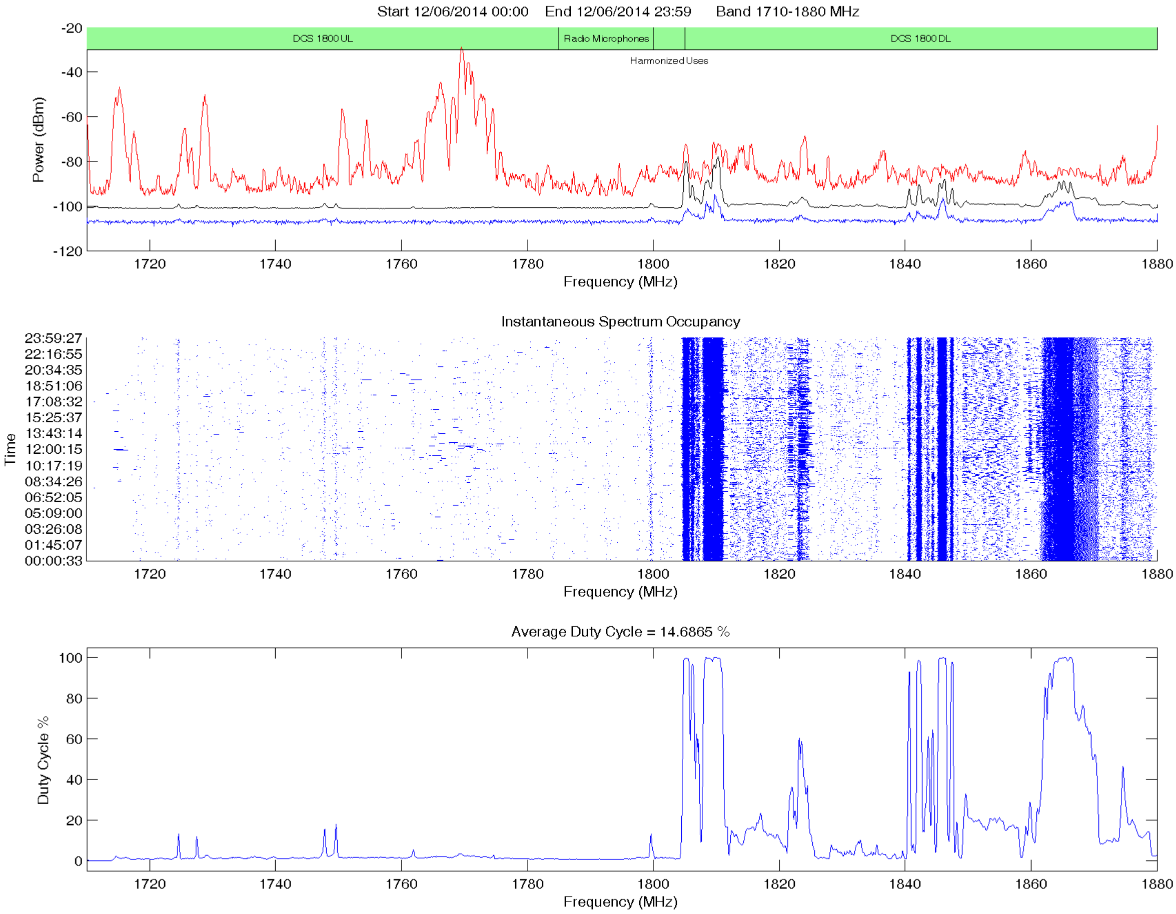

Figure 31: Band 5 (1710 - 1880 MHz).

Figure 31 shows the different spectrum occupancy metrics on Band 5 (1710 - 1880 MHz). This band is mainly allocated for Digital Cellular Services (DCS), which has been usually known as the GSM-1800 band. The 1710 - 1785 MHz band is the Uplink and the 1805 - 1880 MHz is the Downlink. Comparing the GSM-1800 with GSM-900, it can be seen how the Downlink band in GSM-900 has almost a 100% Duty Cycle, while in GSM-1800 exist some whitespaces between the Downlink channels of the different service providers.

The Uplink band has a similar behaviour of the GSM900 Uplink band, as it experiences high activity during the day, while at night the activity is almost null. Note also that the transmission power on DCS1800 Uplink band is more limited than in GSM900, what makes it harder to detect the Uplink activity on that band.

The 1785 - 1805 MHz band is allocated for radio microphones and Harmonized Uses. The average duty cycle on this band is 14.68%.

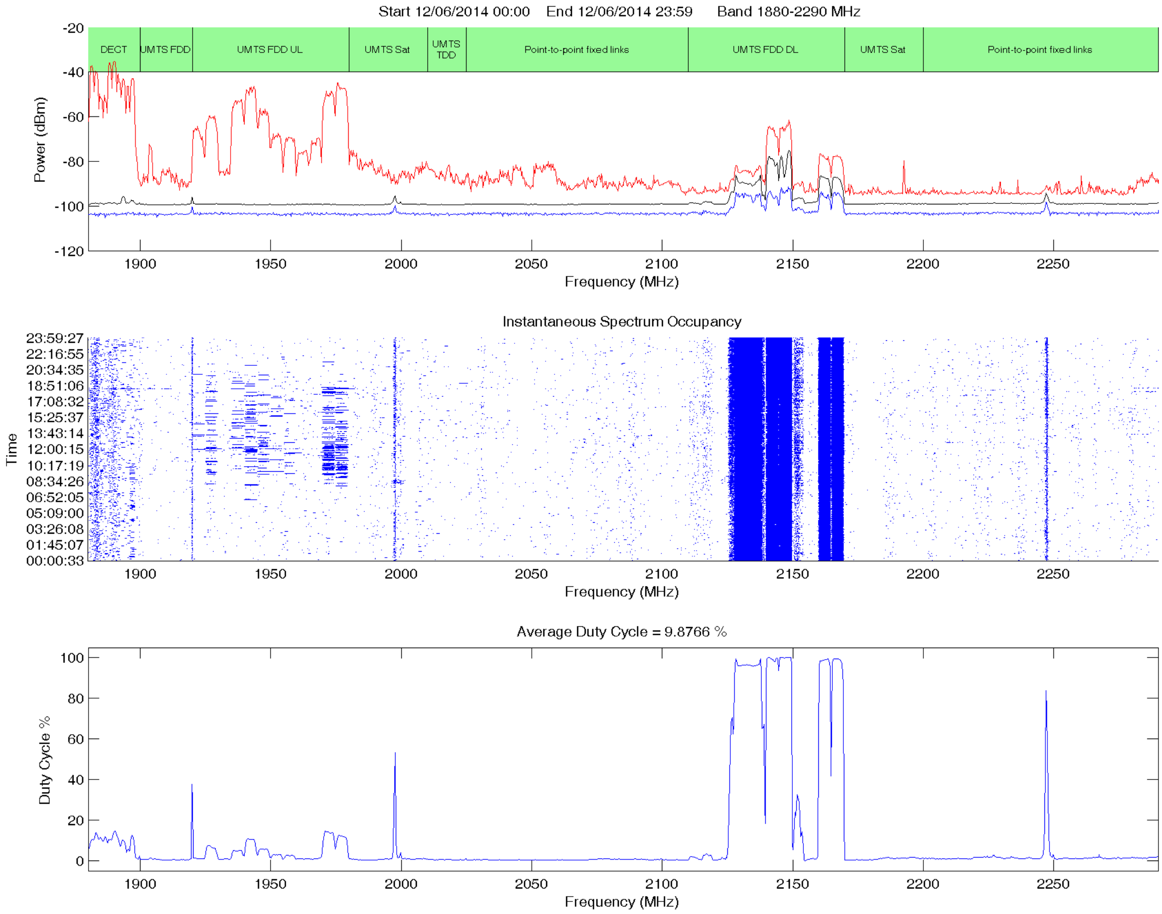

Figure 32: Band 6 (1880 - 2290 MHz).

Figure 32 shows the different spectrum occupancy metrics on Band 6 (1880 - 2290 MHz). This band is mainly allocated for the Universal Mobile Telecommunication Service (UMTS). The 1920 - 1980 MHz band is the Uplink and the 2110 - 2170 MHz is the Downlink. The 5 MHz channels can be distinguished in both uplink and downlink bands. As happens in GSM-900 and GSM-1800, the Downlink has a duty cycle of almost 100%, while the Uplink is heavily utilized during the day, while at night remains almost idle. Other UMTS modes as the Satellite UMTS or the UMTS TDD are also present on this band.

The 1880 - 1900 MHz band is allocated for the Digital Enhaced Cordless Telecommunications system (DECT), which is used by many cordless telephones. As the measurements have been taken on the Engineering School, the activity registered on this band is very high. The rest or frequencies are allocated for point-to-point fixed links, which have low activity, leading to low duty cycles. The average duty cycle on this band is 9.87%.

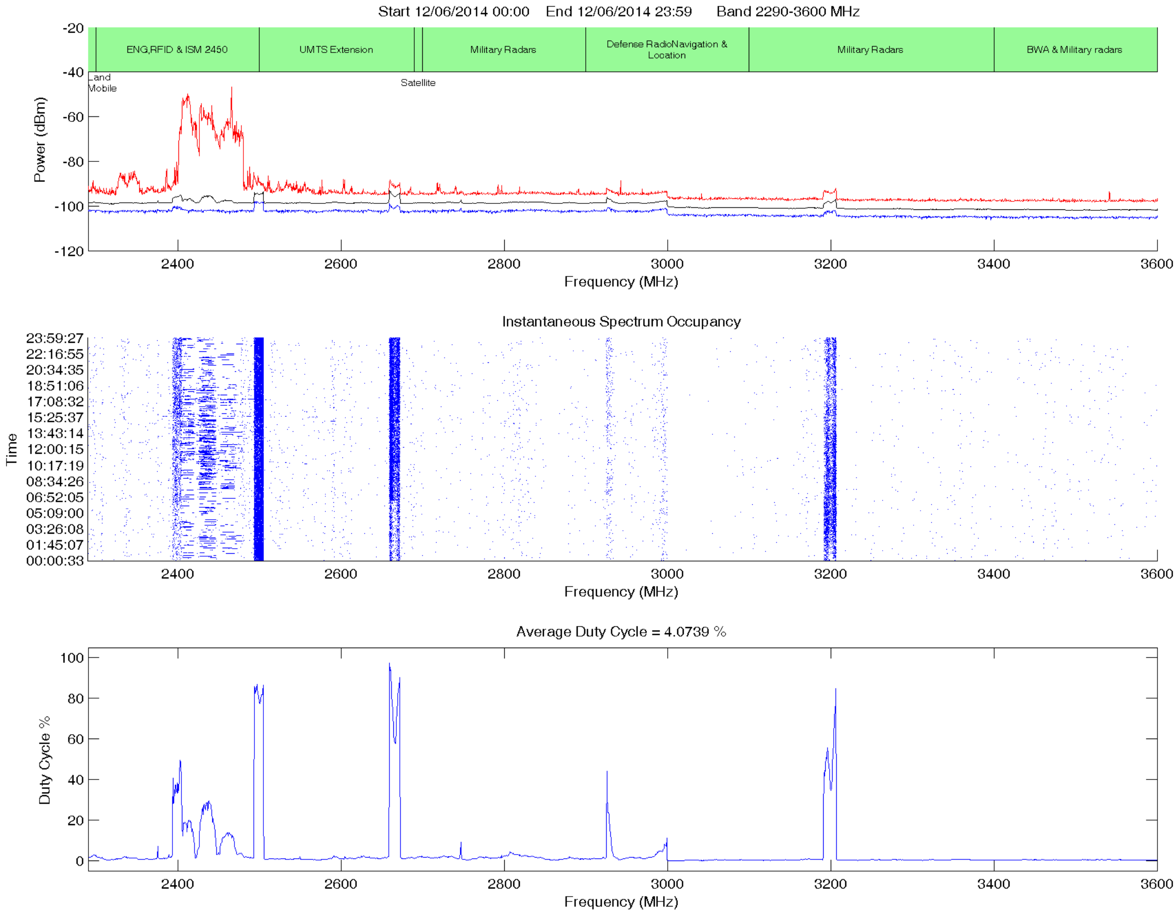

Figure 33: Band 7 (2290 - 3600 MHz).

Figure 33 shows the different spectrum occupancy metrics on Band 7 (2290 - 3600 MHz). The 2290 - 2300 MHz band is allocated for the Land Mobile Radio System, a wireless system used by emergency first responder organizations, public works organizations, or companies with large vehicle fleets. It can be seen how its duty cycle is very low in our geographical area. The 2300 - 2500 MHz band is allocated for different services, like the Electronic News Gathering (ENG), the Industrial, Scientifical and Medical 2400 MHz band, as well as the RFID 2400 band. It can be seen how the activity on this band is quite active, as the IEEE 802.11 standard makes use of this band, which is utilized by Wi-Fi wireless devices. The 2500 - 2690 is used as an extension of the UMTS band, and it can be observed how there is a channel with an almost 100% duty cycle, while the rest of the band seems to be idle. The 2290 - 3600 MHz band is mainly allocated for Military Uses, like military radars or Defense Radionavigation systems. The average duty cycle on this band is 4.07%.

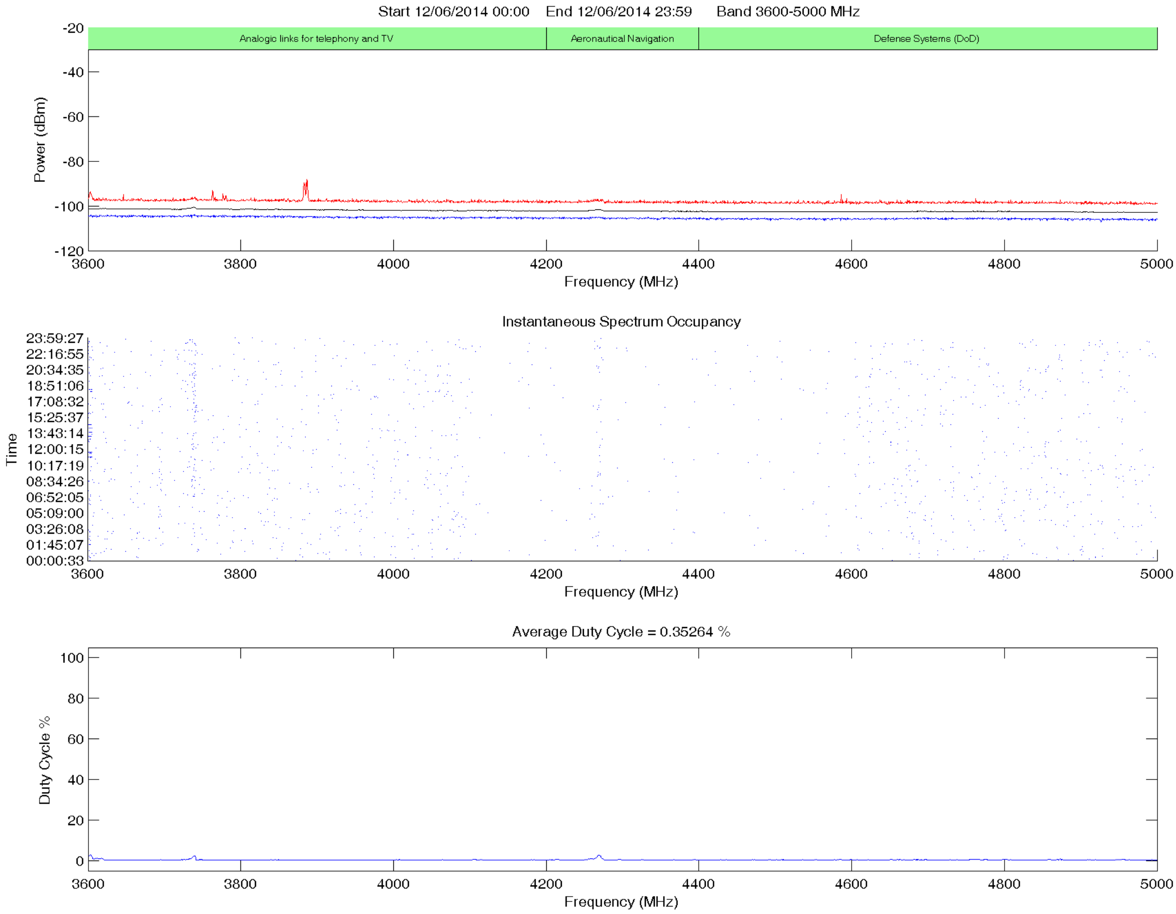

Figure 34: Band 8 (3600 - 5000 MHz).

Figure 34 shows the different spectrum occupancy metrics on Band 8 (3600 - 5000 MHz). In that band are allocated some analogic links for telephony and TV, as well as Aeronautical Navigation Services and Defense Systems. It can be seen how the activity on that band in a short radius area from where the measurement has been taken is almost null, as the duty cycle on this band is almost zero for all the services present on this band. The average duty cycle on this band is 0.35%.

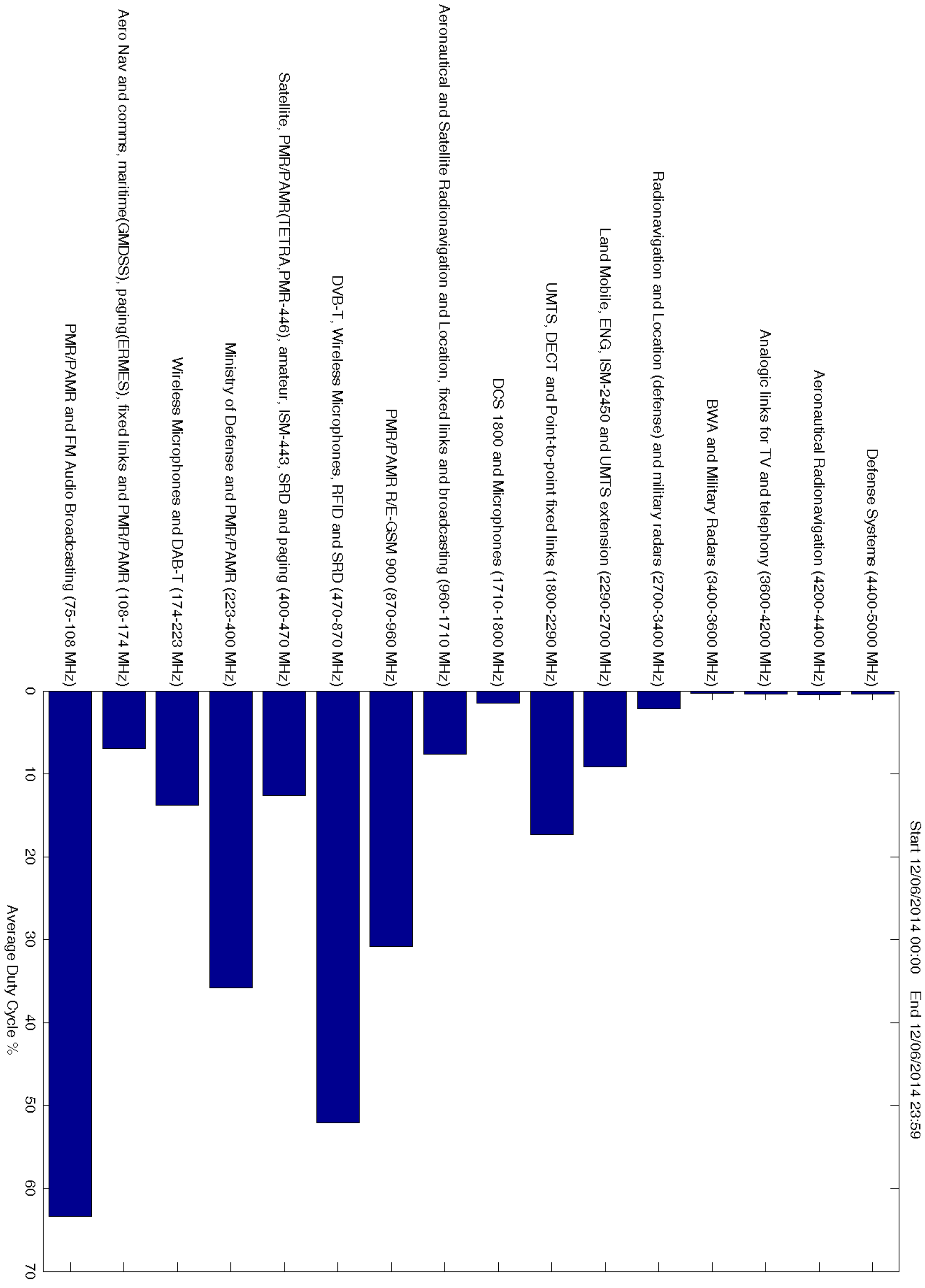

Figure 35: Band Occupancy Rates.

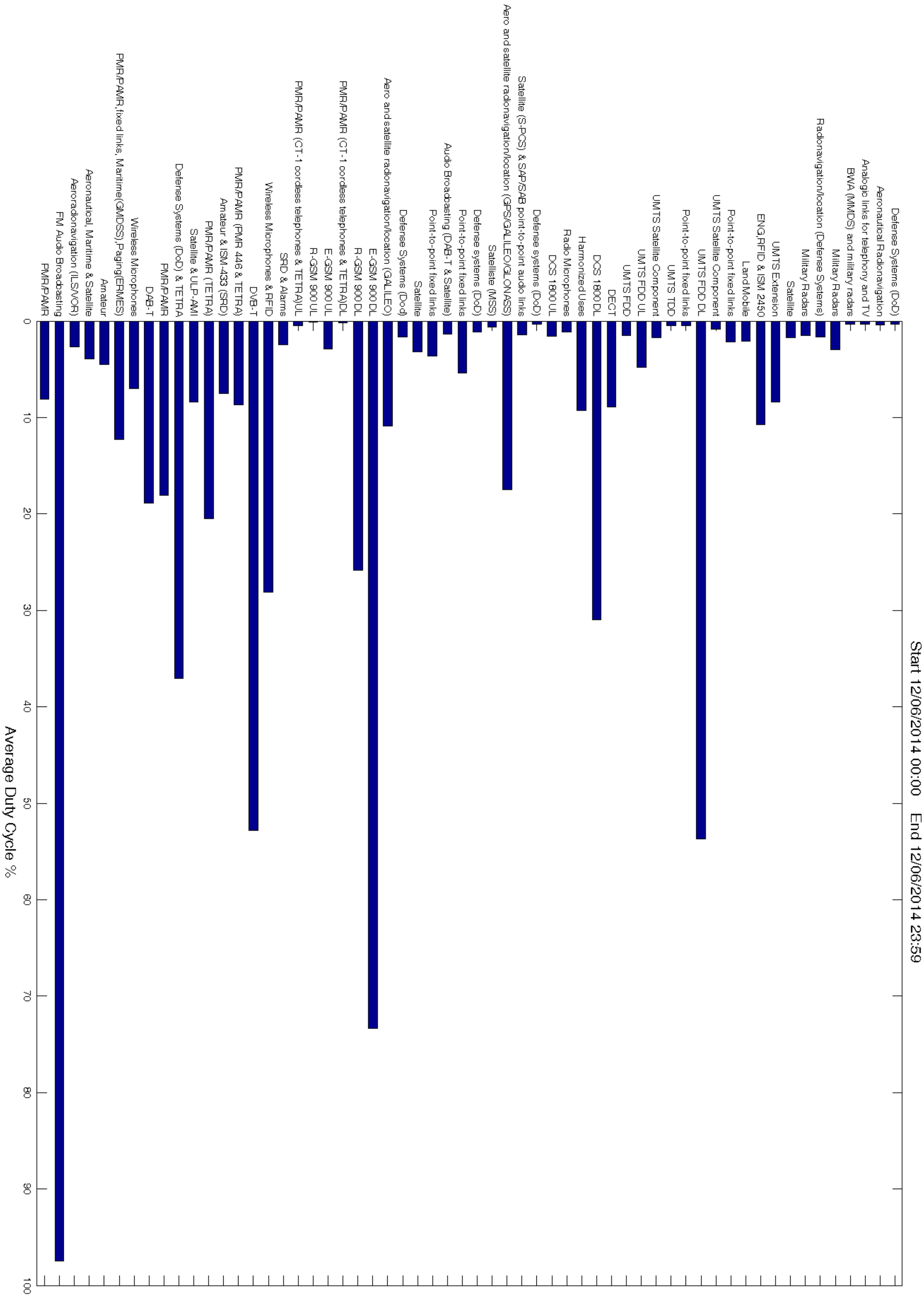

Figure 36: Service Occupancy Rates.

Table 3: Service Occupancy Statistics

F_{Start} (MHz)	F_{Stop} (MHz)	Bandwidth (MHz)	Service	Occupied Bandwidth(MHz)	Duty Cycle Avg.(%)
75	87,5	12,5	PMR/PAMR	1,01	8,12
87,5	108	20,5	FM Audio Broadcasting	19,98	97,49
108	137	29	Aeroradionavigation (ILS/VOR)	0,77	2,66
137	144	7	Aeronautical, Maritime & Satellite	0,27	3,89
144	146	2	Amateur	0,09	4,49
146	174	28	PMR/PAMR,fixed links, Maritime(GMDSS),Paging(ERMES)	3,44	12,29
174	195	21	Wireless Microphones	1,47	6,98
195	223	28	DAB-T	5,28	18,86
223	235	12	PMR/PAMR	2,17	18,05
235	400	165	Defense Systems (DoD) & TETRA	61,19	37,08
400	406	6	Satellite & ULP-AMI	0,50	8,41
406	430	24	PMR/PAMR (TETRA)	4,92	20,49
430	440	10	Amateur & ISM-433 (SRD)	0,75	7,51
440	470	30	PMR/PAMR (PMR 446 & TETRA)	2,60	8,67
470	862	392	DVB-T	206,93	52,79
862	868	6	Wireless Microphones & RFID	1,69	28,13
868	870	2	SRD & Alarms	0,05	2,48
870	876	6	PMR/PAMR (CT-1 cordless telephones & TETRA)UL	0,03	0,51
876	880	4	R-GSM 900 UL	0,00	0,11
880	915	35	E-GSM 900 UL	1,01	2,89
915	921	6	PMR/PAMR (CT-1 cordless telephones & TETRA)DL	0,01	0,21
921	925	4	R-GSM 900 DL	1,04	25,88
925	960	35	E-GSM 900 DL	25,66	73,32
960	1350	390	Aero and satellite radionavigation/location (GALILEO)	42,48	10,89
1350	1400	50	Defense Systems (Dod)	0,83	1,65
1400	1427	27	Satellite	0,87	3,22
1427	1452	25	Point-to-point fixed links	0,91	3,65
1452	1492	40	Audio Broadcasting (DAB-T & Satellite)	0,53	1,32
1492	1517	25	Point-to-point fixed links	1,35	5,40
1517	1530	13	Defense systems (DoD)	0,15	1,12
1530	1559	29	Satelliste (MSS)	0,17	0,60
1559	1610	51	Aero and satellite radionavigation/location (GPS/GALILEO/GLONASS)	8,92	17,48
1610	1675	65	Satellite (S-PCS) & SAP/SAB point-to-point audio links	0,95	1,46
1675	1710	35	Defense systems (DoD)	0,12	0,35
1710	1785	75	DCS 1800 UL	1,16	1,54
1785	1800	15	Radio Microphones	0,17	1,13
1800	1805	5	Harmonized Uses	0,46	9,24
1805	1880	75	DCS 1800 DL	23,26	31,01
1880	1900	20	DECT	1,78	8,89
1900	1920	20	UMTS FDD	0,31	1,54
1920	1980	60	UMTS FDD UL	2,87	4,78
1980	2010	30	UMTS Satellite Component	0,53	1,76
2010	2025	15	UMTS TDD	0,07	0,46
2025	2110	85	Point-to-point fixed links	0,37	0,44
2110	2170	60	UMTS FDD DL	32,21	53,68
2170	2200	30	UMTS Satellite Component	0,26	0,86
2200	2290	90	Point-to-point fixed links	1,98	2,20
2290	2300	10	Land Mobile	0,21	2,07
2300	2500	200	ENG,RFID & ISM 2450	21,51	10,76
2500	2690	190	UMTS Extension	15,99	8,41
2690	2700	10	Satellite	0,18	1,76
2700	2900	200	Military Radars	2,99	1,49
2900	3100	200	Radionavigation/location (Defense Systems)	3,34	1,67
3100	3400	300	Military Radars	8,81	2,94
3400	3600	200	BWA (MMDS) and military radars	0,64	0,32
3600	4200	600	Analogic links for telephony and TV	2,03	0,34
4200	4400	200	Aeronautical Radionavigation	0,86	0,43
4400	5000	600	Defense Systems (DoD)	2,04	0,34

7 Analysis

The obtained results show how the registered activity below 1 GHz is moderate due to the good propagation properties on this range of frequencies, while the bands above 1 GHz experience lower occupancy rates as the frequency increase.

Although the highest spectral activity was registered below 1 GHz, the occupancy is not homogeneous in the whole band, and this fact can be exploited by opportunistic occupancy techniques. Starting from the lower frequencies (75 - 470 MHz), in which several narrowband services are allocated, some whitespaces were found, but these whitespaces are mainly narrowband, which are not attractive for the actual multimedia requirements. Moreover, the radio noise in that frequencies is too high, which is an added drawback on that band.

The Television Band (470 - 862 MHz) showed high spectral activity in each one of the 8 MHz multiplex channels, but some attractive whitespaces were found on some channels. But the allocation on this band is going to experience some changes due to the digital divide that will be carried out in 2015, which will force some TV channels on the 800 MHz band to reallocate their transmission frequencies, giving way to the 4^{th} Generation LTE cellular services. For that reason, the results obtained in this band will be invalidated when the reallocation take place on this band. After the reallocation process, the survey should be repeated on this band to see how the different TV channels and the cellular services exploit this spectrum band.Despite of the Television band is being considered one of the most efficient since the digital service was deployed, this band is one of the most attractive for opportunistic purposes due to the high bandwidth spectrum holes that are present on the band.

The 862 - 876 MHz band is allocated for some short range applications like RFID or Cordless Telephones, as well as Professional Mobile Radios or the TETRA uplink channel. The TETRA downlink channels is situated in the 915 - 921 MHz band. The utilization of short range applications on this band invalidates it for its opportunistic occupancy with services with high transmission power, because the coverage of this services can interfere to those short range applications if they are on the coverage area of the high power transmission. However, this characteristic can be exploited to use this band for opportunistic purposes for Wireless Personal Area Networks (WPAN) or Wireles Local Area Networks(WLAN), as the transmission power of these systems is very low and the probability of interfere another system would be very low.

The GSM900 Uplink band (876 - 915 MHz) shows a high occupancy rate during the day, while at night remains almost idle. This characteristic behaviour can be exploited by the opportunistic techniques and take profit of the low occupancy rate of this band during the night. The services that use the radio environment to send data periodically, (e.g. meteorological data), which don't need the information at the moment of being generated, for example if the data collected is for a database, can use this band to transmit the collected data on an opportunistic way. It is also important to highlight that it is difficult to register the activity on the uplink band, due to low transmission power of the mobile terminals, which reduce the detection area on this band, reducing the detection capabilities.

The GSM900 Downlink band (921 - 960 MHz), however, shows one of the higher occupancy rates of the study, as the base stations are always sending information to the mobile terminals, like the time advance or the cell information, through its broadcast channel.

The 960 - 1350 MHz band is allocated for aeronautical and satellite radionavigation. The first half of this band showed moderate occupancy, as there are some frequencies that experience high occupancy levels, while others experience medium or low occupancy levels. The narrowband characteristic of the registered transmissions invalidate this band for opportunistic occupancy. The second half of the band shows few bands with very high duty cycles, leaving wide spectrum holes that could be exploited by opportunistic occupancy techniques. However, as this band is allocated for satellite radionavigation services, the signals that can be present here can be spread spectrum, and it is possible that our measurement system is not detecting them. In this case, another sensing technique should be applied, in order to make the detection more robust in front of spread spectrum signal detection.

The 1350 - 1710 MHz band is allocated for several different services, like defense systems, satellite, fixed links or audio links. This band is sparsely utilized, as only few bands show high occupancy rates. The low occupancy rates in the rest of frequencies make this band attractive for opportunistic access techniques, as it seems to be underutilized.

The DCS1800 Uplink band (1710 - 1785 MHz) has a behaviour similar to the GSM900 band, as it offers the same service, with the difference that the transmission power on this band is lower than for the GSM900 Uplink band, which makes it harder to detect the activity on this band. However, the PSD metrics show several maximums, which reveals the activity on this band. Again, this band can be used in an opportunistic way during the night, as the activity is almost zero in that period.

Between the DCS1800 Uplink and Downlink, the 1785 - 1805 MHz band is allocated for Radio Microphones and Harmonized Uses. As commented above, this radio microphones application is a short range application, and invalidates the opportunistic occupancy for high power transmissions, but it can be exploited by other opportunistic short range applications in that areas in which the primary activity is not present. On the other hand, the harmonized uses band is a band allocated for a common service in Europe, where an European Standard is used. This band can be used for opportunistic transmissions in that geographical areas in which this band remains idle.

The DCS1800 Downlink band (1805 - 1880 MHz), showed high occupancy rates in that bands in which the different base stations transmit the downlink information, but some spectrum holes are shown between those bands. Comparing the GSM-1800 with GSM-900 band, it can be seen how the Downlink band in GSM-900 has almost a 100% Duty Cycle, while in GSM-1800 exist some whitespaces between the Downlink channels of the different service providers. These whitespaces can be also exploited by opportunistic occupancy techniques.

The Digital Enhaced Cordless Telecommunications (DECT) band (1880 - 1900 MHz), showed low duty cycles in every one of its channels, but the whole band presented high activity as it can be observed on the PSD metrics or the time-frequency graphic. This activity invalidates that band to apply opportunistic occupancy techniques in the area where we are, but it can be exploited in other areas where cordless telephones are not present.

The UMTS Uplink Band (1920 - 1980 MHz) showed the same behaviour as the GSM900 and DCS1800 MHz Uplink bands; the band has high activity during the day, achieving almost zero occupancy rate at night. This technology, however has the characteristic that its signals are Wide-Band Code Division Multiple Access (WCDMA), what allow the mobile terminals to transmit with lower power as the power is spread over the band. This fact reduces the detection area of our system, as only the nearest activity is recorded. This characteristic invalidates the opportunistic access of this band for high power transmission communications, but it can be exploited by short range applications.

The UMTS Downlink Band (2110 - 2170 MHz) showed high occupancy rates, as the base stations are always transmitting information to the mobile terminals, which completely invalidates this band for opportunistic occupation purposes. The rest of UMTS bands, like UMTS TDD, UMTS Sat or UMTS FDD showed very low occupancy rates, but as commented above, the WCDMA access technique used in that bands can be hiding the real activity to our measurement system, and our results cannot be completely reliable on these bands.

The Industrial, Scientifical and Medical band on 2450 Mhz showed also high activity due to the presence of the Wi-Fi on that band, which also invalidates this band for opportunistic occupancy techniques in our geographical area, but it can be exploited in other geographical areas in which that band remains idle. Moreover, as it is an unlicensed band, only respecting the transmission power requirements, an opportunistic use can be performed accordingly to law limitations.

The rest of bands, from 2500 MHz to 5000 MHz, showed very low occupancy rates, except for some military radars and one UMTS Extension channel where the occupancy rate is very high. In those frequencies, the propagation characterstics are not so good as for those frequencies below 1 GHz what means that to achieve high coverage areas, the radiated power has to be very high, and that could be one of the reasons why the detected activity is too low. To obtain more accurate occupancy results on those bands, the global measurement should be carried out in different points of our geographical area, which would allow the detection of further activity on those bands.

8 Conclusions

The obtained results demonstrate the heterogeneus occupancy of the spectrum under study, as some bands are subject to high occupancy rates, while others show moderate or low occupancy rates, as they are sporadically used. The highest occupancy rates were found on those bands where the broadcasting services are allocated, like the TV band as well as the FM Radio or the Digital Audio Broadcasting bands. Also the cellular services, like GSM900, DCS1800 or UMTS showed very high occupancy rates, predominantly on the downlink band, although the uplink showed also high occupation rates during the day. Note that the downlink activity is easier to detect with the energy detection technique employed, due to the high power radiated by the base stations, while the power radiated by the mobile terminals is much lower, and as a consequence, only the activity of near terminals is detected. Other services or applications like aeronautical radionavigation and location, the military radars, or some other narrow bands showed different occupancy rates depending on the particular application and allocated band, but the overall occupation rate were found to be very low. Note also that most applications and services are limited on its transmission power, which reduces its detection area. For that reason, to achieve more accurate results, regardless of the sensing technique employed, the global measurement should be carried out in different points of our geographical area, in order to detect further activity on that bands that seems to be idle.

Finally, it is important to mention that this study is not conclusive itself, as the sensing technique utilized is not able to detect all the present transmissions, and a more detailed study must be carried out to obtain fully reliable results. However, this study has been very important to see the spectrum occupation in broad strokes, showing its low occupancy rate, which serves as support to the development of the new Dynamic Spectrum Access (DSA) policies, in order to increment the usage efficiency of the spectrum.

After realizing the inefficient use of spectrum, and thus, the opportunities that exist to implement Dynamic Spectrum Access policies, the future work derived from this study would consist on the miniaturization of the equipment used to sense the spectrum, obtaining a compact device capable of taking the spectrum measurements and sending it to a master server, where the spectrum database would be generated.

Going even further, the next step would be the deployment of a sensing network along the most important cities of our geographical area, starting for example by Barcelona or Madrid, obtaining the information about the spectrum opportunities on that cities where the spectrum demand is really high due to its dense population. The TV Band offers attractive unused wideband channels, and for that reason would be one of the best candidates to carry out the sensing. The parallel future work would be the development of radio devices capable of reconfiguring their band of operation accordingly to the bands where the whitespaces are accessible. That scenario would lead to a double business line, where both the database access service and the device that exploit that service would be commercialized by the same entity. By that way, we would be prepared for the next era of wireless communications.

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