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Spatial Characterisation of Spectrum Occupancy in Urban Environment for Cognitive Radio

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Abstract

Cognitive Radio (CR) has been proposed to solve the so-called spectrum scarcity problem. CR uses opportunistically the licensed bands when they are temporarily unused. The realization of spectrum models and the statistical characterization of spectrum occupancy is an important point to assist the study and the development of various features required to CR. In this context we conducted a measurement campaign in the DCS and UMTS cellular bands in an urban environment. We collected spectral occupation data in order to analyze and characterize the behavior of spatial correlation of the spectrum occupancy. We analyze the spatial correlation by calculating some metrics as a function of the distance. Finally we propose a different approach to the calculation of the metrics, that is to characterize spatial correlation as a function of the SNR-difference at the receiver instead of the distance.

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Acronyms

BS	Base Station
CDMA	Code Division Multiple-Access
CR	Cognitive Radio
CRN	Cognitive Radio Network
CV	Continous Wave
DANL	Displayed Average Noise Level
DC	Direct Current
DCS	Digital Cellular System
DECT	Digital Enhanced Cordless Telecommunication
DSA	Dynamic Spectrum Access
DSP	Digital Signal Processing
DTV	Digital Television
EMC	ElectroMagnetic Compatibility
EMI	ElectroMagnetic Interference
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
FM	Frequency Modulation
GSM	Global System for Mobile Communications
IF	Intermediate Frequency
LO	Local Oscillator
MAC	Medium Access Control

PSD	Power Spectral Density
QoS	Quality of Service
RBW	Resolution BandWidth
RF	Radio Frequency
RMS	Root Mean Square
SFDR	Spurious Free Dynamic Range
SNR	Signal-to-Noise Ratio
SPDT	Single Pole Double Throw
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
UWB	Ultra Wide Band
VBW	Video BandWidth
VSA	Vector Signal Analyzer
xG	NeXt Generation

Chapter 1

Introduction

The work done is part of current research for the development of Cognitive Radio (CR) technology. CR has been proposed to solve the so-called spectrum scarcity problem; the increasing success of wireless services has rapidly run out the free frequencies below 3GHz, that is those one with the more commercially interesting propagation characteristics. Furthermore several researches show that the actual technologies made an inefficient use of their resources: multiple services are active only for a fraction of time or in a fraction of the spatial area where their license is valid for.

CR's main idea is to use opportunistically the licensed bands when they are temporarily unused. When a primary user, that is a user that has a license to operate in that band, requires these resources CR user immediately vacates the band and moves to another one. It is clear that the development of such technology requires special features for correctly managing the various spectrum bands without causing harmful interference to licensed users.

Several measurement campaigns have been conducted to estimate the real spectrum usage by actual technologies. In general the results of these studies show the presence of a number of technologies that make an inefficient use of their resources. Therefore, there exists the margin for CR to operate in those bands that present interesting properties. Furthermore, the vast amount of data generated by various campaigns has been used to analyze the statistical characteristic of spectrum utilization. The realization of spectrum models for CR is an important point to assist the study and the development of various features required to CR.

In this context we conducted a measurement campaign in the bands 1800-1880MHz and 1880-2190MHz; these bands are mainly allocated to Digital Cellular System (DCS) and Universal Mobile Telecommunications System (UMTS) cellular technologies. The campaign was performed at Campus Nord of UPC, in Barcelona. We collected spectral occupation data in various points of the measurement location. Our main objective was to analyze and characterize the behavior of spatial correlation of the spectrum occupation, which may result of significant importance and usefulness on the development of the CR technology.

In *chapter 1* we give a general introduction to CR technology, focusing on the spectrum management tasks required to CR. In *chapter 2* we introduce spectrum analysis and the instrument that permit us to measure spectrum occupancy, that is the spectrum analyzer. In particular we focus on super-heterodyne spectrum analyzer, giving the theoretical basics of its operating principles. In *chapter 3* we describe our measurement equipment, giving a description of each component; we talk about the configuration adopted explaining how it was obtained. Then we describe the measurement location and the methodology used to realize the measurement campaign. In *chapter 4* we analyze the data gathered during the campaign. After briefly showing the spectrum occupancy results we introduce the correlation metrics we use in our analysis. Based on such correlation metrics, we then analyze the spatial correlation of spectrum occupancy and derive the main conclusions.

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Chapter 2

Cognitive Radio Basics

The measurement campaign and the results described in this thesis must be inserted in the context of CR networks (or Dynamic Spectrum Access (DSA) networks or NeXt Generation (xG) networks). To provide a better understanding, in this chapter we provide a brief introduction to the argument in order to correctly set in context the work done. First we describe what CR is and the motivations that led to its development, i.e. the so-called spectrum scarcity problem. Then we focus on CR technology and CR network architecture. Finally we discuss on some spectrum management issues required from CR: spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility.

2.1 Introduction

Current wireless networks are characterized by a static spectrum allocation policy, where governmental agencies assign wireless spectrum to network operators and service providers in order to deliver specific services over delimited geographical regions. Recently, due to the increase in spectrum demand, this policy faces spectrum scarcity in particular spectrum bands. In contrast, a large portion of the assigned spectrum is used sporadically, leading to underutilization of a significant amount of spectrum. Several measurement campaigns have been done in various locations to evaluate the current spectrum occupation (see for example those that have been done in Spain [6] and in Germany [21]). The results show that there exist a significant amount of spectrum available (an example of spectrum utilization is shown in Figure 2.1), suggesting that the current usage of spectrum resources is significantly inefficient as a result of the inflexible spectrum access policies, which preclude the use of any allocated band by non-licensed systems, even if the licensee is not making use of it. The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically. DSA

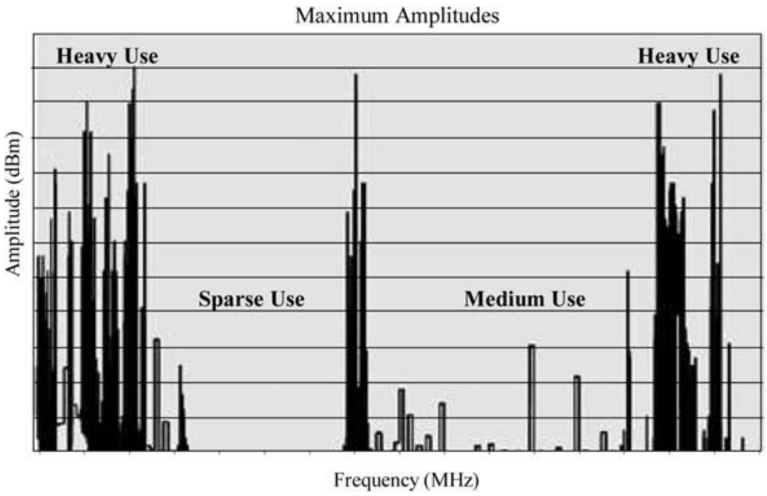

Figure 2.1: Spectrum Utilization.

has been proposed to solve these current spectrum inefficiency problems.

The key technology of the DSA paradigm is CR, which provides the capability to share the wireless channel with licensed users in an opportunistic manner. CR networks are envisioned to provide high bandwidth to CR terminals via heterogeneous wireless architectures and DSA techniques.

2.2 Cognitive Radio Technology

The key enabling technology of DSA networks are the CR techniques that provide the capability to share the spectrum in an opportunistic manner. Formally, a CR is defined as *a radio that can change its transmitter parameters based on interaction with its environment* [3]. From this definition, two main characteristics of CR can be defined:

Cognitive capability. It refers to the ability of the radio technology to capture or sense the information from its radio environment. This capability cannot simply be realized by monitoring the power in some frequency band but more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users.

Reconfigurability. It enables the radio to be dynamically programmed according to the radio environment. More specifically, CR can be programmed to transmit and receive on a variety of frequencies and to use

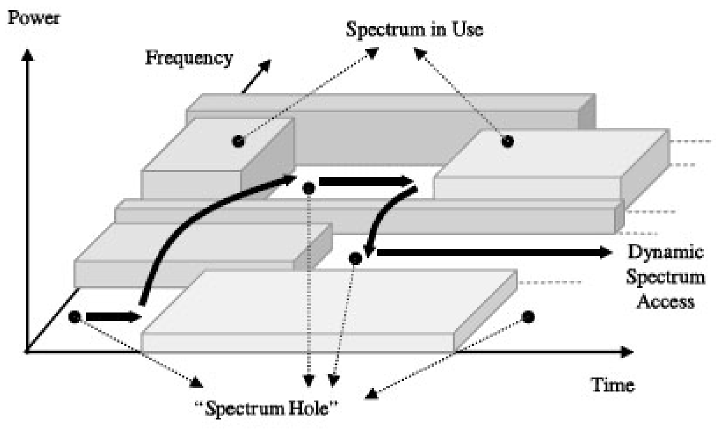

Figure 2.2: Spectrum hole concept.

different transmission access technologies supported by its hardware and software design.

The ultimate objective of the CR is to obtain the best available spectrum through cognitive capability and reconfigurability as described before. Since most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users. The CR technology enables the use of temporarily unoccupied spectrum gaps, which are referred to as *spectrum holes* or *white spaces* [2] (see Figure 2.2). If this band is further used by a licensed user, the CR terminal moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid unacceptable harmful interference levels.

2.3 Cognitive Radio Network Architecture

The components of the CR network architecture can be classified into two groups: the *primary network* and the *cognitive radio network*. The primary network (or licensed network) is referred to an existing network, where the *primary users* have a license to operate in a certain spectrum band. If primary networks have an infrastructure, primary user activities are controlled through *primary base stations*. Due to their priority in spectrum access, the operations of primary users should not be affected by unlicensed users. The CR network (also called the DSA network, secondary network, or unlicensed

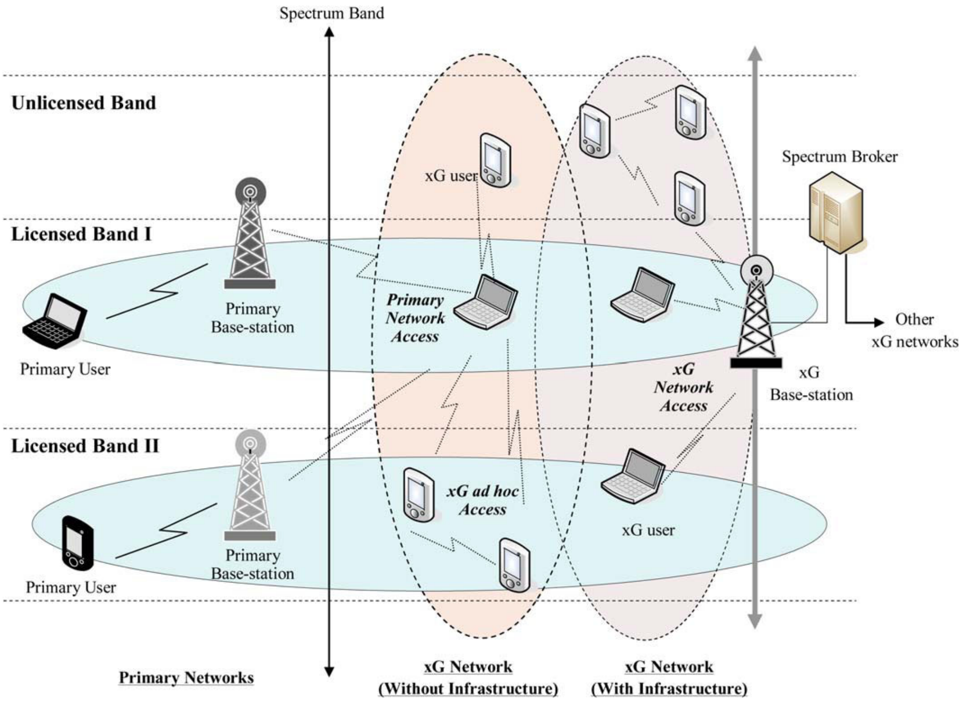

Figure 2.3: Cognitive Radio network architecture.

network) does not have a license to operate in a desired band. Hence, additional functionality is required for CR users to share the licensed spectrum band. CR networks also can be equipped with CR base stations that provide single-hop connection to CR users. Finally, CR networks may include *spectrum brokers* that play a role in distributing the spectrum resources among different CR networks. Figure 2.3 shows the main components of a CR network. CR users are capable of accessing both the licensed portions of the spectrum used by primary users and the unlicensed portions of spectrum through wideband access technology. Consequently, the operation types for CR networks can be classified into *licensed band operation* and *unlicensed band operation.*

- *Licensed band operation.* The licensed band is primarily used by the primary network. Hence, CR networks are focused mainly on the detection of primary users in this case. If primary users appear in the spectrum band occupied by CR users, they should vacate that spectrum immediately.

- *Unlicensed band operation.* In the absence of primary users, CR users have the same right to access spectrum. Hence, sophisticated spectrum sharing methods are required for CR users to compete for the unlicensed band.

According to Figure 2.3, we can notice that CR users have the opportunity to perform three different access types:

- *CR network access:* CR users can access their own CR base station, on both licensed and unlicensed spectrum bands. Because all interactions occur inside the CR network, their spectrum sharing policy can be independent of that of the primary network.
- *CR ad hoc access:* CR users can communicate with other CR users through an ad hoc connection on both licensed and unlicensed spectrum bands.
- *Primary network access:* CR users can also access the primary base station through the licensed band. Unlike for other access types, this requires an adaptive Medium Access Control (MAC) protocol, which enables roaming over multiple primary networks with different access technologies.

According to the xG architecture described above, new spectrum management functions are required, to satisfy the following critical design challenges:

- *Interference avoidance:* CR networks should avoid interference with primary networks.
- *Quality of Service (QoS) awareness:* to decide on an appropriate spectrum band, CR networks should support QoS-aware communication, considering the dynamic and heterogeneous spectrum environment.
- *Seamless communication:* CR networks should provide seamless communication regardless of the spectrum occupancy patterns of the primary users.

2.4 Cognitive Radio Functions

The new functionalities required to CR networks to obtain the challenges described in the previous section are:

- *Spectrum sensing*: the ability to monitor the available spectrum bands, capture their information, and then detect spectrum holes.
- *Spectrum management:* the set of policies that permit to decide when to allocate a channel based on spectrum availability.
- *Spectrum sharing:* because there may be multiple CR users trying to access the spectrum, CR network access should be coordinated to prevent multiple users colliding in overlapping portions of the spectrum.

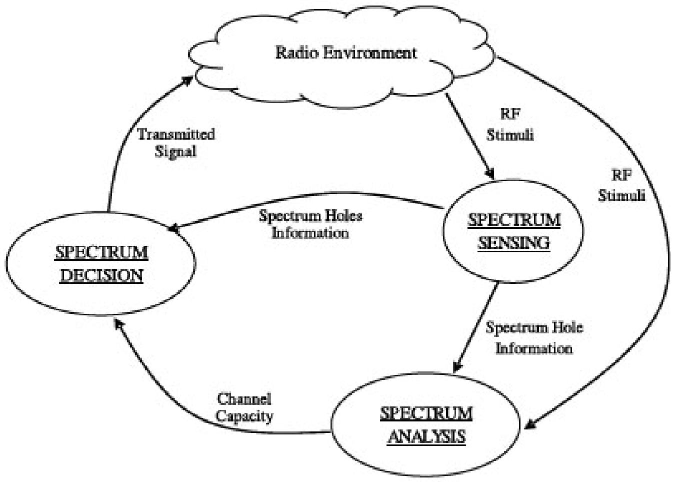

Figure 2.4: Cognitive cycle.

- *Spectrum mobility:* if the specific portion of the spectrum in use is required by a primary user, the communication must be continued in another vacant portion of the spectrum.

In Figure 2.4 a diagram of the operations required by CR is shown. In the following sections we will give a brief description of each of these functionalities.

2.4.1 Spectrum Sensing

Spectrum sensing enables CR users to adapt to the environment by detecting spectrum holes without causing interference to the primary network. This can be accomplished through a real-time wideband sensing capability to detect weak primary signals in a wide spectrum range. Generally, spectrum sensing techniques can be classified into three groups: primary transmitter detection, primary receiver detection and interference temperature management as described in the following.

Primary Transmitter Detection

Transmitter detection is based on the detection of a weak signal from a primary transmitter through the local observations of CR users. Three schemes are generally used for transmitter detection:

- *Matched filter detection:* when the information of the primary user signal is known to the CR user, the optimal detector in stationary gaussian noise is the matched filter. This requires a priori knowledge of the characteristics of the primary user signal.

- *Energy detection:* if the receiver has no sufficient information about the primary transmitter the optimal detector is an energy detector. However, the performance of this detector is susceptible to the uncertainty in noise power and also generates false alarms triggered by unintended signals because they cannot differentiate among intended primary transmissions and man-made noise sources or other undesired signal components.

- *Feature Detection:* in general, modulated signals are characterized by built-in periodicity or cyclostationarity. This feature can be detected by analyzing a spectral correlation function. The main advantage of this kind of signal detection is robustness to uncertainty in noise power. However, it is computationally complex and requires significantly long observation times.

The main problem of primary transmitter detection techniques are:

- *Receiver uncertainly:* transmitter detection techniques alone cannot avoid interference to primary receivers in some cases because of the inability to detect of passive primary receivers that do not transmit (e.g., TV receivers) as depicted in Figure 2.5a.

- *Hidden terminal problem:* a CR user (transmitter) can have a good line of sight to a CR receiver but may not be able to detect the primary transmitter due to shadowing, as shown in Figure 2.5b.

In order to overcome the above mentioned problems, the sensing information from several CR terminals can be gathered and combined for more accurate primary transmitter detection, which is referred to as *cooperative spectrum sensing* of *cooperative detection*. However, cooperative approaches cause adverse effects on resource constrained networks due to the overhead traffic required for cooperation.

Primary Receiver Detection

Although cooperative detection reduces the probability of interference, the most efficient way to detect spectrum holes is to detect the primary users that are receiving data within the communication range of a CR user. Usually, the Local Oscillator (LO) leakage power emitted by the Radio Frequency (RF) front-end of the primary receiver is exploited. However, because the LO leakage signal is typically weak, implementation of a reliable detector may have to face important problems in practice. This detection approach was firstly proposed for the detection of passive TV receivers [22].

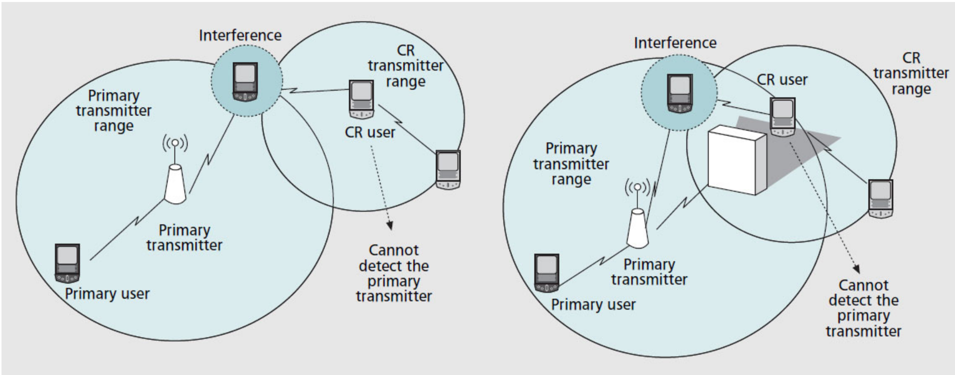

Figure 2.5: Transmitter detection problem: a) receiver uncertainty; b) shadowing uncertainty.

Interference Temperature Management

Traditionally, interference can be controlled at the transmitter through the radiated power and location of individual transmitters. However, interference actually takes place at the receivers, as shown in Figure 2.5. Therefore, a model for measuring interference, referred to as interference temperature, was introduced by the Federal Communications Commission (FCC). This model limits the interference at the receiver through an interference temperature limit, which is the amount of new interference the receiver could tolerate. As long as CR users do not exceed this limit, they can use the spectrum band. Although this model is the best fit for the objective of spectrum sensing, the difficulty of this model lies in accurately determining the interference temperature limit. This model was finally discarded by the FCC due to the its practical implementation problems.

2.4.2 Spectrum Management

CR networks require the capability to decide which is the best spectrum band among the available bands according to the QoS requirements of the applications. This notion is called spectrum management and constitutes constitutes and important but yet rather unexplored topic in CR networks. Spectrum management is closely related to the channel characteristics and operations of primary users. Furthermore, spectrum decision is affected by the activities of other CR users in the network. Spectrum decision usually consists of two steps: first, each spectrum band is characterized, based on not only local observations of CR users but also on statistical information of primary networks, if available. Then, based on this characterization, the most appropriate spectrum band can be chosen. In the following we investigate the channel characteristics and decision procedures.

Spectrum Characterization

Because available spectrum holes show different characteristics that vary over time, each spectrum hole should be characterized considering both the time-varying radio environment and spectrum parameters, such as operating frequency and bandwidth. Hence, it is essential to define parameters that can represent a particular spectrum band as follows:

Interference From the amount of interference at the primary receiver, the permissible power of a CR user can be derived, which is used for the estimation of channel capacity.

Path loss The path loss is closely related to distance and frequency. As the operating frequency increases, the path loss increases, which results in a decrease in the transmission range. If transmission power is increased to compensate for the increased path loss, interference at other users may increase.

Wireless link errors Depending on the modulation scheme and the interference level of the spectrum band, the error rate of the channel changes.

Link layer delay To address different path loss, wireless link error, and interference, different types of link layer protocols are required at different spectrum bands. This results in different link layer delays. It is desirable to identify the spectrum bands that combine all the characterization parameters described previously for accurate spectrum decision. However, a complete analysis and modeling of spectrum in CR networks has not been developed yet.

Decision Procedure

After the available spectrum bands are characterized, the most appropriate spectrum band should be selected, considering the QoS requirements and spectrum characteristics. Accordingly, the transmission mode and bandwidth for the transmission can be reconfigured. To describe the dynamic nature of CR networks, the *primary user activity*, which is defined as the probability that a primary user appears during a CR user transmission, can be used. Because there is no guarantee that a spectrum band will be available during the entire communication of a CR user, it is important to consider how often the primary user appears on the spectrum band. However, because of the operation of primary networks, CR users cannot obtain a reliable communication channel for a long time period. Moreover, CR users might not detect any single spectrum band to meet the users requirements. Therefore, multiple noncontiguous spectrum bands can be simultaneously used for transmission in CR networks, as shown in Figure 2.6. This method

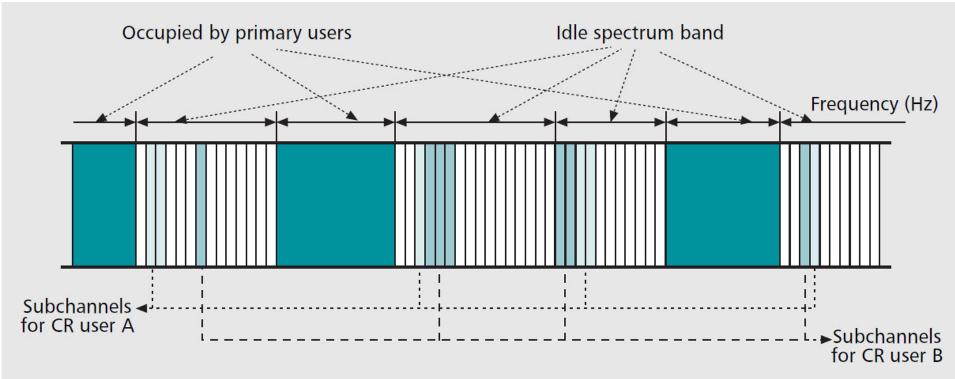

Figure 2.6: Channel structure of the multi-spectrum decision.

can create a signal that is not only capable of high data throughput, but is also immune to interference and primary user activity. Even if spectrum handoff occurs in one of the current spectrum bands, the rest of the spectrum bands will maintain current transmissions.

2.4.3 Spectrum Sharing

The shared nature of the wireless channel requires the coordination of transmission attempts between CR users. In this respect, spectrum sharing should include much of the functionality of a MAC protocol. Moreover, the unique characteristics of CR, such as the coexistence of CR users with licensed users and the wide range of available spectrum, incur substantially different challenges for spectrum sharing in CR networks. The existing work in spectrum sharing aims to address these challenges and can be classified by four aspects: architecture, spectrum allocation behavior, spectrum access technique, and scope.

Classification based on architecture

Centralized spectrum sharing: the spectrum allocation and access procedures are controlled by a central entity. Moreover, a distributed sensing procedure can be used such that measurements of the spectrum allocation are forwarded to the central entity, and a spectrum allocation map is constructed. Furthermore, the central entity can lease spectrum to users in a limited geographical region for a specific amount of time. In addition to competition for the spectrum, competition for users can also be considered through a central spectrum policy server.

Distributed spectrum sharing: spectrum allocation and access are based on local (or possibly global) policies that are performed by each node distributively. Distributed solutions can also be used between different networks such that a Base Station (BS) competes with its interferer BSs according to the QoS requirements of its users to allocate a portion of the spectrum.

Classification based on spectrum allocation behavior

Cooperative spectrum sharing: cooperative (or collaborative) solutions exploit the interference measurements of each node such that the effect of the communication of one node on other nodes is considered. A common technique used in these schemes is forming clusters to share interference information locally. This localized operation provides an effective balance between a fully centralized and a distributed scheme.

Non-cooperative spectrum sharing: only a single node is considered in non-cooperative (or non-collaborative, selfish) solutions. Because interference in other CR nodes is not considered, non-cooperative solutions may result in reduced spectrum utilization. However, these solutions do not require frequent message exchanges between neighbors as in cooperative solutions.

Classification based on spectrum access technique

Overlay spectrum sharing: nodes access the network using a portion of the spectrum that has not been used by licensed users. This minimizes the interference to the primary network since primary and secondary transmissions overlap neither in frequency nor time.

Underlay spectrum sharing: overlapping secondary transmissions are allowed as long as their resulting interference level at the primary receiver is regarded as noise. To this end, the aggregated interferences from several CR nodes should not exceed the primary user's noise floor power. In order to achieve such low interference levels, efficient spread spectrum techniques, such as Code Division Multiple-Access (CDMA) and Ultra Wide Band (UWB), need to be employed.

Classification based on scope

Intranetwork spectrum sharing: these solutions focus on spectrum allocation between the entities of a CR network, as shown in Figure 2.7. Accordingly, the users of a CR network try to access the available spectrum without causing interference to the primary users. Intranetwork spectrum sharing poses unique challenges that have not been considered previously in wireless communication systems.

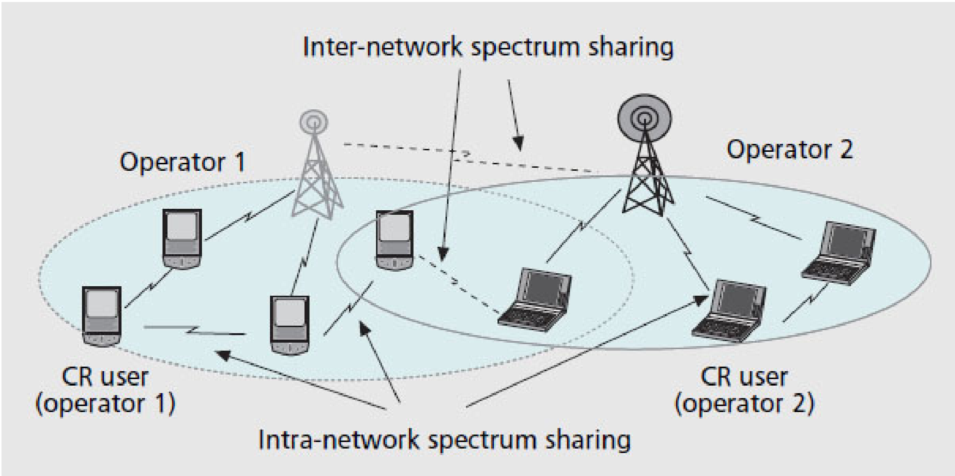

Figure 2.7: Inter-network and intra-network spectrum sharing in CR networks.

Internetwork spectrum sharing: the CR architecture enables multiple systems to be deployed in overlapping locations and spectrum, as shown in Figure 2.7. So far the internetwork spectrum sharing solutions provide a broader view of the spectrum sharing concept by including certain operator policies.

2.4.4 Spectrum Mobility

After a CR captures the best available spectrum, primary user activity on the selected spectrum may necessitate that the user changes its operating spectrum band, which is referred to as spectrum mobility. Spectrum mobility gives rise to a new type of handoff in CR networks, *spectrum handoff*. The purpose of the spectrum mobility management in CR networks is to ensure smooth and fast transition leading to minimum performance degradation during a spectrum handoff. Spectrum handoff mechanisms in a CR network may be triggered by the CR user mobility (i.e., as a result of the change of location, the available spectrum bands may also change, thus requiring a spectrum handoff) as well as a change in the operating conditions (i.e., the CR user may be best served in a different frequency band). Although the mobility-based handoff mechanisms that have been investigated in cellular networks may lay the groundwork in this area, there are still open research topics to be investigated.

2.5 Summary

By exploiting the existing wireless spectrum opportunistically, CR networks are being developed to solve current wireless network problems resulting from the limited available spectrum and the inefficiency in spectrum usage. DSA networks, equipped with the intrinsic capabilities of CR, will provide an ultimate spectrum-aware communication paradigm in wireless communications. In this chapter intrinsic properties of CR networks are presented. In particular, we have described the functions required by a DSA/CR network, namely spectrum sensing, spectrum management, spectrum sharing, and spectrum mobility.A more detailed description of CR networks can be found in [2] and [3].

Chapter 3

Spectrum Analysis Basics

The aim of this chapter is to introduce spectrum analysis and particulary the instrument that permit us to perform spectral measurements: the spectrum analyzer. A basic knowledge of this instrument is important as it will be used intensively for the measure of spectrum occupancy in the context of the cognitive radio. Therefore, this chapter presents the fundamentals of spectrum analysis, including the motivations of spectral analysis, the existing types of spectrum analyzers, their main parameters and how their variation affects the measured signals. This chapter places the emphasis on the operating principles of swept-tuned, superheterodyne spectrum analyzers since this is the type of spectrum analyzer employed in this work.

3.1 Introduction

The theoretical foundation of spectrum analysis is the Fourier transformation. The theory tells us that a time-domain signal can be decomposed into a set of sine waves, referred to as spectral components, of different amplitude, frequency and phase as it can be seen in Figure 3.1. At the most basic level, the spectrum analyzer can be described as a frequency-selective, peak-responding voltmeter calibrated to display the Root Mean Square (RMS) value of the measured spectral components. The main point of the frequency analysis is that it gives us different information with respect to the time-domain analysis. If we are interested in the transient period of a signal or on its peak response then the time analysis would be the most suitable alternative. However, there are many fields in which spectrum analysis is important, in particular in the area of radio communications. Some examples include, but are not limited to:

- Out-of-band and spurious emissions;
- Spectrum monitoring;
- ElectroMagnetic Interference (EMI).

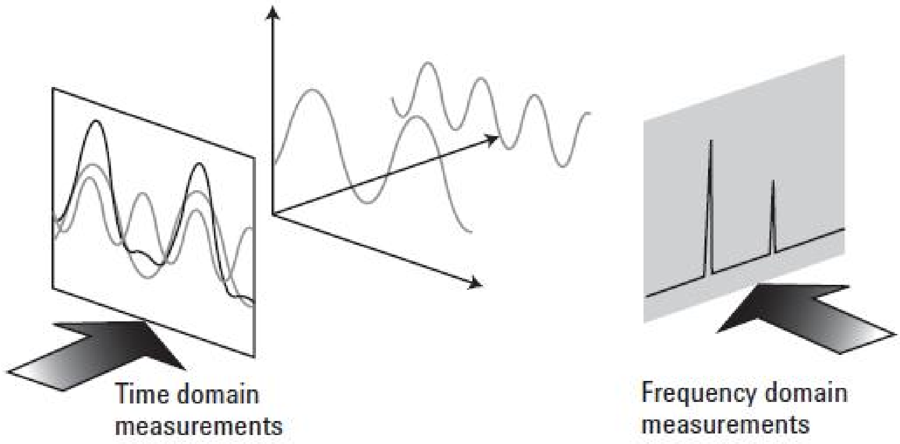

Figure 3.1: Relationship between time and frequency domain.

To make the transformation from the time domain to the frequency domain the signal must be evaluated over all time; in practice a finite time period is used when making a measurement. Generally spectrum analyzers do not give us a complete information about the amplitude and the phase of the spectral components. They only tell us how much energy is present at a particular frequency (or its effective value, they are proportional). A large group of measurements can be made without knowing the phase relationships among the spectral components of a signal, including the kind of studies performed in this work. However, some measurements require that we preserve complete information about the signal (frequency, amplitude and phase). For this type of studies, other signal analysis architectures are required. We can distinguish three main types of signal analyzers:

- *Fourier Analyzer* - it digitizes the time-domain signal and then uses Digital Signal Processing (DSP) techniques to perform a Fast Fourier Transform (FFT) and display the signal in the frequency domain. One advantage of the FFT approach is its ability to characterize single-shot phenomena. Another is that phase as well as magnitude can be measured. However, Fourier analyzers do have some limitations relative to the superheterodyne spectrum analyzer, particularly in the areas of frequency range, sensitivity, and dynamic range. Fourier analyzers are typically used in baseband signal analysis applications up to 40 MHz.
- *Vector Signal Analyzer* - VSAs also digitize the time domain signal

like Fourier analyzers and preserve complete information about the signal (frequency, amplitude and phase), but extend the capabilities to the Radio Frequency (RF) frequency range using downconverters in front of the digitizer. They offer fast, high-resolution spectrum measurements, demodulation, and advanced time-domain analysis. They are especially useful for characterizing complex signals such as burst, transient or modulated signals used in communications.

- *Swept-tuned super-heterodyne Spectrum Analyzer* - measures the power of the various spectral components of the signal using the super-heterodyne technique which uses the frequency mixing to translate the received signal to an Intermediate Frequency (IF), more suitable for the signal processing.

Among the three signal analyzer types described above, vector signal analyzers are able to perform the widest variety of measurements and signal analyses. However, due to the offered high capabilities, their economical cost usually is significantly high. Since the objectives pursued in this work can be fulfilled with lower-cost analyzers, this type of signal analyzer has been discarded. Among the remaining alternatives, the swept-tuned super-heterodyne analyzer is the most attractive option because of its improved capabilities in terms of sensitivity and dynamic range. It is worth noting that the objective of this work is to assess the degree to which spectrum is used in real wireless communications systems, and to this end it becomes necessary to detect signals of the most diverse nature, from weak signals received near the noise floor that may be difficult to detect, to strong signals that may overload the receiving system. Hence, sensitivity and dynamic range are two key requirements. On one hand, higher sensitivities enable the detection of weaker signals, received with low power levels. On the other hand, higher dynamic ranges enable the detection of weaker signals in presence of strong ones. Since superheterodyne spectrum analyzers provide improved performance figures in terms of sensitivity and dynamic range with respect to Fourier analyzers, the former type of analyzers represent a more appropriate choice and have therefore been selected in this work. In the next section we discuss in more detail the superheterodyne spectrum analyzer.

3.2 Super-heterodyne Spectrum Analyzers

This part will focus on the fundamental theory of how a superheterodyne spectrum analyzer works. In Figure 3.2 a simplified block diagram of a super-heterodyne spectrum analyzer is shown. This ideal diagram is aimed at showing the main components of a spectrum analyzer and how and why they affect the measure of a signal. The main components of the circuit are:

- RF attenuator

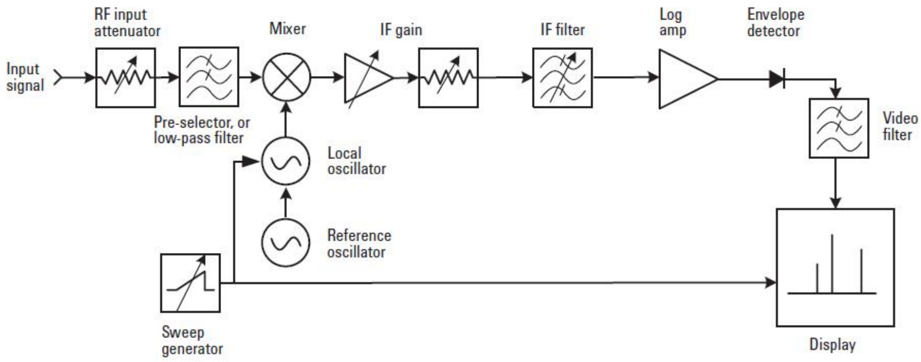

Figure 3.2: Block diagram of a classic superheterodyne spectrum analyzer.

- Low-pass filter
- Mixer and local oscillator
- IF gain amplifier
- Resolution filter
- Envelope detector
- Video filter
- Display

Now we will see shortly the role of each component in the circuit.

3.2.1 RF attenuator

It has the purpose of ensuring that the signal enters the mixer at the optimum level to prevent overload gain compression and distortion. Usually it is set automatically, based on the reference level. Figure 3.3 shows an example of an attenuator circuit: the blocking capacitor is used to prevent the analyzer from being damaged by a Direct Current (DC) signal or a DC offset of the signal. Unfortunately, it also attenuates low frequency signals and increase the minimum usable frequency of the analyzer.

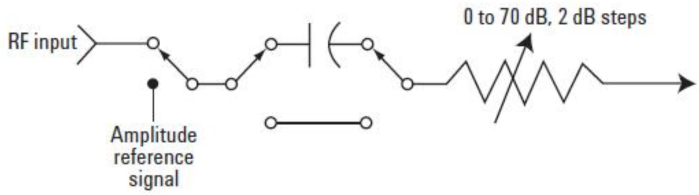

Figure 3.3: RF input attenuator circuitry.

3.2.2 Low-pass filter

The low-pass filter blocks high frequency signals from reaching the mixer. This prevents out-of-band signals from mixing with the local oscillator and creating unwanted responses at the IF.

3.2.3 Mixer and local oscillator

The aim of the mixer and Local Oscillator (LO) block is to traslate the input signal into an IF signal. In this manner the rest of the components of the circuit (filters, amplifiers, etc) can work at a fixed frequency, which enables an easier and more efficient design of such components. To understand how this block works it is necessary to know what is the output of a mixer. A mixer is a nonlinear component that accepts as inputs two signals at different frequencies (the input signal to be measured at frequency f_{sig} and the signal from the local oscillator at frequency f_{LO}) and presents at its outputs a mixture of signals at several frequencies:

- the sum of the frequencies $f_{LO} + f_{sig}$;
- the difference of the frequencies $f_{LO} - f_{sig}$;
- both original input frequencies.

We want a device that sweeps through a desired frequency range. To do this the IF frequency has to be chosen above the highest frequency we wish to tune; using the following tuning equation, that relates the output frequencies of the mixer, we can choose the range of variation of the local oscillator (see Figure 3.4):

$$f_{LO} = f_{sig} + f_{IF};$$

where:
f_{sig} = signal frequency,

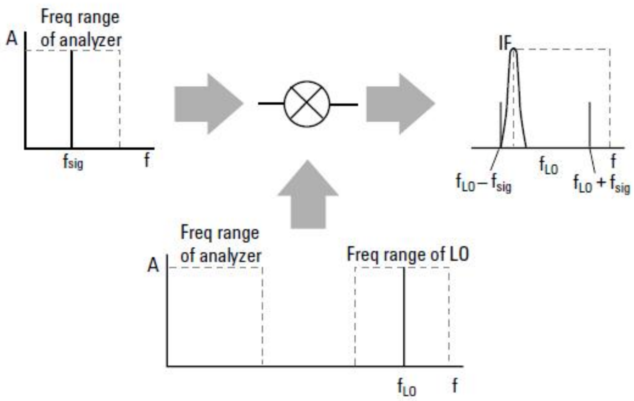

Figure 3.4: The LO must be tuned to $f_{IF} + f_{sig}$ to produce a response on the display.

f_{LO} = local oscillator frequency, and
f_{IF} = IF frequency;

For example, if we want a frequency range from 0 Hz to 3 GHz, choosing an IF of 3.9 GHz, our oscillator has to vary from 3.9 GHz to 6.9 GHz. Depending on the frequency range to be measured, the local oscillator varies temporally its frequency f_{LO} so that the desired range of frequencies f_{sig} is sequentially swept [1] and the energy level measured at each frequency is shown in the display. Since the ramp generator controls both the horizontal position of the trace on the display and the LO frequency, the horizontal axis of the display can be calibrated in terms of the input signal frequency in order to show each measured energy level at the proper frequency point in the horizontal axis.

One major disadvantage to the superheterodyne receiving structure is the well-know *image frequency problem*. Let's assume that we want to receive a signal at $f_{sig'}$. In this case, the local oscillator is tuned to $f_{LO} = f_{sig'} + f_{IF}$. When this oscillator frequency f_{LO} is selected, a response is generated at f_{IF} due to the desired signal at $f_{sig'}$. Unfortunately, signals at $f_{sig'} + 2f_{IF}$ (known as the image frequency f_{image}) also cause a response at f_{IF}, even if no signal is present at $f_{sig'}$. In effect, one of the output frequencies in the mixer would be the difference between the input frequency $f_{sig'} + 2f_{IF}$ and the local oscillator frequency f_{LO}. Since the local oscillator is tuned to $f_{LO} = f_{sig'} + f_{IF}$, a response is obtained at $(f_{image}) - (f_{LO}) = (f_{sig'} + 2f_{IF}) - (f_{sig'} + f_{IF}) = f_{IF}$, i.e. the IF. This response would be observed as if

[1]The superheterodyne spectrum analyzer is also referred to as *swept-tuned spectrum analyzer*.

a signal was present at $f_{sig'}$, when it actually is not. To avoid this problem, a low-pass filter is placed before the mixer as shown in Figure 3.2 in order to prevent such high-frequency signals from reaching the mixing stage. In summary, we can say that for a single-band RF spectrum analyzer, an IF above the highest frequency of the tuning range is chosen, the local oscillator is made tunable from the IF to the IF plus the upper limit of the tuning range, and a low-pass filter is included in front of the mixer that cuts off below the IF.

To separate closely spaced signals, some spectrum analyzers have IF bandwidths as narrow as 1 kHz; others, 10 Hz; still others, 1 Hz. Such narrow filters are difficult to achieve at a center frequency of e.g. 3.9 GHz. In practice, this problem can be solved by adding additional mixing stages, typically two to four stages, to down-convert from the first to the final IF.

3.2.4 IF gain amplifier

After the input signal is converted to an IF, it passes through the IF gain amplifier and IF attenuator which are adjusted to compensate for changes in the RF attenuator setting and mixer conversion loss. Input signal amplitudes are thus referenced to the top line of the graticule on the display, known as the reference level. When the IF gain is changed, the value of the reference level is changed accordingly to retain the correct indicated value for the displayed signals. Generally, we do not want the reference level to change when we change the input attenuator, so the settings of the input attenuator and the IF gain are coupled together. A change in input attenuation will automatically change the IF gain to offset the effect of the change in input attenuation, thereby keeping the signal at a constant position on the display.

3.2.5 Resolution filter

After the IF gain amplifier we find the IF section which consists of the analog and/or digital Resolution BandWidth (RBW) filters.

Frequency Resolution

Frequency resolution is the ability of a spectrum analyzer to separate two input sinusoids into distinct responses, i.e. the smallest frequency interval that can be resolved.

Two signals, no matter how close in frequency, should appear as two lines on the display. But a closer look at our superheterodyne receiver shows why signal responses have a definite width on the display. The output of a mixer includes the sum and difference products plus the two original signals (input and LO). A bandpass filter determines the IF, and this filter selects the desired mixing product and rejects all other signals. Because the input signal

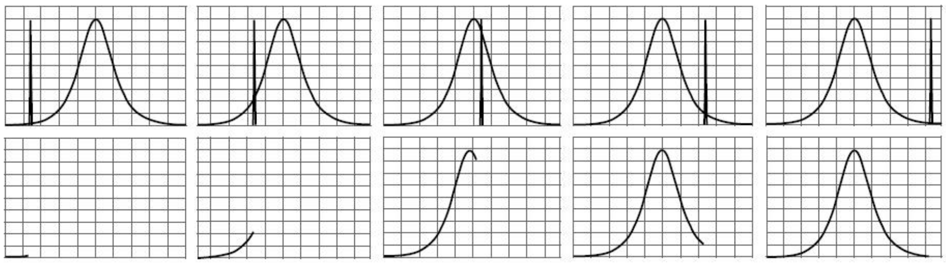

Figure 3.5: As a mixing product sweeps past the IF filter, the filter shape is traced on the display.

is fixed and the local oscillator is swept, the products from the mixer are also swept. If a mixing product happens to sweep past the IF, the characteristic shape of the bandpass filter is traced on the display (see Figure 3.5). So two signals must be far enough apart, or else the traces they make will fall on top of each other and look like only one response. Fortunately, spectrum analyzers have selectable resolution (IF) filters, so it is usually possible to select one narrow enough to resolve closely spaced signals. Narrowing the RBW increases the ability to resolve signals in frequency. To describe the ability to resolve signals usually data sheets list the 3 dB bandwidth: this number tell us how close together equal-amplitude sinusoids can be and still be resolved. In this case, there will be about a 3 dB dip between the two peaks traced out by these signals (see Figure 3.6).

More often than not we are dealing with sinusoids that are not equal in amplitude. The smaller sinusoid can actually be lost under the skirt of the response traced out by the larger. This effect is illustrated in Figure 3.7. The top trace looks like a single signal, but in fact represents two signals: one at 300MHz (0dBm) and another at 300.005 MHz (-30dBm). The lower trace shows the display after the 300 Mhz signal is removed. Another specification is listed for the resolution filters: bandwidth selectivity (or selectivity or shape factor). Bandwidth selectivity helps determine the resolving power for unequal sinusoids. It is generally specified as the ratio of the 60 dB bandwidth to the 3 dB bandwidth.

Sweep Time

As explained before, narrowing the RBW increases the ability to resolve signals in frequency. However, the drawback of choosing a narrow resolution

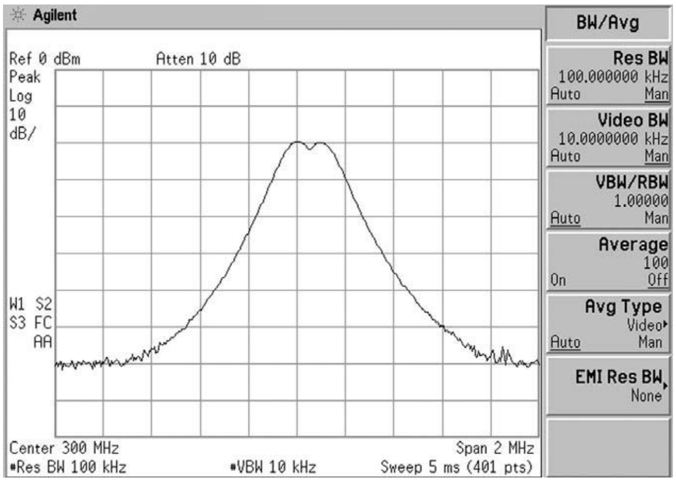

Figure 3.6: Two equal-amplitude sinusoids separated by the 3 dB BW of the selected IF can be resolved.

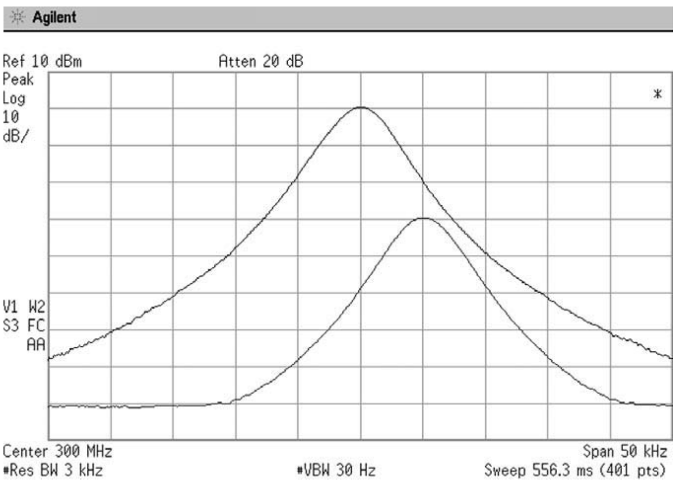

Figure 3.7: A low-level signal can be lost under skirt of the response to a larger signal.

filter is that this increases sweep time that directly affects how long it takes to complete a measurement.

In the analog case, resolution comes into play because the IF filters are band-limited circuits that require finite times to charge and discharge. If we think about how long a mixing product stays in the passband of the IF filter, that time is directly proportional to bandwidth and inversely proportional to the sweep in hertz per unit time, or:

$$Time\ in\ passband\ = \frac{RBW}{\frac{Span}{ST}} \tag{3.1}$$

where RBW = resolution bandwidth, and ST = sweep time.

The rise time of a filter is inversely proportional to its bandwidth, and if we include a constant of proportionality, k, then

$$\text{RiseTime} = \frac{k}{RBW} \tag{3.2}$$

$$\text{ST} = \frac{k \cdot Span}{RBW^2} \tag{3.3}$$

The important message here is that a change in resolution has a dramatic effect on sweep time (e.g., reducing the RBW by a factor of 10 increases the sweep time by a factor of 100). Spectrum analyzers automatically couple sweep time to the span and resolution bandwidth settings. Sweep time is adjusted to maintain a calibrated display.

Some spectrum analyzers use digital techniques to realize their RBW filters. Digital filters can provide important benefits, such as dramatically improved bandwidth selectivity. Another important advantage is that digital filters are from 2 to 4 times faster, due to the fact that the signal being analyzed is processed into frequency blocks.

Noise Floor

The selection of different RBWs has an impact not only on the ability to resolve signals in frequency and the sweep time but also on the system's noise floor and thus on the ability to detect the presence of weak signal. When modifying the RBW, the noise floor observed in the spectrum analyzer changes. Although there are various noise sources inside a spectrum analyzer, this variation is mainly due to the effect of the thermal noise. The thermal noise power P_N of a receiver can be expressed as $P_N = kTB$, where k is the Boltzmann's constant, T is the absolute temperature in Kelvin, and B is the system bandwidth (the resolution bandwidth in the case of a spectrum analyzer). From the previous expression, it is clear that if we increase the RBW, the captured noise power also increases, thus degrading the receiving Signal-to-Noise Ratio (SNR). This effect is clearly appreciated

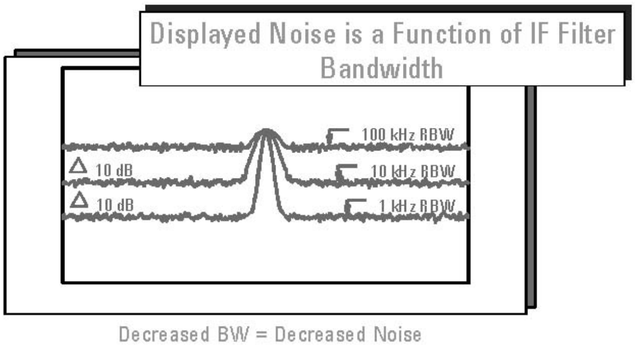

Figure 3.8: Displayed noise is a function of IF filter bandwidth.

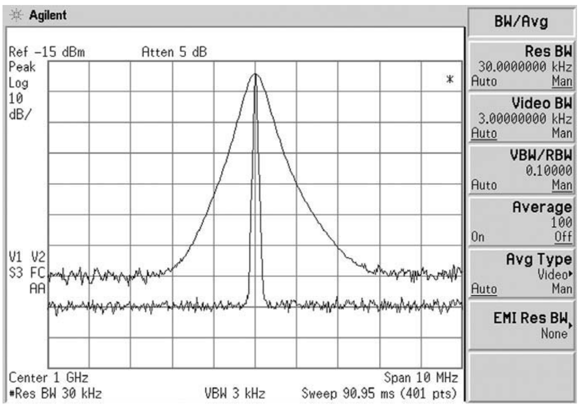

Figure 3.9: Displayed noise level change with the ratio of resolution and video bandwidth.

in Figure 3.8. Therefore, by narrowing the RBW we increase not only the ability to resolve signals in frequency but also the ability to detect weak signals, at the cost of an increased sweep time (measurement time).

3.2.6 Envelope detector

The aim of the envelope detector is to convert the IF signal into video (i.e. a signal whose frequency range extends from zero to some upper frequency determined by the circuit elements). It is important to remark that we are interested in the power of each spectral component of the input signal. As it

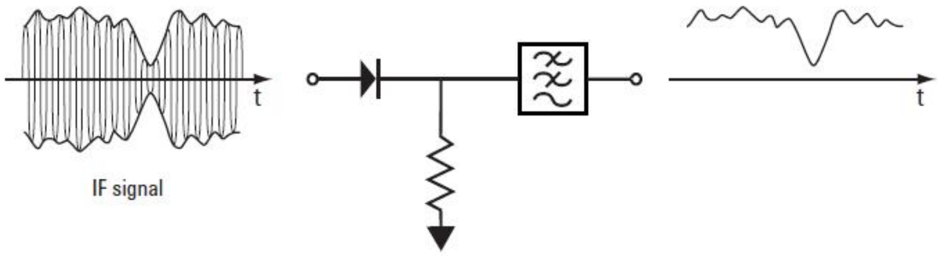

Figure 3.10: Envelope detector.

can be seen in Figure 3.10 the response of the detector follows the changes in the envelope of the IF signal, but not the instantaneous value of the IF sine wave itself. For most measurements, we choose a RBW narrow enough to resolve the individual spectral components of the input signal. If we fix the frequency of the LO so that our analyzer is tuned to one of the spectral components of the signal, the output of the IF is a steady sine wave with a constant peak value. The output of the envelope detector will then be a constant (DC) voltage, and there is no variation for the detector to follow. So the envelope detector follows the changing amplitude values of the peaks of the signal from the IF chain but not the instantaneous values, resulting in the loss of phase information.

The logarithmic amplifier in front of the envelope detector in Figure 3.2 can be enabled in order to display the detected signal in logarithmic scale (decibels).

3.2.7 Video filter

Spectrum analyzers display signals plus their own noise. To reduce the effect of the noise on displayed signal amplitude a variable video filter is included. The video filter is a low-pass filter that comes after the envelope detector. This filtering has the effect of reducing the peak-to-peak variations of the signal at the output of the envelope detector. The video filter does not affect any part of the trace that is already smooth (for example, a sinusoid displayed well above the noise level). This smoothing effect however is more noticeable in measuring noise. As it can be appreciated in Figures 3.11 and 3.12, when we reduce the Video BandWidth (VBW), the peak-to-peak variations of the noise are reduced, thus improving the detection of weak signals near the noise level. However, the degree of reduction is a function of the ratio of the VBW to RBW (see Figure 3.9). If the VBW is greater

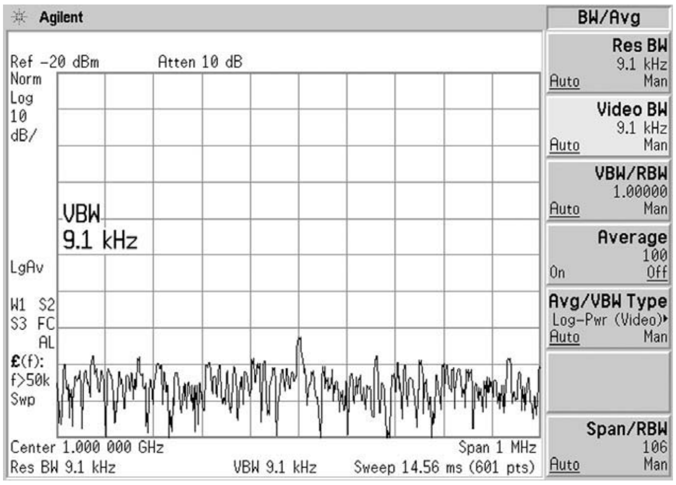

Figure 3.11: Spectrum analyzers display signal plus noise.

than the RBW there is no reduction. On the other hand, when the VBW is narrower than the RBW, the video system can no longer follow the more rapid variations of the envelope of the signals passing through the IF chain. The result is an averaging or smoothing of the displayed signal.

It is important to note that, because the video filter has its own response time, the sweep time increases approximately inversely with VBW when the VBW is less than the RBW.

Video filters appeared in the analogical era, when it was the only method to average noise and smooth the signal displayed in the screen. With the advent of the digital technology, a new method to achieve the same effect appeared. The same effects of the video filter can be achieved in the digital domain by an averaging of the measured traces. Because the noise we are dealing with has zero mean, trace averaging has the same effects of reducing the amplitude of the noise. In this case the tunable parameter is the number of sweeps over which averaging occurs. In general, averaging over a greater number of sweeps provides a greater peak-to-peak noise reduction, at the expense of the time required to achieve a certain smoothing level.

3.2.8 Display

With digital displays we have a limited amount of points to show the signal. No matter how many data points we use across the display, each point must

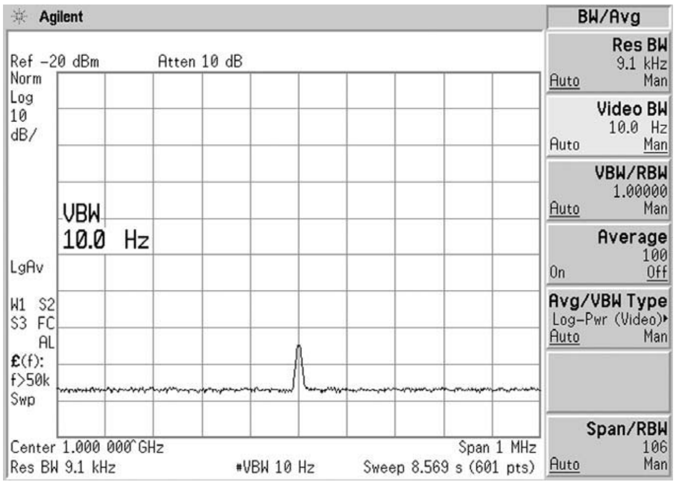

Figure 3.12: Display of Figure 3.11 after full smoothing.

represent what has occurred over some frequency range. For example, if we have a 551 points display and we set a 551 MHz span then every point in the display represents the power of 1 MHz band).

The number of points that a display can show is usually limited while the number of points that the spectrum analyzer memorizes after the IF filter is greater. So for each point in the display we have much more points of information - we can say we have a bucket of points of a certain length. Now for every bucket we have to take only one value to send to the display. There are various types of detectors, i.e. various ways to choose the value that will be shown (see Figure 3.13):

- Sample
- Positive peak
- Negative peak
- Normal
- Average

Sample Detection

This method just selects the data point as the instantaneous level at the center of each bucket. While the sample detection does a good job of indicating randomness of noise it is not a good mode for analyzing sinusoidal signals because it does not catch all the signals, nor does it necessarily reflect the

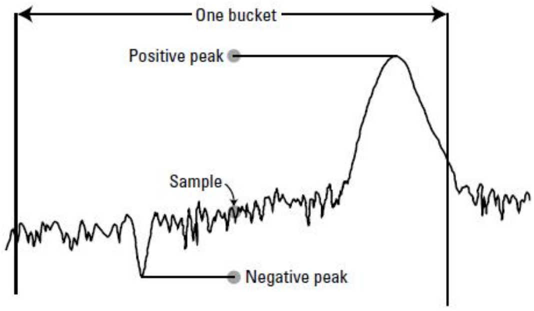

Figure 3.13: Trace point saved in memory is based on detector type algorithm.

true peak values of the displayed signals. When RBW is narrower than the sample interval (i.e., the bucket width), the sample mode can give erroneous results.

Positive Peak Detection

One way to insure that all sinusoids are reported at their true amplitudes is to display the maximum value encountered in each bucket. This is the positive peak detection mode. It ensures that no sinusoid is missed, regardless of the ratio between resolution bandwidth and bucket width. However peak detection does not give a good representation of random noise because it only displays the maximum value in each bucket and ignore the true randomness of the noise.

Negative Peak Detection

Negative peak detection displays the minimum value encountered in each bucket. It is generally available in most spectrum analyzers, though it is not used as often as other types of detection. Differentiating Continuous Wave(CW) from impulsive signals in Electro-Magnetic Compatibility (EMC) testing is one application where negative peak detection is valuable.

Normal Detection

The normal detection provides a better visual display of random noise than peak and avoide the missed-signal problem of the sample mode.
The normal detection algorithm:

```
If the signal rises and falls within a bucket:
   Even numbered buckets display the minimum (negative peak)
```

```
    value in the bucket. The maximum is remembered.
    Odd numbered buckets display the maximum (positive peak)
    value determined by comparing the current bucket peak with
    the previous (remembered) bucket peak.
If the signal only rises or only falls within a bucket, the peak
is displayed.
```

Peak detection is best for locating CW signals well out of the noise, sample detection is best for looking at noise, and normal detection is best for viewing signals and noise.

Average Detection

While spectrum analyzers usually collect amplitude data many times in each bucket, sample detection keeps only one of those values and throws away the rest. An averaging detector uses all the data collected within the time (and frequency) interval of a bucket. Averaging detector is usually referred to as Root Mean Square (RMS) detector when it averages power (based on the RMS of voltage). Average detection is an improvement over using sample detection for the determination of power. Sample detection requires multiple sweeps to collect enough data points to give us accurate average power information.

3.3 Summary

This chapter has presented the basic operating principles of a superheterodyne spectrum analyzer, also referred to as swept-tuned spectrum analyzer. This kind of spectrum analyzer constitutes the key element of the measurement setup employed in this work to measure and characterize the degree to which spectrum is currently used. Therefore, it becomes necessary to have a general picture of spectrum analysis basics for a better understanding of the material presented in next chapters, especially in the areas of configuration parameters and obtained results.

Chapter 4

Measurement Setup

There are many factors that need to be considered when defining a strategy to meet a particular radio spectrum occupancy measurement need. There are some basic dimensions that every spectrum occupancy measurement strategy should clearly specify, namely frequency (frequency span and frequency points to be measured), location (measurement site selection), direction (antenna pointing angle), polarization (receiving antenna polarization) and time (sampling rate and measurement period). The measurement setup employed in the evaluation of spectrum occupancy should be designed taking into account the previous factors since they play a key role in the accuracy of the obtained results. In the next sections we will describe the measurement scheme employed with detailed information about every component, the Spurious Free Dynamic Range (SFDR), the locations and the measurement method.

4.1 Measurement scheme

The measurement setup should be able to detect, over a wide range of frequencies, a large number of transmitters of the most diverse nature, from narrow band to wide band systems and from weak signals received near the noise floor to strong signals that may overload the receiving system. Our study is based on a spectrum analyzer setup where different external devices have been added in order to improve the detection capabilities of the system and hence obtain more accurate and reliable results. A simplified scheme of the measurement configuration is shown in Figure 3.1. The design is composed of:

- two broadband antennas;
- a switch to select the desired antenna;

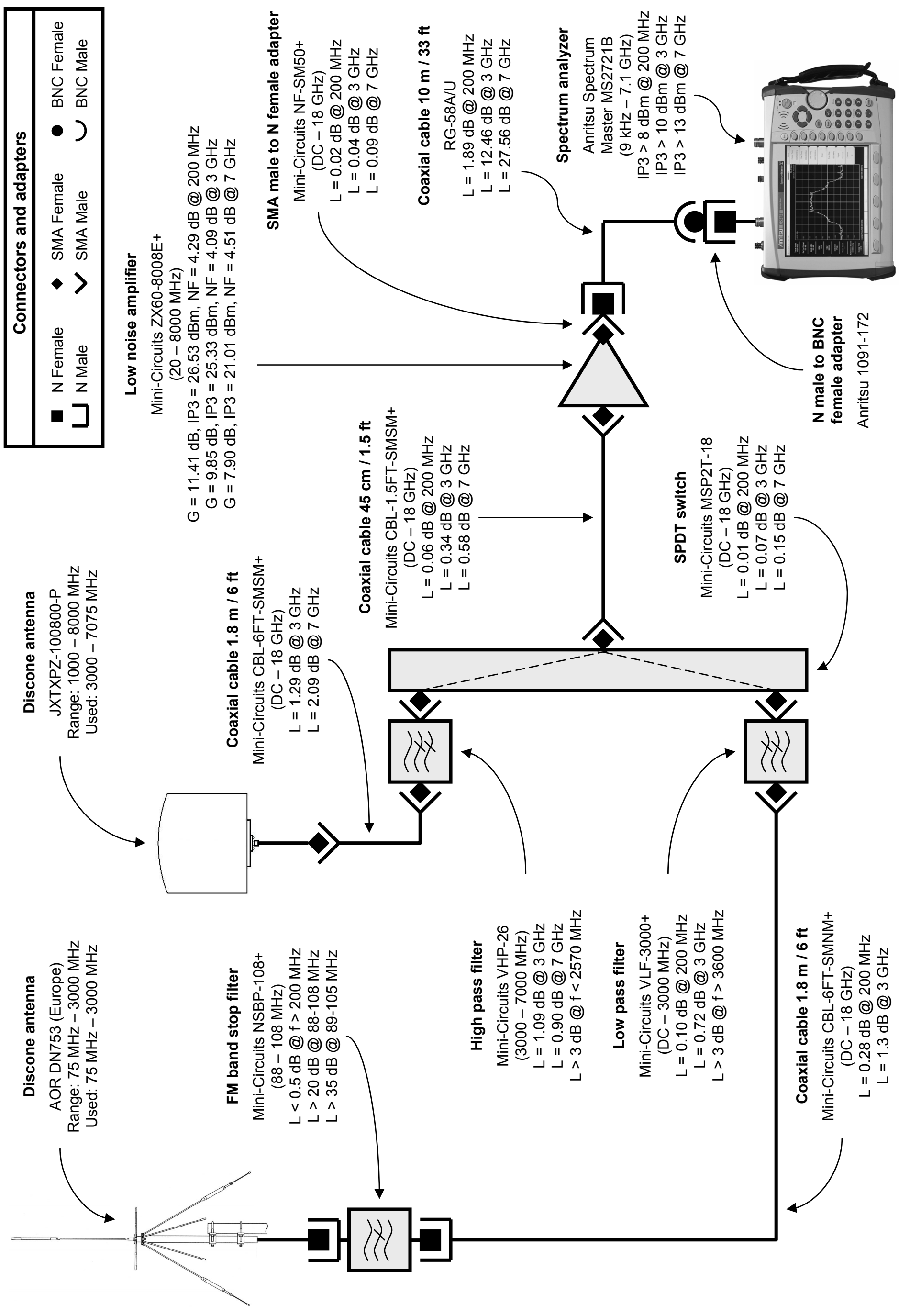

Figure 4.1: Measurement Scheme.

- several filters;
- a low noise amplifier;
- high performance spectrum analyzer.

In the next subsections we will see the technical characteristics of every component and we will explain their role in the measurement setup.

4.1.1 Antennas

When covering small frequency ranges or specific licensed bands a single antenna may suffice. However, in broadband spectrum measurements from a few megahertzs up to several gigahertzs two or more broadband antennas are required in order to cover the whole frequency range. Most of spectrum measurement campaigns are based on omni-directional measurements in order to detect primary signals coming for any directions. To this end, omni-directional vertically polarized antennas are the most common choice. Our antenna system comprises two broadband discone-type antennas, which are vertically polarized antennas with omni-directional receiving pattern in the horizontal plane. Even though some transmitters are horizontally polarized, they usually are high-power stations (e.g., TV stations) that can still be detected with vertically polarized antennas. The antennas employed in the measurement were:

- AOR DA753G Compact Discone Aerial; vertically polarized, designed to receive across the frequency range of 75MHz to 3000MHz (3GHz) and with an impedance of 50Ω [7].
- JXTXPZ-100800/P 1.0 8.0GHz Discone-type Antenna; vertically polarized, designed to receive the frequency range of 1GHz to 8Ghz and with an impedance of 50Ω [1].

4.1.2 Filters

The filters employed in our setup are:

- high-pass filter Mini-Circuits VHP-26 with pass-band 3000-7000 MHz [17];
- low-pass filter Mini-Circuits VLF-3000+ with pass-band DC-3000 MHz [10];
- a band-stop filter Mini-Circuits NSBP-108+ with stop-band 88108 MHz [11];

The high-pass and low-pass filters are employed to remove out-of-band signals which may induce desensitization and intermodulation interference. In fact when wireless transmissions operate in close proximity to each other in the frequency domain, there exists the potential for these signals to interact. This interaction can negatively impact the ability of the spectrum analyzer to measure the desired signal. By identifying the spectral characteristics of the signals located within a frequency range of interest, it is possible to classify the type of interference expected [5]. Five types of interference that could exist between the measured signal and powerful signals are shown in Figure 4.2. The differences between each of these types of interference are based on the relative frequency spacing between the two transmissions, and their relative transmission power levels. For instance, when the measured signal spectrum is located at channel n, and the powerful signals are also located at the same channel, this is referred to co-channel interference. Filtering has no effects on this type of interference. Another type of interference can occur if the powerful signals are located in an adjacent channel, such as channel n +1. In this case, the measured signal may experience adjacent channel interference from the powerful signals since the transmitted spectrum of the latter may not be totally confined to its allocated band. Note that as the amplitude level of the powerful transmission is increased, so does the amount of out-of-band radiation that could interfere with the primary signal. If the powerful signals are located further away from the signal that we want to measure, such as the second adjacent channel, the impact of adjacent channel interference is substantially reduced, relative to powerful signals operating closer to the desired signal, given the same power levels. However, if the power level of the powerful signals is increased, it is possible that some out-of-band radiation may interfere with the primary signal. In fact, when the powerful signals are substantially stronger than the signal we want to measure and are located in the vicinity of a desired frequency, desensitization interference can potentially occur. In this scenario, the powerful signals overloads the spectrum analyzer, inhibiting its ability to measure weak signals. Receiver intermodulation interference occurs when two or more signals are present within the same frequency range that are mixed in a receiver RF amplifier or mixer stage during non-linear operation, producing a signal that interferes with a desired signal. Consequently, these receiver-generated signals could prevent the measurement of the desired signal.

Usually the received power at low frequencies is higher than at high frequencies; anyway it is more safe to employ both filters to guarantee that no interference is present in the measurement system. The band-stop filter is employed to eliminate the 87.5-108 MHz band, because in our measurement scenario there is a very powerful Frequency Modulation (FM) transmission that was found to produce saturation in the spectrum analyzer and reduce the dynamic range. Since the FM band 87.5-108 MHz is of low interest for secondary usage (high occupancy and high transmission power) we filter this band in order avoid any potential problems.

4.1.3 Switch

The switch employed in our scheme was Single Pole Double Throw (SPDT) switch Mini-Circuits MSP2T-18 [12] that can be used in the DC-18 GHz frequency range. The function of the switch is to select what antenna we want to use without the need of changing the setup manually. The switch employed is a SPDT that is a switch with one output that can be connected to one of the two inputs while the other one is isolated. This device requires a power supply of 24V Direct Current (DC). When the switch is not fed the low-frequency (75-3000 MHz) antenna is selected while when it is fed the high-frequency (3000-7000 MHz) antenna is selected.

4.1.4 Pre-amplifier

In our measurement setup the antenna is connected to the spectrum analyzer by means of a 10-meter coaxial cable. This cable introduces relevant losses which make the detection of weak signals difficult. To compensate for this losses and to improve the capabilities of our system we could use the built-in high-gain pre-amplifier of the spectrum analyzer. Nevertheless, due to the high length between the antenna and the built-in pre-amplifier a better option is to place a external low-noise pre-amplifier right after the antenna system. To reach this conclusion four possible configurations have been analyzed:

- without external pre-amplifier and without internal pre-amplifier;
- without external pre-amplifier and with internal pre-amplifier;
- with external pre-amplifier and without internal pre-amplifier;
- with external pre-amplifier and with internal pre-amplifier;

For every configuration the noise figure has been calculated using the parameters of every component. The best configuration is the one with external pre-amplifier and with internal pre-amplifier. In Table 4.1 we report the results of the calculation of the noise figure for the selected configuration: the upper 3 GHz value is in the upper-limit of the low-frequency branch of the measurement setup, while the lower 3 GHz value corresponds to the lower-limit of the high-frequency branch of the measurement setup. The high **NF!** (**NF!**) value observed at FM is due to the high attenuation introduced by the FM band, while the high NF value at 7 GHz is due to the high attenuation introduced by the 10-meter cable at high frequencies.

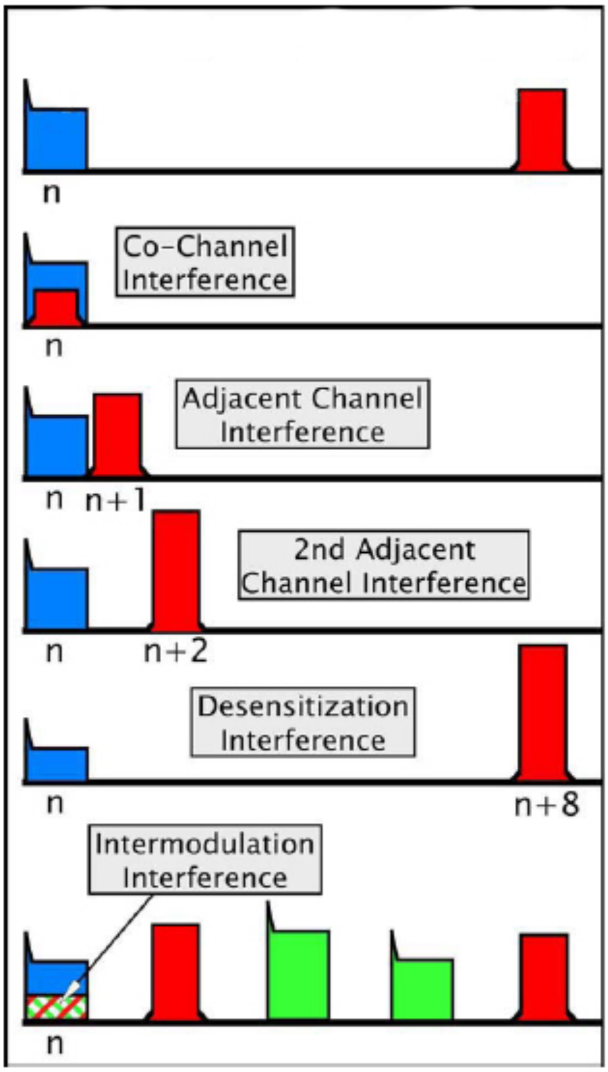

Figure 4.2: Types of interference.

	NF [linear]	NF [dB]
FM	302.34	24.80
200 MHz	3.39	5.30
3 GHz	8.48	9.28
3 GHz	8.21	9.14
7 GHz	233.26	23.68

Table 4.1: Noise Figure results for the adopted configuration.

In our setup we have utilized a *Mini-Circuits ZX60-8008E+* [8] amplifier with a frequency range from 20 MHz to 8 GHz. It is worth noting that choosing an amplifier with the highest possible gain is not always the best option in broadband spectrum surveys, where very different signal levels may be present. The existing tradeoff between sensitivity and dynamic range must be taken into account. To choose the correct preamplifier, we must look at our measurement needs. If we want absolutely the best sensitivity and are not concerned about measurement range, we would choose a high-gain, low-noise pre-amplifier. If we want better sensitivity but cannot afford to give up any measurement range, we must choose a lower-gain pre-amplifier. A reasonable design criterion is to guarantee that the received signals lie within the overall systems SFDR, which is defined as the difference between a threshold or lower limit at which signals can be detected without excessive interference by noise (constrained by the systems noise floor) and the input level that produces spurs at levels equal to the noise power. If the maximum level is exceeded, some spurs might arise above the systems noise floor and would be detected as signals in truly unoccupied bands, thus resulting in inaccurate results and erroneous conclusions about the primary activity.

4.1.5 Spectrum Analyzer

The spectrum analyzer is the main component of the measurement setup. In the first chapter we described the general operation of a super-heterodyne spectrum analyzer. The one we utilized for our measurements is a Anritsu Spectrum Master MS2721B [4]. It is a high-performance handheld spectrum analyzer with frequency range from 9 KHz to 7.1 GHz, low noise floor (Displayed Average Noise Level (DANL) of -163dBm with a Resolution BandWidth (RBW) of 1kHz) that permits a reliable detection of weak signals. It has tunable RBW and Video BandWidth (VBW) from 1 Hz to 3MHz. The sweep speed is automatically changed by the analyzer to the fastest sweep speed that will yield accurate results. It has an internal pre-amplifier and the possibility to store the measured data into an external Universal Serial Bus (USB) device, that permits a more comfortable data analysis.

4.1.6 Other components

To connect the antennas, the spectrum analyzers and the amplifier we use several cables and connectors. Following there is a list of the components utilized in our measurement scheme.

- Test Cable CBL-1.5FT-SMSM+ [13]; used to connect the switch with the pre-amplifier.
- Test Cable CBL-6FT-SMSM+ [15]; used to connect the discone antenna JXTXPZ-100800-P to the switch.
- Test Cable CBL-6FT-SMNM+ [14]; used to connect the discone AOR DN753 antenna to the switch.
- Test Cable RG-58A/U [16]; used to connect the pre-amplifier to the spectrum analyzer.
- Coaxial Adapter N male to BNC female NF-SM50+ [9] used to connect the coaxial cable to the spectrum analyzer.
- Coaxial Adapter SMA male to N female NF-SM50+ [9] used to connect the pre-amplifier to the coaxial cable.

4.2 Spurious Free Dynamic Range (SFDR)

As previously explained the SFDR is defined as the difference between the power of signals that generate spurious responses and the power of the noise floor at the input. It is necessary to calculate the SFDR to guarantee that the received signals will not exceed the maximum allowed level; if this happened, then the measurement setup might work in non-linear regime, thus yielding to spurious responses.

To calculate the SFDR we use the following equations:

$$SFDR(dB) = \frac{m-1}{m}[IP_i(dBm) - P_{N_i}(dBm)]$$

with $m = i = 3$, where P_{N_i} is the noise power and the IP_i is the intercept point of order i. Here we consider the third-order intercept point because it is the more constraining one. The calculation of the total SFDR has been made splitting our setup scheme into two quadripoles: the first one includes the antenna, the filters, the switch, the coaxial cable, the amplifier and the adaptor; the second one includes the coaxial cable, the adaptor and the spectrum analyzer. To calculate the noise power we could use the following equation:

$$P_{N_i} = KT_0FB_N;$$

	IP3 [linear]	IP3 [dBm]	Noise [dBm](RBW=10 KHz)	SFDR [dB]	P_{max} [dBm]
FM	78.70	18.96	-82.40	67.57	-14.83
200 MHz	0.87	-0.62	-105.10	69.65	-35.45
3 GHz	23.90	13.78	-95.42	72.80	-22.62
3 GHz	23.14	13.64	-95.56	72.80	-22.76
7 GHz	47.69	16.78	-69.12	57.27	-11.85

Table 4.2: SFDR at various frequencies for the measurement setup.

where $K = 1.38 \cdot 10^{-23} J \cdot K^{-1}$ is Boltzmann's constant, $T = 290K$ is temperature, $B_N = 10KHz$ is the resolution bandwidth and F is the noise figure. It is necessary to include the noise figure in this equation because the maximum value of power that we are looking for is referred to the input of the measurement setup while the noise power $P_N = KTB$ is referred only to the input of the spectrum analyzer. So to obtain the noise power at the input we must include the noise figure of the whole setup. To be more accurate we have to consider that the thermal noise is not the only source of noise, as explained in the previous chapter. If we substitute the antenna with a 50Ω load we obtain at the display the DANL that is the equivalent noise floor at the input. If we comparate the noise floor with the calculated thermal noise we notice that the first one is greater. In the end to calculate the maximum noise power of our system we use the DANL of the spectrum analyzer at various frequencies, because the DANL includes all potential noise sources present in the equipment (including amplifier noise, oscillator phase noise, etc.), and we multiply it (in linear scale) by the noise figure of the whole system (which is also different at various frequencies). For calculating the intercept point of third order we use the following equation:

$$\left(\frac{1}{IP_{i,tot}}\right)^q = \left(\frac{1}{IP_{i,1}}\right)^q + \left(\frac{G_1}{IP_{i,2}}\right)^q + ... + \left(\frac{G_1 G_2 ... G_{M-1}}{IP_{i,1}}\right)^q.$$

with $q = \frac{m-1}{2}$. The calculation has been done for the two quadripoles and then for the entire quadripole at various frequencies. In table 4.2 we report the results of the SFDR calculation, which were proven to satisfy the dynamic range required in practice at our measurement location..

4.3 Measurement scenario

We performed our measurements in the Campus Nord of UPC (Universitat Politècnica de Catalunya) in Barcelona, Spain. The location of the measurement is shown in Figure 4.3. The measurements of the spectrum have been performed over 25 distinct points forming a regular grid of 5x5 (five rows of points, each row having five points). The distance between two consecutive points was 15 meters. Nevertheless the geometry of our measurement site

Figure 4.3: Campus Nord of UPC.

did not allow us to perform the measurement of each point of such grid because two points (precisely the first and the last point of the fifth row) were not reachable by our equipment. Instead we analyzed two other points placed at a much longer distance respect to the step size, in order to have a wider range of distances for the calculation of the metrics (see Figure 4.3, points 24 and 25).

Differently from other spectrum measurement campaigns, see [18] and [20], in which two identical equipments were used simultaneously in order to determine the correlation between spectral occupation in different points, we had at our disposal only one measurement equipment. So we measured a point for each day of the week with the exception of the weekends because

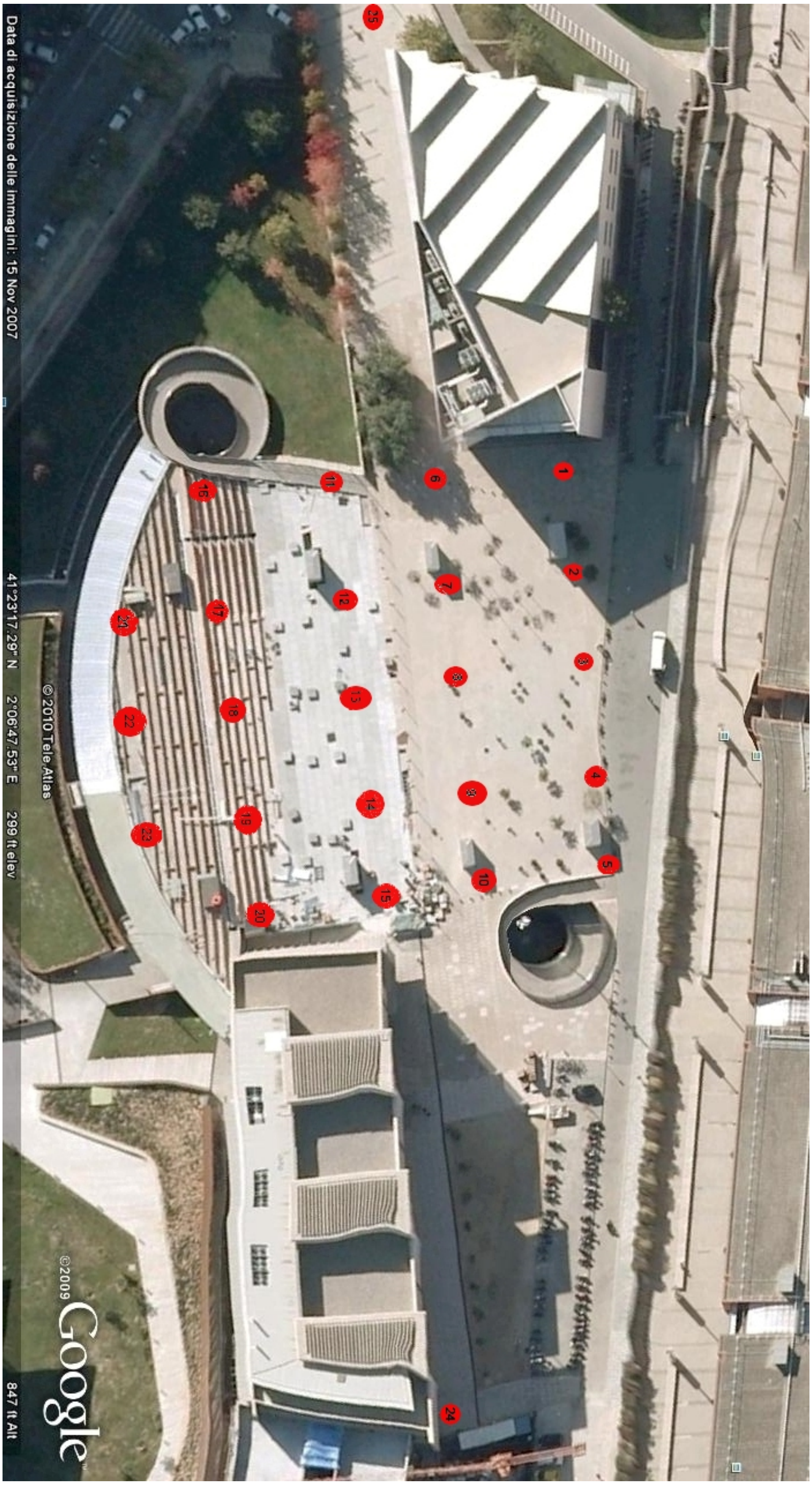

Figure 4.4: Location of the measurement points.

	Parameter	**Value**	
Frequency	Frequency Range	1800-1880 MHz	1880-2290 MHz
	Frequency Span	45-600 MHz	
	Frequency bin	81.8-1090.9kHz	
	Resolution BandWidth (RBW)	10KHz	
	Video BandWidth (VBW)	10kHz	
Time	Measurement Period	8 hours/5 days	
	Sweep time	Auto	
Amplitude	Built-in Preamplifier	Deactivated	
	Reference Level	-20dBm	
	Reference Level Offset	0dB	
	Scale	10 dB/division	
	Input Attenuation	0dB	
	Detection Type	Average RMS Detector	

Table 4.3: Spectrum analyzer configuration.

the traffic conditions of the cellular network could have been very different respect of the other days, affecting the results.

4.4 Measurement methodology

The spectral analysis of each point was divided in two parts, each one of the duration of four hours. The first part was taken in the morning (from 9.00 to 12.00) and the second one in the afternoon (from 14.00 to 18.00). In this two parts different bands were measured:

- in the first part the 1800-1880MHz band was measured. This band is mainly used by *DCS 1800 downlink* service;
- in the second part the 1880-2280MHz band was investigated. In this band several services are active: *DECT*, *UMTS TDD*, *UMTS FDD*, *UMTS sattelite* and for *Point to Point fixed links*.

As the frequency bands we chose to analyze could be measured by a single antenna we used the Compact Discone Aerial, with a frequency range from 75MHz to 3000MHz [7]. In table 4.3 the spectrum analyzer configuration is shown, while in Figure 4.5, 4.6 and 4.7 the elements of our measurement equipment are shown.

Our campaign was focused on cellular bands. As we wanted to measure primary signals we chose to investigate the occupation of those services that present an high level of spectrum occupancy. In this manner we can account on a big number of signal samples. If we decided to measure band with lower occupation levels, the number of signal samples would have been

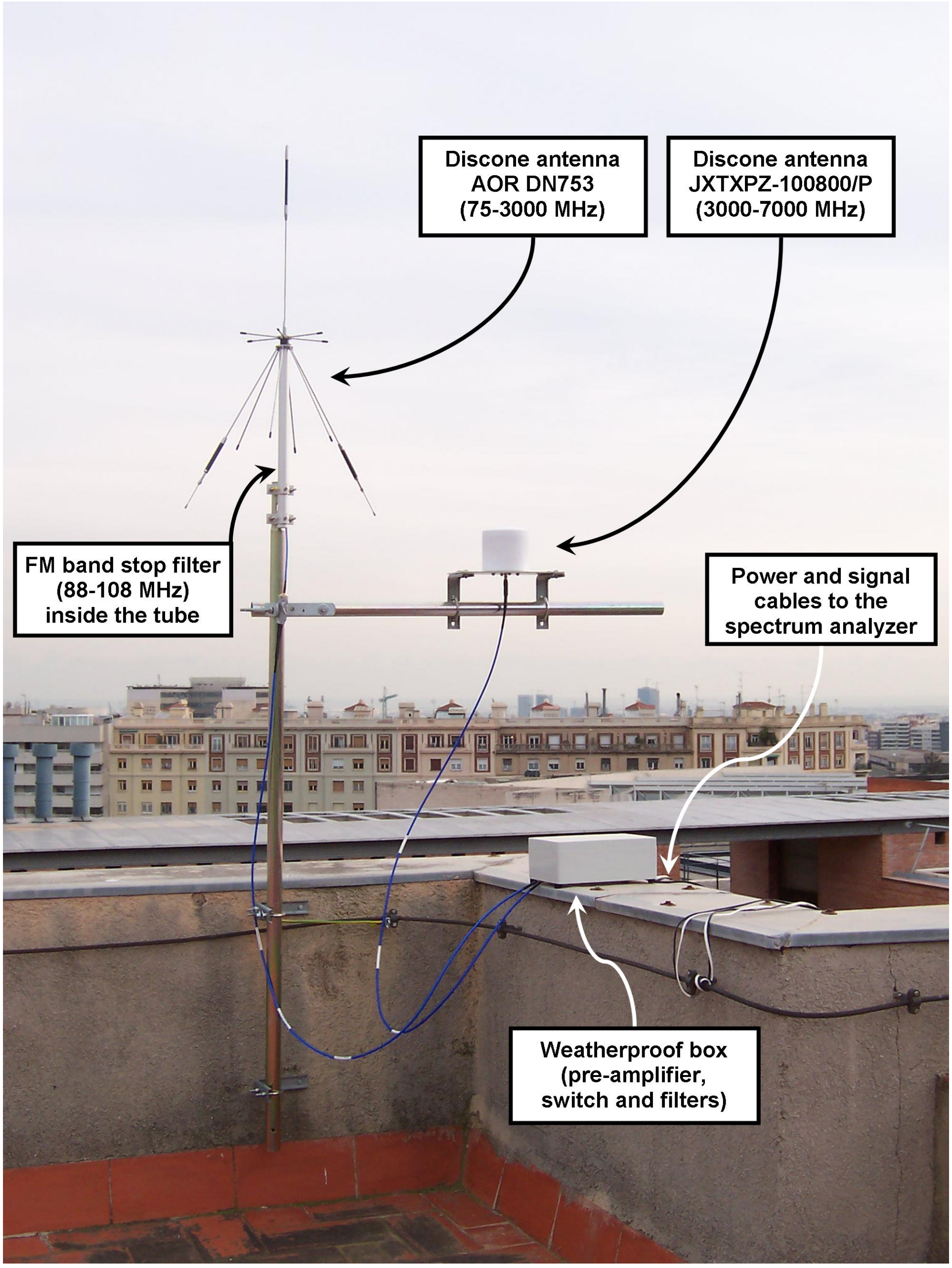

Figure 4.5: Measurement setup available at UPC (Antenna subsystem).

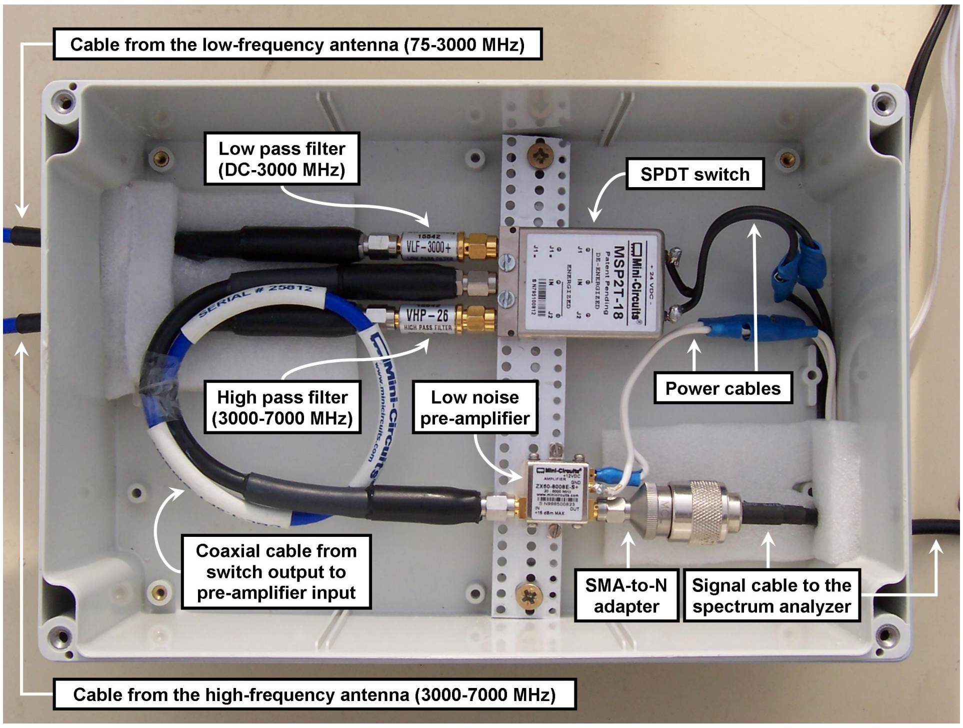

Figure 4.6: Measurement setup available at UPC (RF subsystem).

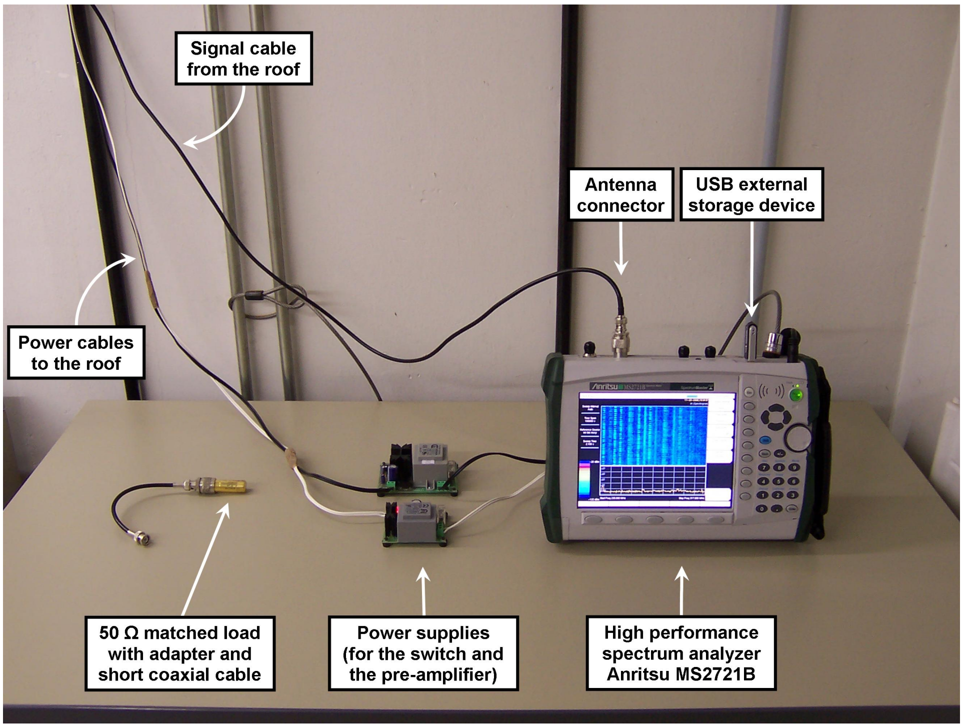

Figure 4.7: Measurement setup available at UPC (spectrum analyzer).

lower within the same measurement period. Moreover this choice permitted us to perform our measurement campaign in a relatively small are. If we considered for example TV bands, which are also subject to an intensive usage (TV channels are active 100% of the time), due to the large coverage area of TV transmitters and their high power level, we would have to perform our study over a large area, in the order of several square kilometers. The selected bands therefore allow us to capture a high number of primary signal samples within practical measurement periods in a practical reduced area.

At the end of every measurement the data were saved in a USB pen and post-processed offline with MATLAB and appropriate analysis scripts that were developed to this end.

4.5 Summary

In this chapter we described every component of the equipment used to perform the spectrum occupancy measurement. We also illustrated the criteria used to find the optimal configuration for our needs, i.e. the analysis of the SFDR. We showed the site where the campaign was carried out, the frequency bands measured and the methodology that we used to perform the measurement campaign.

Chapter 5

Measurement Results

5.1 Introduction

In this chapter we discuss the results obtained from the analysis of the data of our measurement campaign. First we take a look at the spectral occupation of the measured bands. Then we introduce and describe the correlation metrics used to analyze the data. After that we illustrate the results obtained applying these metrics to our data and explain the observed behavior.

5.2 Spectral occupancy

Before introducing the main results we give a look to the spectral occupancy results obtained in our measurement campaign. We analyzed the 1800-1880 MHz band and the 1880-2290 MHz band, which comprise the DCS and the UMTS, respectively. There are several reasons that support our decision to analyze these spectrum bands. The main objective is to analyze spectrum occupancy and its correlation. In order to obtain reliable estimates of the spectral occupancy and its correlation, it is necessary to capture a sufficiently high number of primary signal samples. If we select channels with low occupancy levels, most of the captured samples would correspond to noise, meaning that the measurement sessions would then need to be extended to long measurement periods in order to capture a high number of signal samples. By selecting channels with high occupancy levels, the measurement period required to capture a sufficiently high number of primary signal samples then reduces to feasible values. Although some parts of the selected bands remain unused, the channels being actually used in such bands are, in general, subject to significant occupancy levels. According to this criterion, it would also be possible to select TV bands, since the channels employed in the TV bands are used virtually 100% of the time. However, in this case it is important to note that TV transmitters are normally intended to provide large coverage areas and, as a result, spectrum occupancy is expected to be correlated over large areas, meaning that the measured locations should be separated by long distances. Mobile communication systems, on the other hand, are intended for much lower coverage areas and, as result, a shorter separation among measured points is required to observe correlation variations over space. By selecting mobile communication bands, it is possible to carry out our correlation study within more practical geographical regions.

To analyze the spectral occupation we used three main metrics: the minimum, maximum and average Power Spectral Density (PSD), the instantaneous spectral occupancy and the duty cycle, as shown in Figures 5.1 and 5.2. In each figure, the upper graph shows the minimum, maximum and average PSD measured as a function of frequency. The middle graph shows the temporal evolution of the spectrum occupancy during the 4-hours measurement periods. A black dot indicates that the corresponding frequency point was measured as occupied at that time instant, while the white color means that the frequency point was measured as idle. To determine whether a given frequency was occupied or not, energy detection was employed. Different sensing methods have been proposed in the literature to detect whether a frequency band is being used by a licensed user. They provide different trade-off between required sensing time, complexity and detection capabilities. Depending on how much information is available about the signal used by the licensed network different performances can be reached. However, in the most generic case no prior information is available about the licensed signal. In such a case, the energy detection method is the only possibly left. Energy detection compares the received signal energy in a certain frequency band to a predefined threshold. If the signal is above the threshold, the band is determined to be occupied by the licensed network. Otherwise the band is supposed to be idle and could be used by a Cognitive Radio Network (CRN). Following this principle, the measured PSD is compared to a given threshold. Measured samples above the threshold are assumed to be occupied; the rest of frequencies are assumed to be idle. To compute the decision threshold, the antenna was replaced by a matched load of 50Ω in order to measure the system's noise. At each frequency point the decision threshold was fixed such that the only 1% of the measured noise samples lied above the threshold, which implies a false alarm probability of about 1%. It is worth noting that the decision threshold obtained with this method is not constant since the system noise floor slightly increases with the frequency. Finally the lower graph in each figure shows the duty cycle or percentage of time that each frequency point is measured as occupied by a licensed signal. The average duty cycle over the whole spectrum block is also shown.

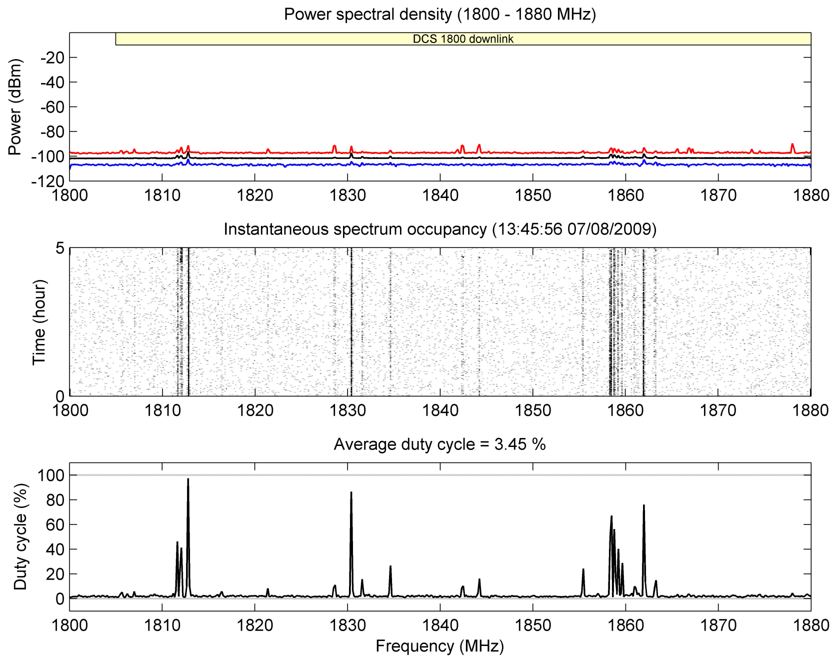

Figure 5.1: Occupation results between 1800 and 1880MHz for location 1.

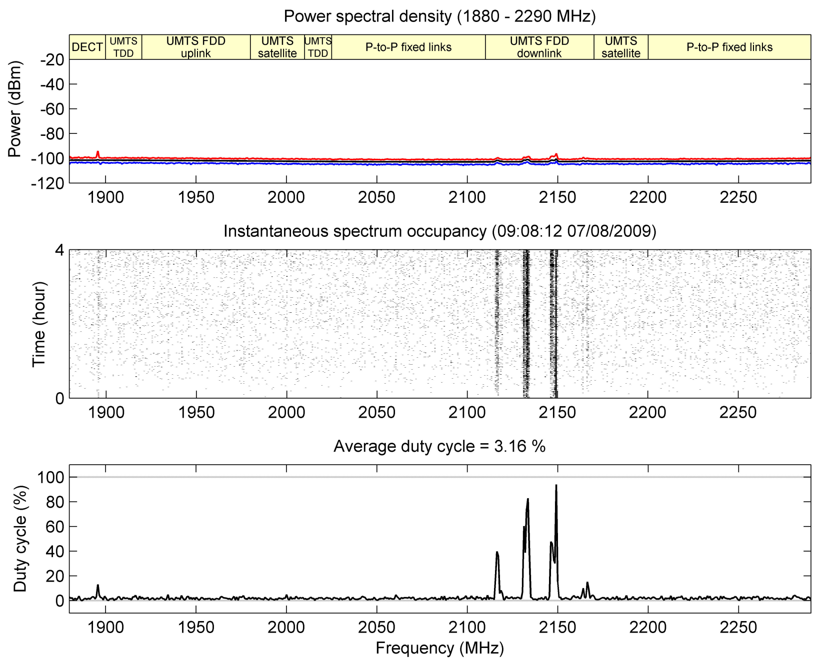

Figure 5.2: Occupation results between 1880 and 2290MHz for location 1.

5.2.1 Analysis of Spectrum Occupancy

The occupancy results shown in Figures 5.1 and 5.2 refer to a specific measurement location that we named *location 1* and that is marked in Figure 4.3 with the number *1*. The results obtained in the other measurement points do not present important differences from the spectrum occupancy point of view. So we briefly analyze here the results obtained in *location 1* assuming that the conclusions are valid for all the measurement points. Nevertheless the occupancy results are shown just to give a general idea about occupancy in these bands; more accurate results can be found in [21] and [6].

The 1800-1880 MHz band is almost completely dedicated to the mobile cellular communication system DCS-1800. This frequency block is used by Global System for Mobile Communications (GSM) mobile phones in downlink. Despite the fact that the average duty cycle is low there are some frequencies that are subjected to intensive usage during all the measurement period. The 1880-2290 MHz band is used by various services: they generally show a low occupation. The most significant utilization of this band is done by the UMTS technology, in particular for the frequency slot reserved for FDD downlink. We notice that other blocks reserved to UMTS and DECT remain in practice unused. We conclude that spectrum usage is rather inefficient because even if some services present an intensive activity on certain frequencies, most of the band assigned presents low usage. This means that from a practical point of view other new services and operators could be allowed to make use of spectrum, since there exists free capacity in reality. The main obstacle is the fixed and restrictive allocation spectrum access policies employed, which prevent unlicensed users to access allocated spectrum bands, even if the licensees are not making use of the spectral resources.

From our point of view we are interested in those frequencies that exhibit an high occupation, since they can be used to study some characteristics of spectrum occupation. Therefore we selected some frequencies from each band in order to carry out the calculation of the metrics described in the following sections. The frequencies that have been chosen are:

- **1800-1880 MHz**: f_1 = 1812 MHz; f_2 = 1830 MHz; f_3 = 1859 MHz.
- **1880-2290 MHz**: f_1 = 2117 MHz; f_2 = 2132 MHz; f_3 = 2147 MHz; f_4 = 2166 MHz;

The graphs in Figures 5.3 and 5.4 show, for DCS and UMTS, the values of mean PSD for one of the frequencies listed above as function of the location where the measure was taken.

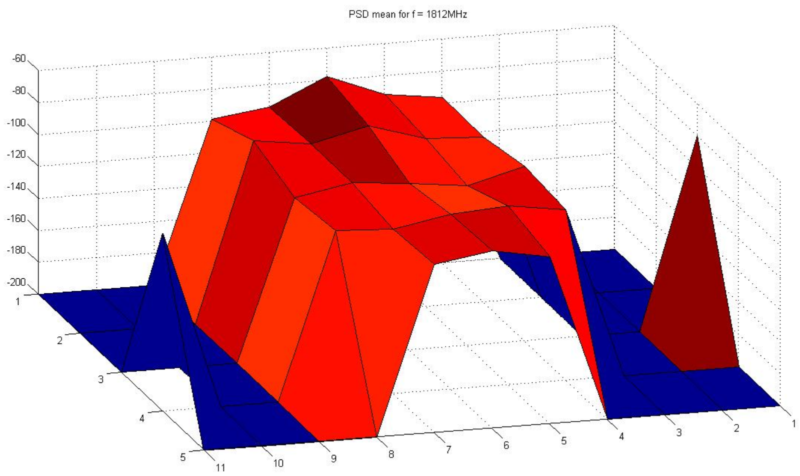

Figure 5.3: Values of the mean PSD for f=1812 MHz as function of the location of the measurement point. The distribution of the points in this figure corresponds to the measurement locations shown in Figure 4.3.

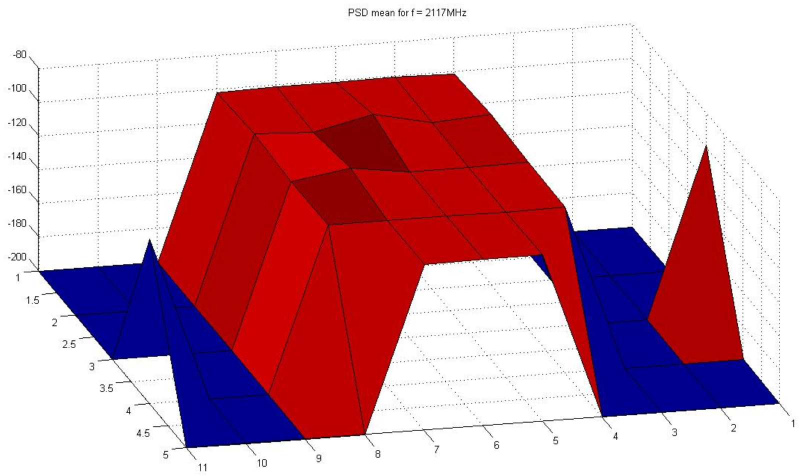

Figure 5.4: Values of the mean PSD for f=2117 MHz as function of the location of the measurement point. The distribution of the points in this figure corresponds to the measurement locations shown in Figure 4.3.

5.3 Evaluation Criteria

Given the results of the measurement campaign, our aim was to investigate the behavior of the spectral occupancy as function of the distance by the calculation and the comparison of appropriate metrics. Before introducing these metrics, and to understand the reasons behind this choice, in the following we give a brief introduction about spatial statics and its relation with cooperative sensing.

5.3.1 Cooperative sensing and spatial statistics

In chapter 2 we gave an introduction to cognitive radio. The main idea of Congitive Radio (CR) is to permit its users to access those parts of the spectrum licensed to other services but that are temporarily unused. As soon as a primary user (an user who has a license to operate in the band considered) shows up, CR user immediately vacates the spectrum and moves to another free location. In this context it is clear that detection of the primary users by CR is a fundamental task, in order to avoid harmful interference with licensed users. This task takes the name of *spectrum sensing*. However there are several scenarios in which a single secondary user is likely to miss a primary transmission and mistakenly assumes a spectrum band to be free. As previously told in section 2.4.1, several methods have been proposed to ensure a reliable detection. One of the most interesting detection methods, due to its ability to overcome practical spectrum sensing limitations, is *cooperative sensing*. The basic idea behind cooperative sensing is that if two or more CR users, located in the area of the same primary network, exchange each other their information about spectral occupation, then their probability to take a right decision is increased. This method helps to prevent detection errors of primary users that might be caused by various problems, among which the most important are the hidden terminal problem and fading and shadowing effects.

In the hidden terminal problem the secondary user is either too far away from the primary transmitter or the signal is attenuated because of buildings or other obstacles in the propagation path. This could lead a CR user to consider free a frequency that is actually used. The use of cooperative sensing coupled with the presence of another secondary user that that does not suffer from the same problem can avoid this kind of situations.

Fast fading may cause a severe drop in the received signal and and hence a missed detection. Cooperative sensing can help to solve this problem because fast fading is only correlated over distances of the order of the used wavelength. The case of shadowing is more complicated because shadowing is correlated over longer distances. There are several studies on the characteristics of these correlations, but they have been developed in the context of cellular networks and therefore present several drawbacks when applied to DSA networks. As a consequence, more suitable statistical models are needed for better understand the spatial behavior of spectrum utilization. More in general, the analysis of several aspects of DSA systems requires good spatial models of spectrum usage: the development of this aspects will receive a great benefit from the development of a spectrum model with the possibility to generate synthetic data for testing purposes.

In this context we focused our attention on the spatial correlation of the spectral occupancy. Differently from the work in [20], in which two points were measured simultaneously, our equipment allowed us to measure just one single location per measurement session. Therefore our analysis could not be based on instantaneous PSD, because the data were taken sequentially at different times. Instead we considered the average PSD obtained during the measurement period. We considered only the frequencies cited in the previous section as they presented a high occupation and therefore ensure more reliable results.

5.3.2 Correlation metrics

Before introducing the metrics used we give a short explanation of the method used to treat the gathered data. In section 4.3 we explained that the measurements of the spectrum have been performed over 25 distinct points forming a regular grid of 5x5 (five rows of points, each row having five points). At the end of the campaign for each point measured we had information about the instantaneous power spectral density during the time that the measure was performed. The locations on which we performed our measurement formed a regular grid (with the exception of two points), with a step of 15 meters. As showed in Figure 4.3 we marked each point with a number. The following step was to group all pair of locations having the same distance. For example, if we consider a 15 meters length, we have to group location 1 and 2, location 2 and 3, location 4 and 5 and so on, that is all the pairs of points 15 meters apart from each other. We did this for each distance that we could find from the grid. In the calculation of the pairs of points far-between the same length we used a binning procedure: we considered two pairs of points to belong to the same set if $h-\Delta \leq \| x_j - x_i \| \leq h+\Delta$ where we h denotes the length considered, $\| x_j - x_i \|$ the distance between the two points and Δ an appropriate margin included in order to group points that are separated by a similar, but not exactly the same, distance. In this way we also assured vectors to have a significant number of elements. Therefore, for each considered length, we could create two vectors $\mathbf{U}(h)$ and $\mathbf{V}(h)$. These vectors contained the average PSD of all the pairs of points for the considered length h. For example, previously we considered a 15 meters length: in this case the first element of vector $\mathbf{U}$ was the average PSD measured in location 1. The corresponding element (that is the one having the same index) for the vector $\mathbf{V}$ was the average PSD of the location

2. Therefore, each couple of points having the same distance were placed in the same position/index within the two vectors. In the following we present the employed correlation metrics.

Cross correlation

The cross-correlation between two independent processes is defined as

$$R(\mathbf{U}, \mathbf{V}) = \frac{1}{N_s} \sum_{t=1}^{N_s} U_t \cdot V_t \tag{5.1}$$

where N_s is the number of samples, $\mathbf{U}$ and $\mathbf{V}$ are the vectors to be compared, and U_t and V_t are their components, respectively. In our case $\mathbf{U}$ and $\mathbf{V}$ correspond to the vectors previously defined, containing the average PSD of the pairs of points located at a certain distance.

Covariance

The covariance is obtained from the cross-correlation by subtracting from each vector its mean (which is the average of the various mean powers)

$$\text{cov}(U, V) = \frac{1}{N_s} \sum_{t=1}^{N_s} (U_t - \overline{U}) \cdot (V_t - \overline{V}) \tag{5.2}$$

where $\overline{U}$ and $\overline{V}$ denote the average of the vectors U and V, respectively.

Normalized covariance

The covariance is often extended by normalization:

$$\rho(U, V) = \frac{1}{N_s} \sum_{t=1}^{N_s} \frac{U_t - \overline{U}}{\sigma_U} \cdot \frac{V_t - \overline{V}}{\sigma_V} \tag{5.3}$$

where σ_U and σ_V are the standard deviations of the vectors U and V, respectively.

Semivariance

The empirical semivariance is described as

$$\widehat{\gamma}(h) = \frac{1}{2|N(h)|} \sum_{t=1}^{N_s} (U_t - V_t)^2 \tag{5.4}$$

where we denote with $|N(h)|$ the cardinality of the vector U (or equivalently V), where we emphasized the dependence by the distance h. A plot of semivariances versus distances between ordered data in a graph is known as a semivariogram.

5.4 Results

5.4.1 Correlation metrics vs. distance

In Figure 5.5, 5.6, 5.7 and 5.8 we show the metrics calculated for the selected frequencies of DCS band. In Figure 5.9, 5.10, 5.11 and 5.12 we show the metrics calculated for the selected frequencies of UMTS band.

Previous studies suggest that the expected behavior for cross-correlation, covariance and normalized covariance is to decrease as the distance increases, while we expected the semivariance to increase with distance. The results obtained with our data do not show in general a well defined trend. In some cases, as for example the cross-correlation in Figure 5.5, the cross-correlation seems to increase with the distance, that is the opposite behavior with respect to the expected one. As the shape of the metrics graphs could be due to a few pairs of points having an abnormal behavior (that might happen, for example, if during the measurement our equipment was subject to some noise source causing an alteration in the measured PSD) we analyzed the computed graphs. We checked for each distance that the values considered, that is, using the above notation, the products $U_t \cdot V_t$ for each value of t, lied near the average. If we had found some couples of points laying far away from the average then we could explain the strange behavior of the correlation metrics. As in our analysis we did not find any anomaly we concluded that the correlation metrics as a function of the distance had a random behavior. The more likely hypothesis explaining the random behavior versus distance is that different locations separated by the same distance may experience significantly dissimilar primary signals. The primary power level observed at each location is the result of the constructive/destructive combination of all the primary signal components received through different propagation paths, which depend on the particular measured location and its surrounding propagation environment (buildings, walls, etc.). Therefore, various points separated by the same distance may observe dissimilar primary power levels depending on the particular location of each point. This can explain the random behavior observed for the analyzed correlation metrics as a function of the distance. In the following we analyze a different approach for analyzing spatial correlation of spectrum occupancy.

5.4.2 Correlation metrics vs. SNR difference

The results obtained for the correlation parameters as a function of the distance did not show the expected trend. Therefore we thought to compute the correlation parameters as a function of the SNR difference. The calculation

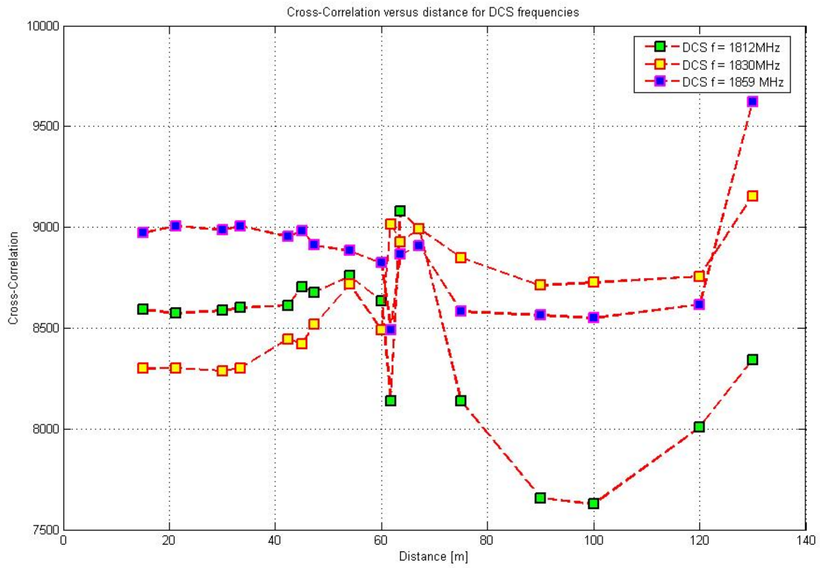

Figure 5.5: Cross-correlation vs distance for DCS.

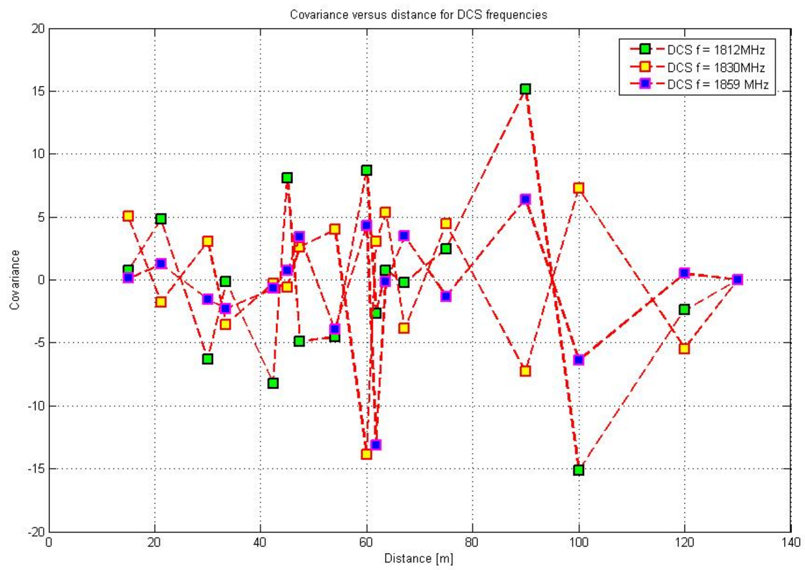

Figure 5.6: Covariance vs distance for DCS.

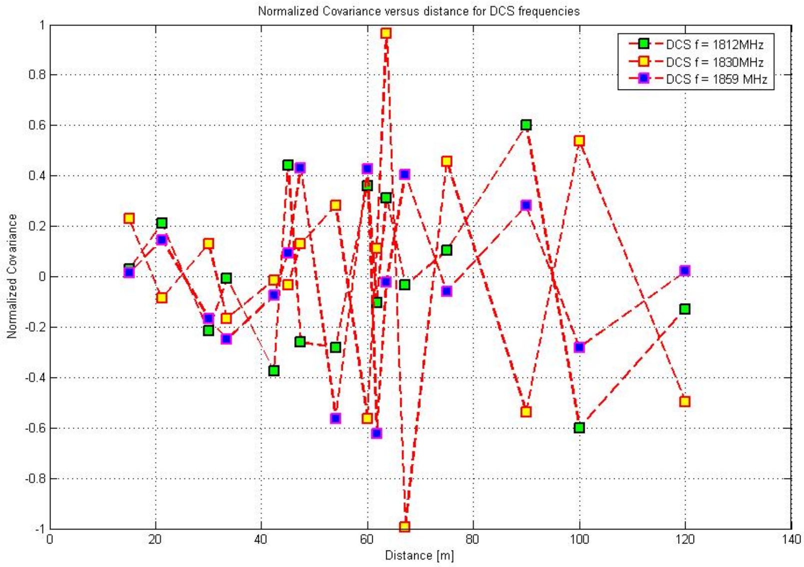

Figure 5.7: Normalized Covariance vs distance for DCS.

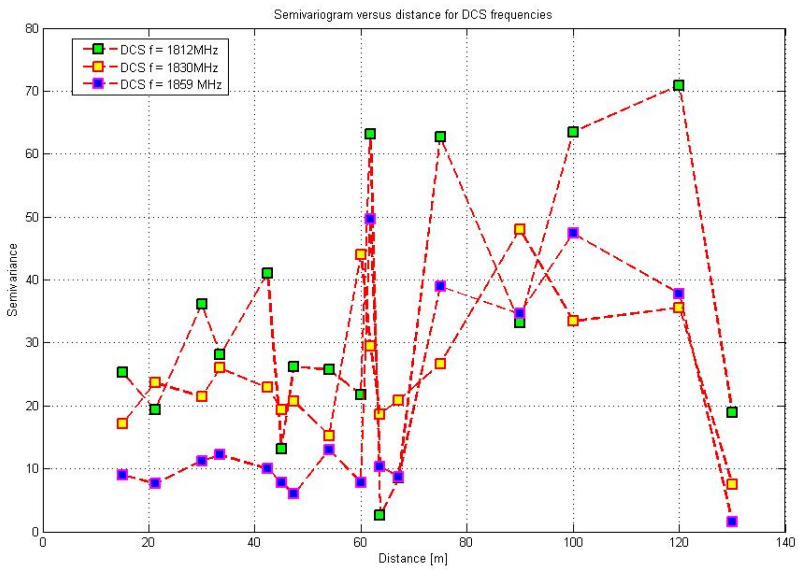

Figure 5.8: Semivariance vs distance for DCS.

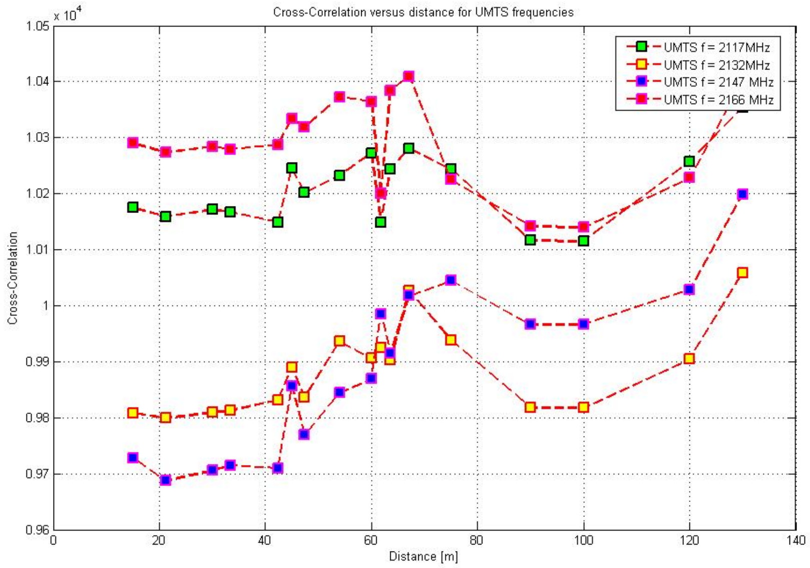

Figure 5.9: Cross-correlation vs distance for UMTS.

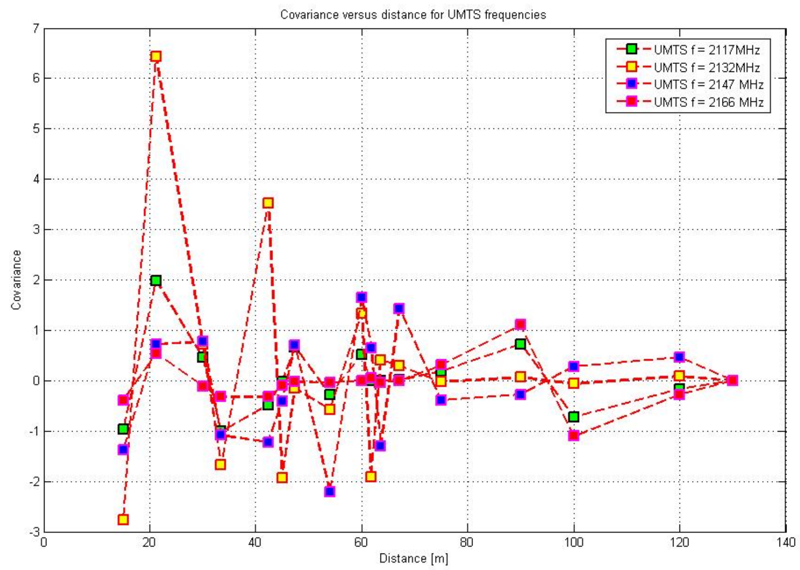

Figure 5.10: Covariance vs distance for UMTS.

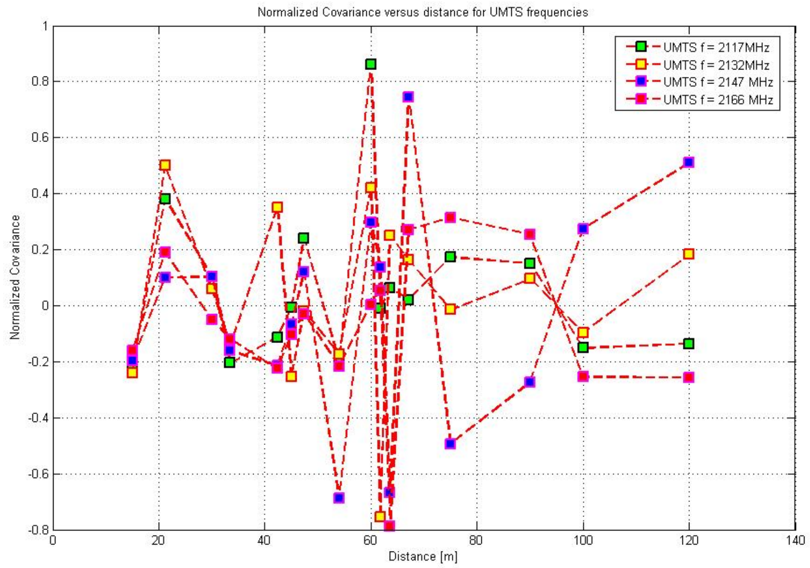

Figure 5.11: Normalized Covariance vs distance for DCS.

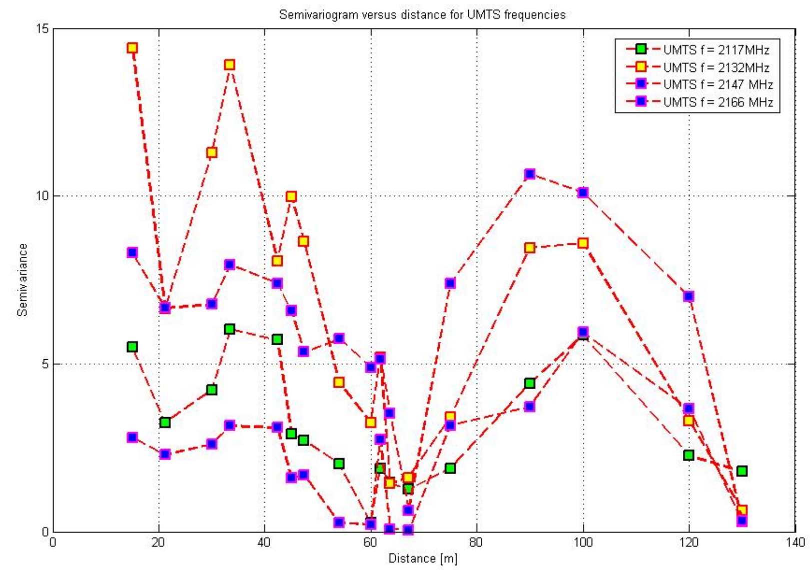

Figure 5.12: Semivariance vs distance for UMTS.

of these new metrics required to rearrange the pairs of points considered. In the previous section we grouped pairs of points based on their distance. Now we sort them by their SNR difference, that is given the average PSD of two points (in dBm) the SNR difference (in dB) is simply the difference between these values. We notice that this classification of the points generate much more pairs of points. Also in this case we applied a binning procedure: we classified two points as being part of the same set if their SNR difference verify the relation $k - \Delta \leq \parallel P_j - P_i \parallel \leq k + \Delta$ where we denote with k a selected value of SNR difference, with P_i and P_j the average values of PSD for two points i and j and with Δ an appropriate margin. The formulas in the previous section remain valid also for this case. The only difference is that the two vectors U and V contain different pairs of points.

In Figure 5.13, 5.14, 5.15 and 5.16 the graphs computed with the new method are shown for DCS band. In Figure 5.17, 5.18 and 5.19 the graphs computed with the new method are shown for UMTS band. We notice that now the correlation parameters seem to show a defined trend. In particular the cross-correlation, the covariance and the normalized covariance tend to decrease as SNR increase. The semivariance seems to increase as SNR difference increase. These graphs show a well defined and logical trend, thus indicating that the SNR difference can be considered as an appropriate parameter as a function of which spatial correlation metrics can be adequately analyzed and described.

We tried to explain this difference of the behavior of the correlation metrics when calculated as a function of the distance and as a function of the SNR difference. The observed behaviors can be explained by the fact that for pairs of points separated by the same distance, the SNR difference may be significantly different depending on the particular propagation conditions at each measured location. The received primary power at a given location does not depend only on the distance from the primary transmitter (path loss component) but also on additional propagation phenomena such as multipath propagation (fast fading component) and shadowing (slow fading component). As a result, for the same distance, different and uncorrelated primary power (SNR) values may be experienced, which would explain the random behavior of correlation as a function of the distance. However, when the same correlation parameters are analyzed as a function of the SNR difference, the impact of all the affecting propagation phenomena is implicitly taken into account, thus showing a well defined and logical trend as a function of the SNR difference. Therefore, the SNR difference is a more reliable and realistic parameter to base the comparison on. This explains why correlation parameters calculated as a function of the distance have no logical shape while when calculated as a function of the SNR difference they show a logical trend.

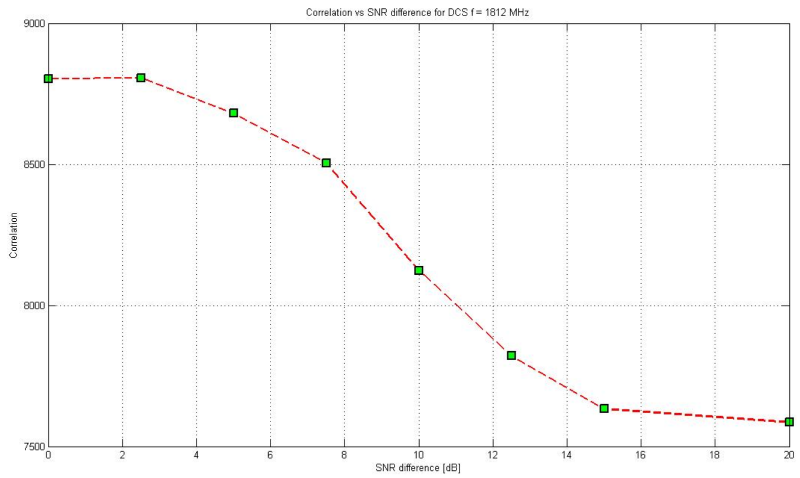

Figure 5.13: Cross-correlation vs SNR difference for DCS.

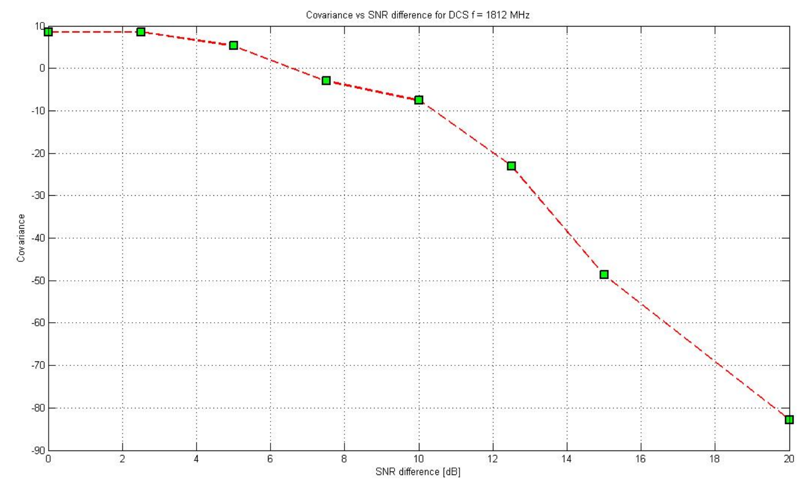

Figure 5.14: Covariance vs SNR difference for DCS.

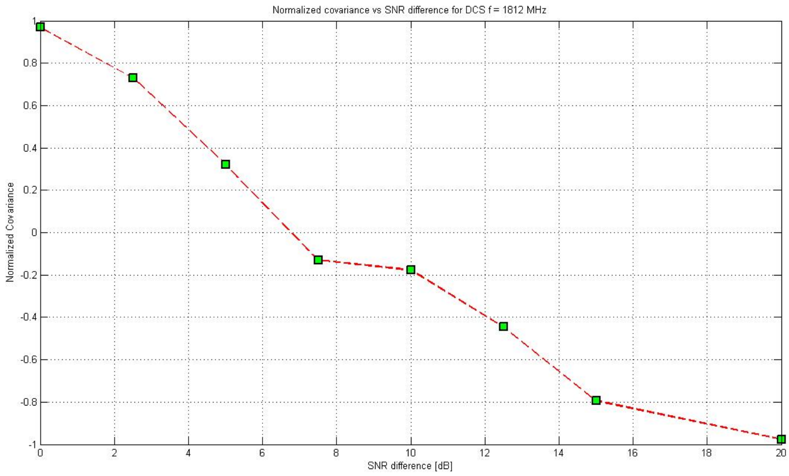

Figure 5.15: Normalized covariance vs SNR difference for DCS.

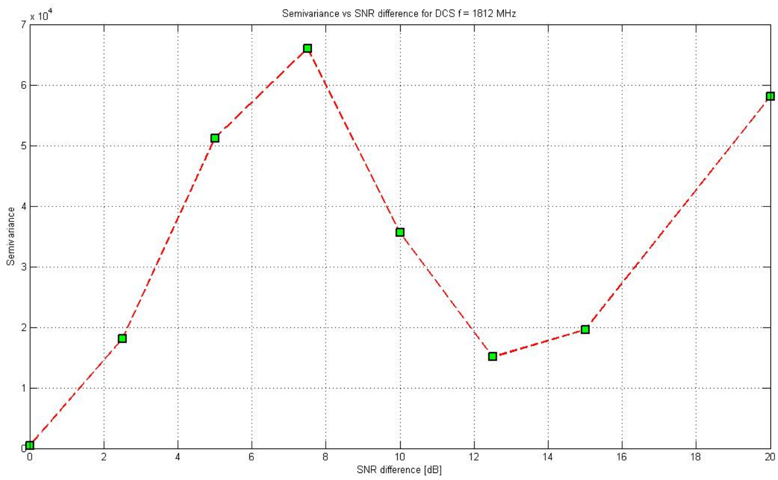

Figure 5.16: Semivariance vs SNR difference for DCS.

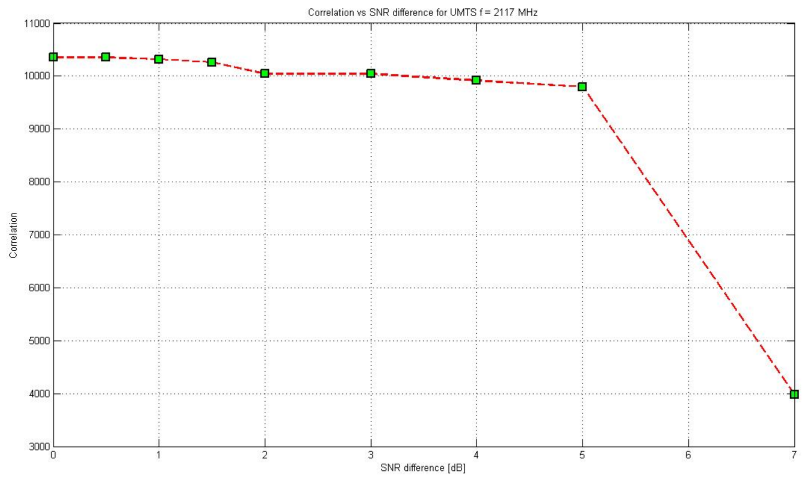

Figure 5.17: Cross-correlation vs SNR difference for UMTS.

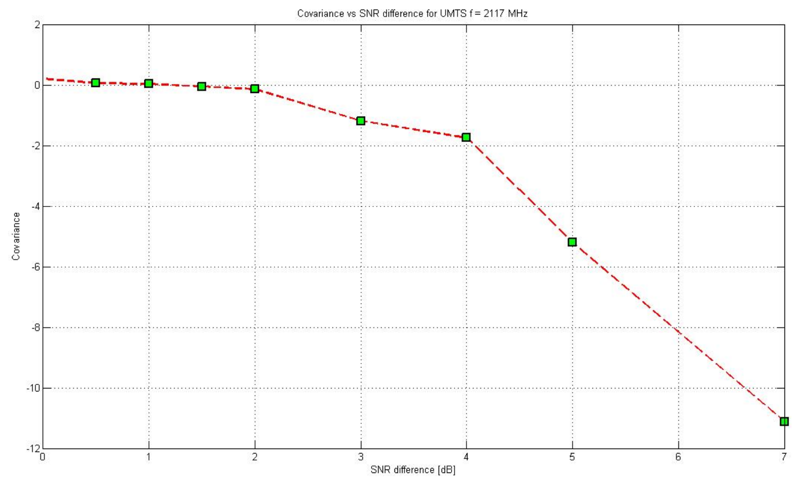

Figure 5.18: Covariance vs SNR difference for UMTS.

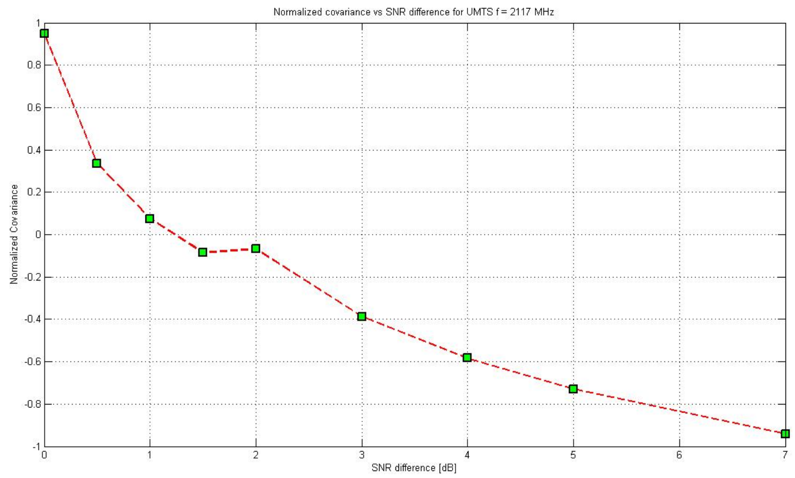

Figure 5.19: Normalized covariance vs SNR difference for UMTS.

5.5 Summary

In this chapter we analyzed the data gathered during the measurement campaign. First we estimate the spectral occupancy of the measured bands. Given the occupation results we choose some frequencies that showed an intensive activity and used the corresponding data for the successive analysis. We returned on *spectrum sensing* to explain the importance of spatial statics and spectrum modeling in cognitive radio. The correlation metrics were introduced; we provided a description of the methods used in the calculation of the metrics as a function of the distance and we showed the results. We tried to explain the results and we made an hypothesis on the reason of their random behavior. Finally we calculated the correlation metrics in a different way, that is as a function of the SNR difference and we saw that the metrics exhibited a logical shape. On this basis we explained the results obtained, showing that spatial correlation of spectrum occupancy can be more appropriately studied as a function of the SNR difference than as a function of the physical distance between different geographical locations.

Chapter 6

Conclusions and future work

Nearly no free frequencies below 3GHz, that have the commercially most interesting propagation characteristics, are available. Furthermore several studies show that actual technologies do an inefficient use of their spectral resources. Cognitive Radio has been proposed as a solution. The main idea of the cognitive radio technology is to use those portions of the spectrum temporarily unused by licensed users. When a primary user requires that frequency block, CR user immediately moves to another spectrum location. In order to permit this kind of communication several features are required to a cognitive Radio Network. The development of the required features would receive a great benefit from the realization of spatial statistic models of the spectral occupancy. The large amount of data generated by various measurement campaign has been developed for the creation of suitable spectrum models. These studies used spatial statistics and random fields methods to provide spectrum models.

We conducted a measurement campaign in the Campus Nord of UPC. We investigated the spectral occupancy of two of the most important cellular bands, that is DCS band and UMTS band. We focused on these bands because they present a high occupancy and because their wavelength and transmission power ranges permitted us to study the spatial statistics of spectrum usage in a relatively small area. Our aim was to verify the spatial correlation of the spectrum occupancy. The expected behavior of the spectral occupancy was to be correlated for short distances and to be uncorrelated for longer distances. Of course the decorrelation length depends on the considered wavelength. Differently from other studies, instead of comparing the instantaneous PSD measured in different locations, we compared the average values of the power measured. This assumption was crucial for our analysis. In fact we showed that the randomness caused by measuring the spectrum in different time instants plays a fundamental role and the spectral occupancy appears to be spatially uncorrelated when considered in different time instants.

We showed that a more reliable parameter on which base a statistical analysis of the spectral occupancy, when not considering the instant values, could be the SNR difference. In fact when we consider the distance as an evaluating parameter, in the time between two measurements, very different propagation conditions could be present; this cause the spectrum to be uncorrelated over the distance. The received power depends instead on the SNR in the measurement location, which also depends on the distance, but not in a linear manner because of the great variability of the propagation conditions. This conclusion was supported by the results of the correlation metrics calculated as a functions of the SNR difference, which showed a well defined trend, as we expected, thus indicating that the spatial correlation characteristics of spectrum occupancy in the context of DSA/CR can be more appropriately analyzed and characterized in terms of the SNR difference, instead of in terms of the distance between different locations as it has been considered in previous studies on spatial correlation.

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