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On the Feasibility of the Communications in the TVWS Spectrum Analysis and Coexistence Issue

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Introduction

In the last decade, the enormous growth in the wireless industry has come from using only a small part of the wireless spectrum, nominally less than 10% under 3 GHz. Nowadays, the vast majority of the available spectral resources have already been licensed. It thus appears that there is little or no room to add any new services, unless some of the existing licenses are discontinued. The current spectrum allocation resides on a static approach in which each radio communication system has its own fixed frequency bands within the transmission power is limited in order to reduce the radio coverage and potential interference. This type of approach leads to a paradox situation in which much of the prized spectrum lies idle for most of the time. Furthermore, the large guard bands nowadays obsolete due to the technological progress diminish even more the mean utilization of the frequency spectrum.

Measurements made by the Federal Communication Commission (FCC) have shown that a great part of the spectrum, although allocated, is virtually unused [1]. Such spectrum portions vary from place to place and time to time. Emblematic was the case of the average TV market in the United States which used approximately 7 high-power channels of the 67 that it was allocated. The US government passed in 2009 bills requiring television broadcasts to switch from analog to digital and the 700 MHz band (channels 52 to 69) was cleared of programming and moved to lower frequencies (channels 2 to 51). Also in the UK studies commissioned by the "Independent regulator and competition authority for the UK communications industries" (Ofcom) revealed that over 50% of location in the United Kingdom have more than 150 MHz of TV spectrum virtually available [2].

For all this reasons, in the last years, several countries have already (USA) or are in the process (EU [3], China [4], Japan [5], South Korea [6]) of switching off analog TV broadcasting in favor of Digital Terrestrial Television (DTT) broadcasting systems [7] and digital switchover plans have driven a thorough review of TV spectrum exploitation. The resulting unused channels within this band are called "TV white spaces" (TVWS).

Even after the redistribution of the digital TV channels, the problem of an efficient utilization of the allocated frequencies is still far from being solved. For example, there are still large territorial areas on which, although allocated, the TV channels result unused, due to coverage problems.

New spectrum allocation approaches such as the dynamic spectrum access method have been studied. This new concept implies that the radio terminals have the capacity to monitor their own radio environment and consequently adapt to the transmission conditions on whatever frequency band are available (adaptive radio). If this concept is supplemented with the capacity of analyzing the surrounding radio environment in search of white spaces, the term adaptive radio is extended to Cognitive Radio. The term Cognitive Radio (CR) was initially proposed by Joseph Mitola in his doctoral thesis [8] as an intelligent wireless communication system that is aware of its surrounding environment. Further extensions of this term lead to a more extended definition [9] which presents a CR as “an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding-by-building to learn from the environment and adapt to statistical variations in the input stimuli, with two primary objectives in mind, namely highly reliable communication whenever and wherever needed, and efficient utilization of the radio spectrum”. CRs may adapt various functional parameters such as used frequency, type of modulation, transmission power and antenna characteristics. The CR paradigm has emerged in the last years as a much-praised alternative for counterbalancing the overcrowded radio frequency spectrum suffering from the current static frequency allocation.

The spectrum management rule of CR is that all new users for the spectrum are secondary (cognitive) users (SU) and requires that they must detect and avoid the primary (licensed) users (PU) in terms of used frequencies, transmission power and modulation scheme. A critical operation in the architecture of a CR is the survey of the radio surrounding, the so-called spectrum sensing. Particular issues are the reliable detection of radio transmissions in a particular frequency band and accurate classification of the detected radio signals. The spectrum sensing techniques focus on primary transmitter detection and usually can be classified as in three main categories: matched filter, energy detection and signal feature detection [10]. The matched filter, also known as pilot detection, is considered as being an optimal spectrum sensing method because it maximizes the received SNR. The drawback of such a method is that there is the need of an a-priori knowledge on the primary source characteristics and also a dedicated receiver for each type of PU. Energy detection is the most common sensing method because of its low computational burden. It is a non-coherent approach that does not need knowledge of pilot data, but has the disadvantage of setting a threshold to determine whether a frequency sub-band is occupied or not. Thresholds are difficult to define, as they are susceptible to noise, fading and in-band interference. Another drawback of this method is the incapacity to differentiate different signal types. The signal feature detection method is based on the fact that primary signals have non-random components (features) that can be used to discriminate the signal from noise and also to classify the signal, even for very low signal to noise ratios (SNR). One disadvantage of the method is that it still requires some prior knowledge of the type of PU. Another shortcoming concerns the computational complexity, a bottleneck for the practical implementations. In order to achieve good results in terms of sensitivity, computational time and signal classification, two-stage spectrum sensing is proposed initially in [11] and then refined in [12] and especially in [13]. The proposed two-stage schemes perform a coarse detection based on the energy detection method, followed by a feature detection stage performed on the sub-bands that have been declared free by the previous stage.

In the TV bands specifically, the presence of PUs (e.g. TV broadcasters) can be revealed both performing a spectrum sensing operation and considering the information provided by the external databases called “geo-location databases” (GL-DB). In the United States, the FCC has already named several operators and performed first field tests with such GL accessible to CR devices at no operational cost. The database provides, for a certain location, the list of the free TV channels and the allowable maximum effective isotropic radiated power (EIRP) for transmitting without harmful interference to incumbent users [14]. In other countries such as the UK the management of Program Making and Special Events (PMSE) band already makes extensive use of similar databases to license radio microphones and in-ear monitor (IEMs) users within the UHF band. The drawback of using GL-DBs, even upgraded on a daily basis, resides in the values corresponding to a specific geographical point that are still the results of calculations based on a certain signal propagation model and estimated power level. Due to this static (for short term at least) approach, the provided data might be inaccurate for different reasons such as variable atmospheric conditions or multipath and fading phenomena.

Decision thresholds are still a critical parameter for protecting services in a scenario where cognitive devices would be operating. There are cases where the approach based on GL Spectrum Occupancy DB might not be available, either because the database does not exist for that area (for example in non densely populated areas) or in the case that access to the database is not possible (deep indoor operation, low populated areas etc.). Several studies [15] have suggested that radio noise has increased significantly over the last decades and consequently the assumptions about decision thresholds and interference protection ratios might be outdated. The Hidden Node Margin (HNM) is a parameter that quantifies the difference between the potential interfered signal values at the location where it is measured or estimated by the cognitive device, and the actual value at the location where the receiving antenna for this signal is located. HNM is a key parameter to define the protection requirements that cognitive devices must comply in order not to create any harmful interference to broadcast receiving systems.

The BBC conducted a study [16] on compatibility problems for broadcasting networks and devices operating in the Digital terrestrial TV (DTT) band. The study identified the joint use of spectrum sensing techniques, GL-DBs and EIRP control as a possible way to effective safe communications. This conclusion is being supported also by a research conducted by the Electronic Communication Committee (ECC) [17] and is implemented by the first worldwide TVWS cognitive radio standard, the IEEE 802.22 WRAN [18, 19].

In this context, this thesis goes in a precise direction, with four main topics related to the feasibility of communication cognitive systems operating in the TVWS, considering coexistence as the main operational issue.

The first topic studies new spectrum sensing approaches in order to improve the more critical functionality of CRs. In the first part the implementation of a new two-stage spectrum sensing method is is described: it is based on the use of Discrete Wavelet Packet Transformation (DWPT) instead of classical Fast Fourier Transformation (FTT) methods for analyzing and calculating the signal power in the TV frequency band. It is an iteratively method in which the free channels can be used for further communication while the channels which have a signal power that surpasses a certain threshold are passed to the second detection stage, the feature detector for distinguishing between PU (in the specific case DVB-T transmitters) and possible SU. The feature detection method used here exploits the normalized histogram generation of the coefficients of the DWPT. An application scenario and a Test Bed have been proposed for performing a series of test in order to validate the presented method and to compare it with the best methods presented in the literature [20, 21].

In the second part a new cooperative spectrum sensing architecture [22], based on sensor networks is presented. This scenario is applicable both for outdoor and indoor applications. Cooperative spectrum sensing is typically divided into operational networks, handling cognitive transmissions, and sensing networks. In concrete a proof-of-concept on the use of spectrum sensing for populating a GL-DB by implementing and deploying a sensor network – based sensing architecture and extending the functionality of the GL-DB towards human users. This approach features the concepts of cluster radio mapping and natural sensing information perception through 3D Virtual Reality (VR) representations of the GL-DB relevant information for the benefit of a spectrum manager or developer.

In the second topic we carry out an unlicensed indoor short-range distribution system for the wireless retransmission in the DTT band of High definition TV (HDTV) contents with immediate implementations as home entertainment systems. For this practical project we start considering the study conducted by the BBC [16] on compatibility challenges for DTT broadcasting networks and devices operating in the DTT band. The study identifies the joint use of spectrum sensing techniques, GL-DBs and EIRP control as a possible way to effective safe communications. This conclusion is supported by a broader research conducted by the ECC within the European Conference of Postal and Telecommunications Administrations (CEPT): Report 159 [17] aims at providing appropriate technical and operational requirements for radio systems in the frequency band 470-790 MHz to ensure protection of the incumbent radio services which are DTT broadcasting, PMSE, radio astronomy (RAS), aeronautical radio navigation (ARNS) within the band and mobile/fixed services in bands adjacent.

By the light of that, spectrum holes in TV bands, with respect to certain limited low power applications, can be a candidate to reduce, in example, the congestion in the 2.4 GHz band. For all this reasons a proof-of-concept DVB-T/T2 compliant prototype [23] has been implemented on a test-bed based on commercial DTT receivers in combination with software defined radio (SDR) hardware devices. The system relies on the perfect knowledge of the spectrum opportunities irrespective of the techniques (e.g., GL-DBs and spectrum sensing) adopted to obtain them. To assess the feasibility of the proposed system extended measurements in real indoor environments have been performed with respect to the protection of the existing broadcasting TV services which verify the suitability for multi-floor environments.

The third topic of this thesis is about a particular database developed in order to provide information to easily calculate HNM values and associated statistics, TV Channel Occupancy and Man Made Noise Upper Limits. The empirical data for this work has been recorded in different locations of Spain and Italy during 2011 and 2012 thanks to the partnership between the

Department of Electrical and Electronic Engineering (D.I.E.E.) of the University of Cagliari and the Department of Electronics and Telecommunications of the University of Bilbao (UPV/EHU).

The database is composed of three different data sets, each one associated to one of the measurement bandwidths and resolutions: 8 MHz, 1 MHz and 100 kHz. The 8 MHz bandwidth measurements provide the typical spectral information that a potential cognitive device could achieve by typical spectral sensing techniques. The 1 MHz and 100 kHz measurements, not feasible for typical cognitive radio implementations, have been carried out having in mind further spectral analysis of the UHF band as well as a crosscheck benchmark for correctly evaluating the 8 MHz results.

In the last topic we focus on the IEEE 802.22 WRAN [18] standard. The objective is to evaluate the performance of an 802.22 system operating into the same coverage range of a DTT receiver. We performed extended measurements for evaluating the protection of the existing broadcasting services. In order to evaluate the performance of DTT systems interfered by 802.22 transmissions in their adjacent channels their Bit Error Rate (BER) levels were monitored changing the 802.22 signal power level for each different transmission bandwidth. The goal of the study is to find the maximum transmission power level of an 802.22 signal in an adjacent channel of an active DTT transmission in order to respect the condition for the minimum BER level of the DTT receiver, according to the standards. The maximum transmission power levels of an 802.22 signal transmitting in adjacent channels of an active DTT system in order to respect the condition for the minimum BER level of a DTT receiver are shown.

Related Papers

- **M. Fadda**, M. Murroni and V. Popescu “Spectrum sensing in the DVB-T Bands using Combined Energy Detection and Signal Classification in the Wavelet Domain”, *The International Symposium on Wireless Personal Multimedia Communications*, Recife, Brazil, October 2010.

- **M. Fadda**, M. Murroni, V. Popescu and V. Stoianovici “TV White Spaces Exploitation for Signal Distribution”, *Conference on Mobile Multimedia Communications* (MobiMedia 2011), Cagliari (Italy), September 2011.

- **M. Fadda**, M. Murroni, V. Popescu and V. Stoianovici “Cooperative Spectrum Sensing for Geo-Location Databases”, *Conference on Mobile Multimedia Communications* (MobiMedia 2011), Cagliari (Italy), September 2011.

- **M. Fadda**, M. Murroni and V. Popescu “A Cognitive Radio Indoor HDTV Multi-Vision System in the TV White Spaces”, *International Conference on Consumer Electronics* (ICCE), Las Vegas (USA), January 2012.

- **M. Fadda**, M. Murroni, C. Perra and V. Popescu “TV white spaces exploitation for multimedia signal distribution”, *Signal Processing: Image Communication*, February 2012.

- **M. Fadda**, M. Murroni, V. Popescu, P. Angueira, J. Morgade and M. Sanchez “Hidden Node Margin and Man-Made Noise Measurements in the UHF Broadcasting Bands”, *The IEEE International Symposium on Broadband Multimedia Systems and Broadcasting* (BMSB 2012), Seoul (Republic of Korea), June 2012.

- **M. Fadda**, M. Murroni and V. Popescu “An Unlicensed Indoor HDTV Multi-Vision System in the DTT Bands”, *IEEE Transactions on Broadcasting*, September 2012.

- **M. Fadda**, M. Murroni and V. Popescu “A Cognitive Radio Indoor HDTV Multi-Vision System in the TV White Spaces”, *IEEE Transactions on Consumer Electronics*, October 2012.

Chapter 1

Cognitive Radios in the TV White Spaces

Current spectrum allocations are based on a command-and-control philosophy; that is, spectrum is allocated for a particular application (e.g., TV broadcasting), and such allocations do not change over space and time. There have been several important developments in the past few years in the spectrum policy and regulatory domains to accelerate opportunistic uses of spectrum. The most recent of these are the publication of the National Broadband Plan (NBP) in March 2010 [24], the publication of the final rules for unlicensed devices in the TV bands in September 2010 [25], and the ongoing proceeding for secondary use of the 2360–2400 MHz band for medical body area networks (MBANS) [26].

The NBP is a policy document that was the culmination of almost a year's worth of work by the Federal Communications Commission (FCC) with input from industry and government agencies on how to formulate spectrum policy in order to facilitate broadband usage for the coming years. One of the main recommendations of the NBP is to free up 500 MHz of spectrum for broadband use in the next 10 years with 300 MHz being made available for mobile use in the next five years. The Plan proposes to achieve this goal in a number of ways: incentive auctions, repacking spectrum, and enabling innovative spectrum access models that take advantage of opportunistic spectrum access and cognitive techniques to better utilize spectrum. The Plan urges the FCC to initiate further proceedings on opportunistic spectrum access beyond the already completed TV white spaces (TVWS) proceedings.

The major worldwide regulatory agencies involved in developing rules for the unlicensed use of TVWS are the FCC in the United States, the Office of Communications (Ofcom) in the United Kingdom, and the Electronic Communications Committee (ECC) of the Conference of European Post and Telecommunications (CEPT) in Europe.

The FCC released the final rules for "Unlicensed Operation in the TV Broadcast Bands" in September 2010 [24]. This was the culmination of many years of deliberations on the subject, starting with the first NPRM in May 2004 and followed by laboratory and field testing of sensing devices through 2007 and 2008 and the second report and order in 2008 [24]. A recent study shows the opportunity provided by TVWS showing to be potentially of the same order (~62MHz) as the recent release of "beachfront" 700MHz spectrum for wireless data service [26], while New America Foundation has another estimate of 15–40 channels available in major cities [27].

CR technology plays a significant role in making the best use of scarce spectrum to support the increasing demand for emerging wireless applications, such as TV bands for smart grid, public safety, broadband cellular, and the MBAN band for medical applications. In order to take advantage of these new opportunities, a number of standards (e.g. IEEE 802.22 [28], IEEE 802.11af, ECMA 392 [29], IEEE SCC41, and ETSI RRS [30]) are either in development or have already been completed. An overview of these standards can be found in chapter 5.

1.1 Cognitive Radios

The first definition of cognitive radio was given by J. Mitola [8]. He defined cognitive radio as follows: "The term cognitive radio identifies the point at which wireless personal digital assistants and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to: (a) detect user communications needs as a function of use context, and (b) to provide radio resources and wireless services most appropriate to those needs."

The definition of CRs developed by Working Party (WP) 1B of the ITU Radiocommunication Sector (ITUR) represents this common understanding: "a radio system employing technology that allows the system: to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained" [31].

The following key capabilities of the CRs are underlined in the ITU-R WP 1B definition: the capability to obtain knowledge, the capability to adjust operational parameters and protocols, and the capability to learn. Within the CR paradigm, as a highly praised alternative for overcoming the inherent limitations of the radio frequency spectrum, the current worldwide situation of the VHF and UHF TV channels is an excellent application scenario.

One of the most prominent features of CRs is the ability to switch between radio access technologies, transmitting in different portions of the radio spectrum as unused frequency band slots arise. This dynamic spectrum access is one of the fundamental requirements for transmitters to adapt to varying channel quality, network congestion, interference and service requirements. CRs also need to coexist with legacy PUs, which have the right to their spectrum slice and thus cannot accept interference.

In order to obtain knowledge, CRs can use various approaches, including:

- Collecting information from component radio systems: typically perform a lot of measurements, such as received signal power, signal-to-interference and noise ratio, and load. Also, they are aware of their current state, for example, frequency bands and radio access technologies (RATs) used by base stations and terminals, and transmission power values. All this information contributes a lot to the knowledge of the CRs.
- Geolocation methods for obtaining positions of radios (e.g., base stations and terminals) that are components of the CRs and other radio systems. Can be performed during professional installation or using a localization system (e.g., Global Positioning System and wireless positioning system).
- Access to a cognitive pilot channel (CPC) is also very important in some CRS deployment scenarios. The CPC serves as a means to exchange information between components of the CRs.
- Spectrum sensing and geolocation databases (GL-DB) are very important in some deployment scenarios of the CRs. These two approaches are used to identify white spaces and detect Pus or even SUs.

Within this topic, spectrum sensing plays a crucial role, along with GL-DBs [24]. In the US, the FCC has already commissioned the creation of GL-DBs, free to access for any CR device. The database entries provide, for a certain location (geographical coordinates), the list of available channels and the allowable maximum effective isotropic radiated power (EIRP) useful to transmit without providing harmful interference [10]. Even if the GL-DBs are up-to date, the values provided for a specific geographical point are still the results of applying a signal propagation models and estimated power levels. Due to this static approach, the provided data might be inaccurate for different reasons such as variable atmospheric conditions or multipath and fading phenomena [11, 12]. Therefore, there is still the need of a validation in terms of frequency occupancy and maximum EIRP of the free frequency channels provided by the

GLDBs, using specific spectrum sensing methods. In next section the most known spectrum sensing methods are shortly presented.

1.1.1 Spectrum Sensing

Spectrum sensing is a critical functionality of CR allowing unlicensed SUs to detect spectral holes and to opportunistically use under-utilized frequency bands without causing harmful interference to legacy systems.

1.1.1.1 Problem Formulation

Spectrum sensing is based on a well known technique called signal detection. In a nutshell, signal detection can be described as a method for identifying the presence of a signal in a noisy environment. Signal detection has been studied for radar purposes since the fifties. Analytically, signal detection can be reduced to a simple identification problem, formalized as a hypothesis test:

$$y(k) = \begin{cases} n(k): & H_0 \\ s(k) + n(k): & H_1 \end{cases}, \qquad (1)$$

where $y(k)$ is the sample to be analyzed at each instant k, $n(k)$ is noise (not necessarily white Gaussian noise) of variance σ^2, $s(k)$ is the signal the network wants to detect, and H_0 and H_1 are the noise-only and signal plus noise hypotheses, respectively.

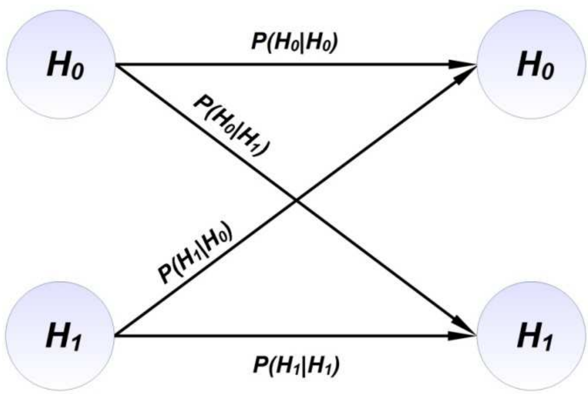

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Figure 1 Hypotesis test and possible outcomes with their corresponding probabilities.

H_0 and H_1 are the sensed states for absence and presence of signal, respectively. Then, as shown in figure 1, four possible cases for the detected signal can be defined:

1. declaring H_0 when $H0$ is true (H_0 | H_0);
2. declaring H_1 when $H1$ is true (H_1 | H_1);
3. declaring H_0 when $H1$ is true (H_0 | H_1);
4. declaring H_1 when $H0$ is true (H_1 | H_0).

Case 2 is known as a correct detection, whereas cases 3 and 4 are known as a missed detection and a false alarm, respectively. Clearly, the aim of the signal detector is to achieve correct detection all of the time, but this can never be perfectly achieved in practice because of the statistical nature of the problem. Therefore, signal detectors are designed to operate within prescribed minimum error levels. Missed detections are the biggest issue for spectrum sensing, as it means possibly interfering with the primary system. Nevertheless, it is desirable to keep the false alarm rate as low as possible for spectrum sensing, so that the system can exploit all possible transmission opportunities.

The performance of the spectrum sensing technique is usually influenced by the probability of false alarm P_f = P(H_1 | H_0), since this is the most influential metric. Usually, the performance is presented by receiver operation characteristics (ROC) curves, which plot the probability of detection P_d = P(H_1 | H_1) as a function of the probability of false alarm P_f .

Equation 1 shows that, to distinguish H_0 and H_1, a reliable way to differentiate signal from noise is required. This becomes very difficult in the case where the statistics of the noise are not well known or when the SNR is low, in which case the signal characteristics are buried under the noise. The less one knows about the statistics of the noise, the worse the performance of any signal detector is in the low SNR regime.

Clearly, the noise characteristics are very important for the spectrum sensing procedure. Most works on spectrum sensing consider noise to be AWGN, since many independent sources of noise are added (central limit theory). Nevertheless, in realistic scenarios, this approximation may not be appropriate since receivers modify the noise through processes such as filters, amplifier non-linearities and automatic gain controls.

Poor performance in a low SNR regime means that all of the techniques available are negatively affected by poor channels. In the case of variable channel gains, equation 1 is rewritten as:

$$y(k) = \begin{cases} n(k): & H_0 \\ h(k)s(k) + n(k): & H_1 \end{cases}, \qquad (2)$$

where $h(k)$ is the channel gain at each instant k. In a wireless radio network, since it is reasonable to assume that the spectrum sensing device does not know the location of the transmitter, two options arise:

- A low $h(k)$ is solely due to the pathloss (distance) between the transmitter and the sensing device meaning that the later is out of range and can safely transmit;
- A low $h(k)$ is due to shadowing or multipath, meaning that the sensing device might be within the range of the transmitter and can cause harmful interference.

In the later case, a critical issue arises. Therein, the fading plays an especially negative role in the well known “hidden node” problem. In this problem, the spectrum sensing terminal is deeply faded with respect to the transmitting node while having a good channel to the receiving node. The spectrum sensing node then senses a free medium and initiates its transmission, which produces interference on the primary transmission. Thus, fading here introduces uncertainty regarding the estimation problem.

To solve this issue, cooperative sensing has been proposed. In this approach, several sensing terminals gather their information in order to make a joint decision about the medium availability. Cooperative spectrum sensing will be explored in section 1.1.1.6.

Spectrum sensing methods can be generally divided in two categories differing for their approach:

- in the receiver centric approach an interference limit at the receiver is calculated and used to determine the restriction on the power of the transmitters around it. This interference limit, called the interference temperature, is chosen to be the worst interference level that can be accepted without disturbing the receiver operation beyond its operating point. Although very interesting, this approach requires knowledge of the interference limits of all receivers in a primary system. Such knowledge depends on many variables, including individual locations, fading situations, modulations, coding schemes and services. They have been ruled out by the IEEE SCC41 cognitive radio network standard.

- In the transmitter centric approach, the focus is shifted to the source of interference. The transmitter does not know the interference temperature, but by means of sensing, it tries to detect free bandwidth. The sensing procedure allows the transmitter to classify the channel status to decide whether it can transmit and with how much power.

Therefore spectrum sensing techniques mainly focus on primary transmitter detection and can be classified in three categories: matched filter, energy detection and signal feature detection [10]. The matched filter, also known as pilot detection, is considered as being an optimal spectrum sensing method because it maximizes the received SNR. The drawback of such a method is that there is the need of an a-priori knowledge on the primary source characteristics and also a dedicated receiver for each type of PU. Energy detection is the most common sensing method because of its low computational burden. It is a non-coherent approach that does not need knowledge of pilot data, but has the disadvantage of setting a threshold to determine whether a frequency sub-band is occupied or not. Thresholds are difficult to define, as they are susceptible to noise, fading and in-band interference. Another drawback of this method is the incapacity to differentiate different signal types. The signal feature detection method is based on the fact that primary signals have non-random components (features) that can be used to discriminate the signal from noise and also to classify the signal, even for very low SNR. One disadvantage of the method is that it still requires some prior knowledge of the type of PU. Another shortcoming concerns the computational complexity, a bottleneck for the practical implementations.H_0

1.1.1.2 Matched Filter

The optimal way for any signal detection is a matched filter, since it maximizes received SNR ratio. However, a matched filter effectively requires demodulation of a PU signal. This means that CR has *a priori* knowledge of PU signal at both PHY and MAC layers, e.g. modulation type and order, pulse shaping, packet format. Such information might be pre-stored in CR memory, but the cumbersome part is that for demodulation it has to achieve coherency with primary user signal by performing timing and carrier synchronization, even channel equalization. This is still possible since most PUs have pilots, preambles, synchronization words or spreading codes that can be used for coherent detection. For example: TV signal has narrowband pilot for audio and video carriers; CDMA systems have dedicated spreading codes for pilot and synchronization channels; OFDM packets have preambles for packet acquisition and so on [32].

If a pilot signal is known, then the matched filter signal detector achieves the optimal detection performance in AWGN channel, as it maximizes the SNR. Let us assume that:

- the signal detector knows the pilot sequence $x(k)$ the bandwidth and the center frequency in which it will be transmitted;
- the pilot sequence is always appended to each primary system's transmission (uplink or downlink);
- and the signal detector can always receive coherently.

Then, if $y(k)$is a sequence of received samples at instant $k \in \{1,2,\ldots,N\}$ at the signal detector, the decision rule can be stated as:

$$\text{decide for} \qquad \begin{cases} H_0, \ if \ \gamma < \beta \\ H_1, \ if \ \gamma \geq \beta \end{cases}$$

where

$$\gamma = \sum_{k=1}^{N} y(k)\, x(k)^* \qquad (3)$$

is the decision criterion, β is the threshold to be compared and $x(k)^*$ is the transpose conjugate of the pilot sequence. The hypothesis decision is simplified as the matched filter maximizes the power of γ as seen in equation 3. This means it performs well even in a low SNR regime.

The main advantage of matched filter is that due to coherency it requires less time to achieve high processing gain since only a little number of samples is needed to meet a given probability of detection constraint. However, a significant drawback of a matched filter is that a CR would need a dedicated receiver for every PU class.

1.1.1.3 Energy Detector

One approach to simplify matched filtering approach is to perform non-coherent detection through energy detection. This sub-optimal technique has been extensively used in radiometry.

An energy detector can be implemented similar to a spectrum analyzer by averaging frequency bins of a FFT [33]. Processing gain is proportional to FFT size *N* and observation/averaging time T.

It is based on the principle that, at the reception, the energy of the signal to be detected is always higher than the energy of the noise. The energy detector is said to be a blind signal detector because it ignores the structure of the signal. It estimates the presence of a signal by comparing the energy received with a known threshold β, derived from the statistics of the noise.

Let $y(k)$be a sequence of received samples $k \in \{1,2, \ldots, N\}$ at the signal detector, such as in equation 1. Then, the decision rule can be stated as:

$$\text{decide for} \qquad \begin{cases} H_0, & if \ \gamma < \beta \\ H_1, & if \ \gamma \geq \beta \end{cases}$$

where

$$\gamma = E[|y(k)|^2] \qquad (4)$$

is the estimated energy of the received signal and β is chosen to be the noise variance σ^2. In practice, one does not dispose of the actual received energy power γ. The energy detector uses, instead, the approximation $\hat{\gamma}$ for γ, with

$$\hat{\gamma} = \frac{1}{N}\sum_{k=1}^{N}|y(k)|^2 \qquad (5)$$

Increasing *N* improves frequency resolution which helps narrowband signal detection, then by the law of the large numbers $\hat{\gamma}$ converges to γ. Also, longer averaging time reduces the noise power thus improves *SNR*. Thus, the performance of the energy detector is directly linked to the number of samples. Furthermore, the energy detector relies completely on the variance of the noise σ^2 which is taken as a fixed value. This is generally not true in practice, where the noise floor varies. Essentially this means that the energy detector will generate errors during those variations, especially when the SNR is very low.

There are several drawbacks of energy detectors that might diminish their simplicity in implementation. First, a threshold used for primary user detection is highly susceptible to unknown or changing noise levels. Even if the threshold would be set adaptively, presence of any in-band interference would confuse the energy detector. Furthermore, in frequency selective fading it is not clear how to set the threshold with respect to channel notches. Second, energy detector does not differentiate between modulated signals, noise and interference. Since, it cannot recognize the interference, it cannot benefit from adaptive signal processing for cancelling the interferer. Furthermore, spectrum policy for using the band is constrained only to primary users, so a cognitive user should treat noise and other secondary users differently. Lastly, an energy detector does not work for spread spectrum signals: direct sequence and frequency hopping signals, for which more sophisticated signal processing algorithms need to be devised. In general, we could increase detector robustness by looking into a primary signal footprint such as modulation type, data rate, or other signal feature.

1.1.1.4 Cyclostationary Feature Detector

Another method for the detection of primary signals is Cyclostationary Feature Detection [33] in which modulated signals are coupled with sine wave carriers, pulse trains, repeated spreading, hopping sequences, or cyclic prefixes. This results in built-in periodicity. These modulated signals are characterized as cyclostationary because their mean and autocorrelation exhibit periodicity. This periodicity is introduced in the signal format at the receiver so as to exploit it for parameter estimation such as carrier phase, timing or direction of arrival. These features are detected by analyzing a spectral correlation function. The main advantage of this function is that it differentiates the noise from the modulated signal energy. This is due to the fact that noise is a wide-sense stationary signal with no correlation however modulated signals are cyclostationary due to embedded redundancy of signal periodicity .

Spectral correlation function (SCF) is also known as cyclic spectrum. While power spectral density (PSD) is a real valued one dimensional transform, SCF is a complex valued two dimensional transform. Because of the inherent spectral redundancy signal selectivity becomes possible. Analysis of signal in this domain retains its phase and frequency information related to timing parameters of modulated signals. Due to this, overlapping features in power spectral density are non overlapping features in cyclic spectrum. Hence different types of modulated signals that have identical power spectral density can have different cyclic spectrum.

The works by Gardner [34] in 1991 and Enserink et. al. [35] in 1995 have studied this signal detection scheme in detail. The work of Enserink follows the same line of the one by Gardner, in which the cyclostationary feature detector is based on the magnitude- squared of the spectral coherence, which for any random process X is given by

$$|\rho_X{}^{\alpha}(f)| = \frac{|S_X{}^{\alpha}(f)|^2}{\left[\langle S_X\rangle\left(f+\frac{\alpha}{2}\right)\langle S_X\rangle\left(f-\frac{\alpha}{2}\right)\right]^{\frac{1}{2}}} \qquad (6)$$

where S_X is the spectral correlation density function, is the cyclic frequency and f is the spectral frequency. In the specific case of the cyclostationary feature detector, substituting $\rho_X{}^{\alpha}(f)$ by $\hat{\rho}_X{}^{\alpha}(f)$ and S_X by $\hat{S}_X$, which are the estimated versions of the same quantities, we have the decision metric:

$$\widehat{M} = |\hat{\rho}_X{}^{\alpha}(f)| = \frac{|S_X{}^{\alpha}(f)|^2}{\left[\langle \hat{S}_X\rangle\left(f+\frac{\alpha}{2}\right)\langle \hat{S}_X\rangle\left(f-\frac{\alpha}{2}\right)\right]^{\frac{1}{2}}} \qquad (7)$$

which goes into the decision statistic, given by

$$\text{decide for} \qquad \begin{cases} H_0, \ if \ \widehat{M} < \ \beta \\ H_1, \ if \ \widehat{M} \ \geq \ \beta \end{cases}$$

Among the advantages of the cyclostationary feature detection we can enumerate the robustness to noise because stationary noise exhibits no cyclic correlations, better detector performance even in low SNR regions, the signal classification ability and the flexibility of operation. The disadvantages are a more complex processing needed than energy detection and therefore high speed sensing cannot be achieved. The method cannot be applied for unknown signals because an a priori knowledge of target signal characteristics is needed. Finally, at one time, only one signal can be detected: for multiple signal detection, multiple detectors have to be implemented or slow detection has been allowed.

1.1.1.5 Two Stage Spectrum Methods

Since cyclostationary feature detection is somehow complementary to the energy detection, performing better for narrow bands, a combined approach is suggested in [12], where energy detection could be used for wideband sensing and then, for each detected single channel, a feature detection could be applied in order to make the final decision whether the channel is occupied or not. First a coarse energy detection stage is performed over a wider frequency. Subsequently the presumed free channel is analyzed with the feature detector in order to take the decision.

1.1.1.6 Cooperative Techniques

Detection of primary user by the secondary system is critical in a CR environment. However this is rendered difficult due to the challenges in accurate and reliable sensing of the wireless environment. Secondary users might experience losses due to multipath fading, shadowing, and building penetration which can result in an incorrect judgment of the wireless environment, which can in turn cause interference at the licensed PU by the secondary transmission. This arises the necessity for the cognitive radio to be highly robust to channel impairments and also to be able to detect extremely low power signals. These stringent requirements pose a lot of challenges for the deployment of CR networks. High sensitivity requirements on the cognitive user caused by various channel impairments and low power detection problems in CR can be alleviated if multiple CR users cooperate in sensing the channel. [36] suggests different cooperative topologies which can be broadly classified into three regimes according to their level of cooperation.

In Decentralized Uncoordinated Techniques the cognitive users in the network don’t have any kind of cooperation which means that each CR user will independently detect the channel, and if a CR user detects the primary user it would vacate the channel without informing the other users. Uncoordinated techniques are fallible in comparison with coordinated techniques. Therefore, CR users that experience bad channel realizations (shadowed regions) detect the channel incorrectly thereby causing interference at the primary receiver.

In Centralized Coordinated Techniques an infrastructure deployment is assumed for the CR users. CR user that detects the presence of a primary transmitter or receiver informs a CR controller. The CR controller can be a wired immobile device or another CR user. The CR controller notifies all the CR users in its range by means of a broadcast control message. Centralized schemes can be further classified in according to their level of cooperation into

- Partially Cooperative: in partially cooperative networks nodes cooperate only in sensing the channel. CR users independently detect the channel inform the CR controller which then notifies all the CR users. One such partially cooperative scheme was considered by [37] where a centralized Access Point (CR controller) collected the sensory information from the CR users in its range and allocated spectrum accordingly;

- Totally Cooperative Schemes: in these networks all nodes cooperate in relaying each other information in addition to cooperatively sensing the channel. For example, the cognitive users D1 and D2 are assumed to be transmitting to a common receiver: in the first half of the time slot assigned to D1 it transmits and in the second half D2 relays D1's transmission. Similarly, in the first half of the second time slot assigned D2 transmits its information and in the second half D1 relays it.

For Decentralized Coordinated Techniques various algorithms have been proposed for the decentralized techniques, among which the gossiping algorithms [38], which do cooperative sensing with a significant lower overhead. Other decentralized techniques rely on clustering schemes where cognitive users form in to clusters and these clusters coordinate amongst themselves, similar to other already known sensor network architecture (i.e. ZigBee).

All these techniques for cooperative spectrum sensing, raise the need for a control channel [39] which can be either implemented as a dedicated frequency channel or as an underlay UWB channel. Wideband RF front-end tuners/filters can be shared between the UWB control channel and normal cognitive radio reception/transmission. Furthermore, with multiple cognitive radio groups active simultaneously, the control channel bandwidth needs to be shared. With a dedicated frequency band, a CSMA scheme may be desirable. For a spread spectrum UWB control channel, different spreading sequencing could be allocated to different groups of users.

Combinations of these methods are used for achieving good results in terms of sensitivity, computational time and signal classification, in so-called two-stage spectrum sensing schemes proposed initially in [11] and then refined in [12] and especially in [13]. The mentioned two-stage schemes perform coarse sensing based on energy detection, followed by a feature detection performed on the signals in the sub-bands declared free by the previous stage.

Chapter 2

New Spectrum Sensing Approaches

This chapter consists of two main sections that describe the study and implementation of two new spectrum sensing methods. In section 2.1 a two-stage spectrum sensing approach is described: it is based on the use of Discrete Wavelet Packet Transformation (DWPT) instead of classical Fast Fourier Transformation (FTT) methods for analyzing and calculating the signal power in the TV frequency band. At the end of this first section the application scenario, test bed and the consequently series of test performed in order to validate the presented method and to compare it with the best methods in the literature ([20, 21]) will be shown.

Section 2.2 introduces the implementation of a new kind of approach, far from that previously analyzed: a cooperative spectrum sensing architecture [24], based on sensor networks. Cooperative spectrum sensing is typically divided into operational networks, handling cognitive transmissions, and sensing networks. In concrete a proof-of-concept on the use of spectrum sensing for populating a GL-DB by implementing and deploying a sensor network – based sensing architecture and extending the functionality of the GL-DB towards human users. This approach features the concepts of cluster radio mapping and natural sensing information perception through 3D Virtual Reality (VR) representations of the GL-DB relevant information for the benefit of a spectrum manager or developer.

2.1 New Two Stage Spectrum Sensing Method

Within this section a different two-stage spectrum sensing approach is described; it is implemented using the DWPT for dividing the analyzed DVB-T frequency band and calculating the signal power in the resulting sub-bands (channels). The free channels can be used for further communication while the channels which have a signal power that surpasses a certain threshold are passed to the second detection stage, the feature detector for distinguishing between PU (in this specific case DVB-T transmitters) and possible SU. The feature detection method used here exploits the normalized histogram generation of the coefficients of the DWPT.

2.1.1 Wavelet Packets Sub-Bands Analysis

After reviewing the sending methods previously presented in section 1.1.1, the energy detection method was chosen to be implemented in the design of a new spectrum sensing system. Instead of using the FFT for analyzing the power content of the spectrum, we opted for an alternative method based on the wavelet transformation and its discrete application, the DWPT.

The spectrum sensing technique proposed in [40] which performs an energy detection based on wavelet packets sub-bands analysis, has been used. The analysis is performed by deploying polyphase IIR filter banks which reduce the computational complexity and makes the method feasible for dynamic spectrum access communications.

The 52-69 channels in the 700-MHz TV band extend from 698-806 MHz. Each of the 18 channels is 6 MHz wide. Therefore, to cope with the above constraints an initial band 192 MHz wide has been considered, starting from 698 MHz and ending at 890 MHz, which includes the 52-69 TV channels under analysis. A 5-level depth wavelet decomposition tree [41] is performed on this “enlarged” band producing 32 sub-bands. The band is divided by means of a wavelet decomposition tree into sub-bands with a bandwidth specific to the various DTT standards (from 6 to 8 MHz). Only 18 selected sub-bands of the resulting 32, match with the 52-69 TV channels and, thus, have been considered. The matching process is performed taking into account the discrepancy between the TV channels order in the frequency domain and the corresponding sub-bands order in the wavelet domain.

Figure 2 shows the schematic tree for the case under discussion and highlights the labeling of the effective 18 UHF channels, displayed in ascending frequency order. Within each identified sub-band the power level can be estimated in the wavelet domain, and then compared to opportune threshold values so as to identify spectrum opportunities (TVWS).

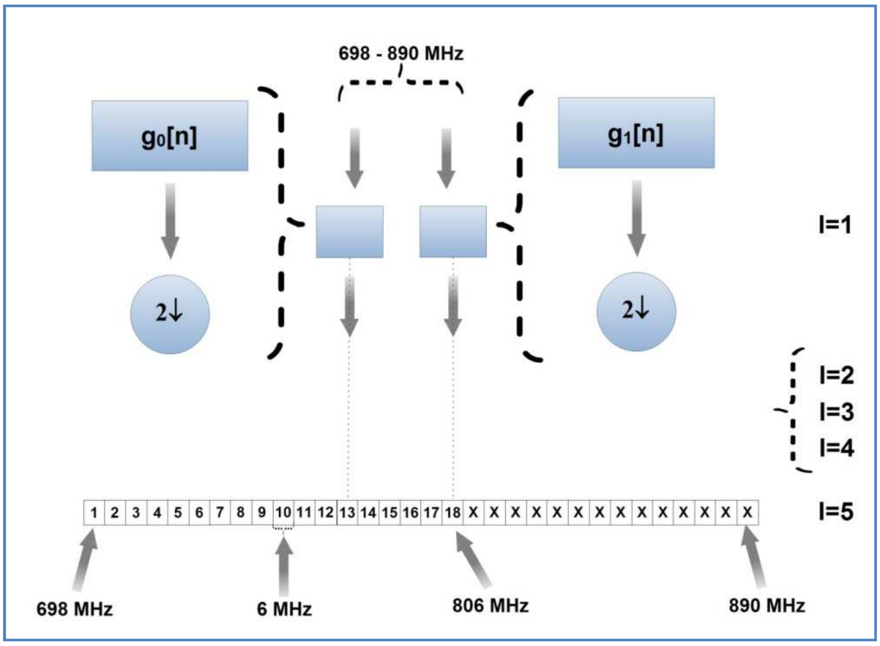

Figure 2 Schematic tree and view of the 18 UHF channels displayed in ascending frequency order.

2.1.2 Energy Detection and Signal Classification in DWPT Domain

This new two-stage approach is based on the work initially proposed in [42]. As previously introduced in section 2.1.1 is a method based on DWPT sub-bands analysis. An initial band centered on the region occupied by the TV channels is considered. The band is divided by means of a wavelet decomposition tree into sub-bands with a bandwidth specific to the various DTT standards (from 6 to 8 MHz). The power level of the received signal in the wavelet domain is calculated by summing the corresponding squared wavelet coefficients for each sub-band. The resulting values are compared to opportune threshold values [43] to mark the channels for the frequencies corresponding to the TV channels of interest as free ("white") or occupied.

As known the drawback of the energy detection method is the reliability of the power level thresholds. Therefore, in the second stage of this spectrum sensing method, for all the channels that previously were identified as not "white", implicitly having a signal power surpassing the noise threshold mentioned in [43], we estimate whether they are occupied by PUs or SUs using a modulation classifier. The wavelet transform has the special feature of multi-resolution analysis (MRA), which provides the necessary parameters to extract the feature of the modulated signals.

The modulation types used by the DTT broadcasting systems are standard, so a feature-based classifier for the modulation schemes typical for terrestrial communications can be used to classify a possible modulated signal. The proposed scheme supports the classification of QPSK, 16QAM and 64QAM modulations, specific for the European DVB-T standard. The algorithm is similar to that proposed in [43]; the normalized histogram generation of wavelet transformed coefficient is used to classify MPSK and MQAM modulations.

The analysis can start initially considering the normalized histogram generation of the wavelet-transformed coefficients with N samples in the particular process

$$p(x_i) = N_i/N \qquad (8)$$

where N_i are the samples in the particular process; the normalized histogram shows only one peak for DVB-T signals. For the classification we need statistical parameters such as moments and medians. For this reason, from the n-th order moment for the normalized histogram $p(x_i)$ given by equation 9

$$\mu_n(x) = \sum_{i=0}^{N-1} (x_i - \mu_1)\, p(x_i) \qquad (9)$$

the first-order and the second-order moment of the statistical process, that respectively represent the mean and the variance, shown in (10) and (11)

$$\mu_1(x) = \sum_{i=0}^{N-1} x_i\, p(x_i) \qquad (10)$$

$$\mu_2 = \frac{1}{N}\sum_{i=0}^{N-1} |\mathrm{c_i}|^2 - \left[\frac{1}{N}\sum_{i=0}^{N-1} |\mathrm{c_i}|\right]^2 \qquad (11)$$

need to be calculated. In 11 $\mathrm{c_i}$ are the wavelet coefficients in each single sub-band. The constellation type, circular (M-ary PSK) or in quadrature (M-ary QAM), can be detected by comparing the mean with a first threshold T_1

$$T_1 = \frac{\mu_{1,M-QAM} \cdot \mu_{2,M-PSK} + \mu_{1,M-PSK} \cdot \mu_{2,M-QAM}}{\mu_{2,M-QAM} + \mu_{2,M-PSK}} \qquad (12)$$

computed using known, pre-calculated mean and variance values for M-ary QAM and M-ary PSK signals. Subsequently, based on the same principle, if the modulation is a M-ary PSK we can compare the variance with a second threshold T_{P2}

$$T_{P2} = \frac{\mu_{1,QPSK} \cdot \mu_{2,PSK} + \mu_{1,PSK} \cdot \mu_{2,QPSK}}{\mu_{2,QPSK} + \mu_{2,PSK}} \qquad (13)$$

to find if it is a QPSK or a different PSK order modulation. If the modulation is an M-ary QAM, we can detect if it is a 16QAM or a 64QAM comparing the variance of the signal with a third threshold T_{Q4} given by equation 14.

$$T_{Q4} = \frac{\mu_{1,16QAM} \cdot \mu_{2,64QAM} + \mu_{1,64QAM} \cdot \mu_{2,16QAM}}{\mu_{2,16QAM} + \mu_{2,64QAM}} \qquad (14)$$

The variance and thresholds mathematical formulas used to implement our classification algorithm can be found in [20], but opposed to this work, in our new approach the wavelet coefficients are singularly considered in each of the sub-bands. Figure 3 presents the flowchart of the proposed feature detection method.

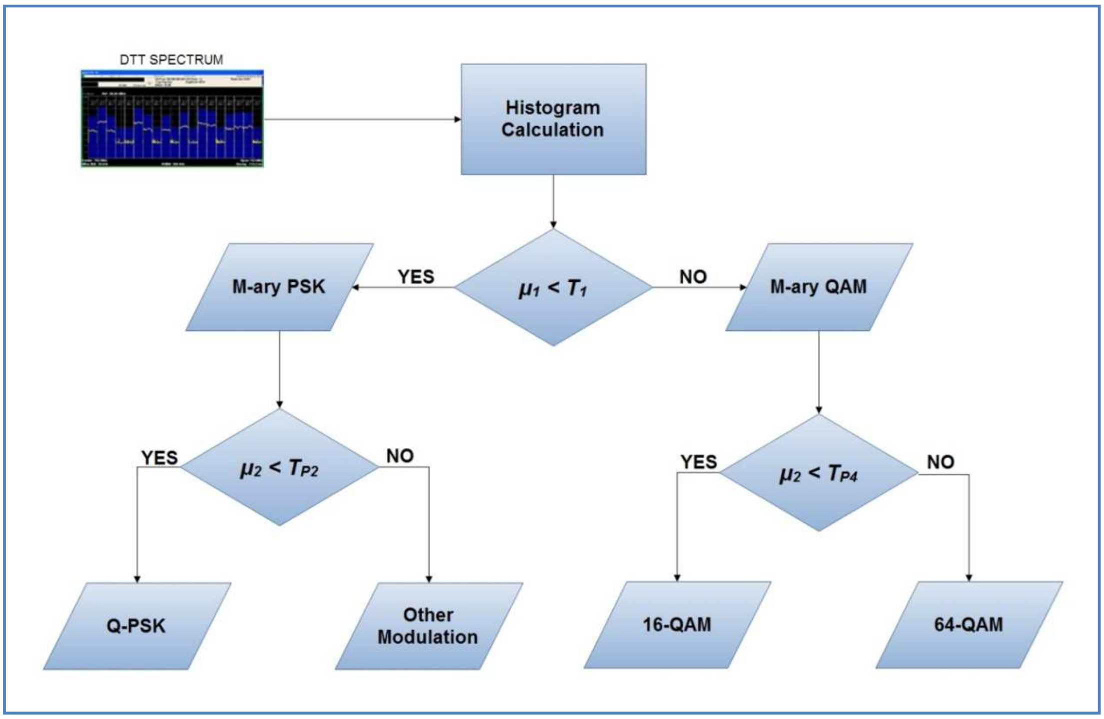

Figure 3 Flowchart of the functionality of the proposed feature detection method.

If the channel is identified as being occupied by a PU, the corresponding channel is definitively marked as “black”, meaning it is undoubtedly used by PUs and therefore not suitable for transmission. If the statistical analysis fails to identify a known type of modulation (QPSK, 16QAM, 64 QAM), we categorize the channel as being “grey”, which means that there is no broadcaster transmitting, but still the channel is occupied, most probably by another SU. Therefore, the channel is not completely discarded, being a potential candidate to be analyzed again after a certain amount of time in order to be re-evaluated and eventually included in the white list.

The channels marked as “black” are not suitable for transmission and therefore, after the first energy and feature detection, we have to consider only the “grey” and “white” channels, thus reducing the number of operations and making the algorithm suitable for the use with real, live signals.

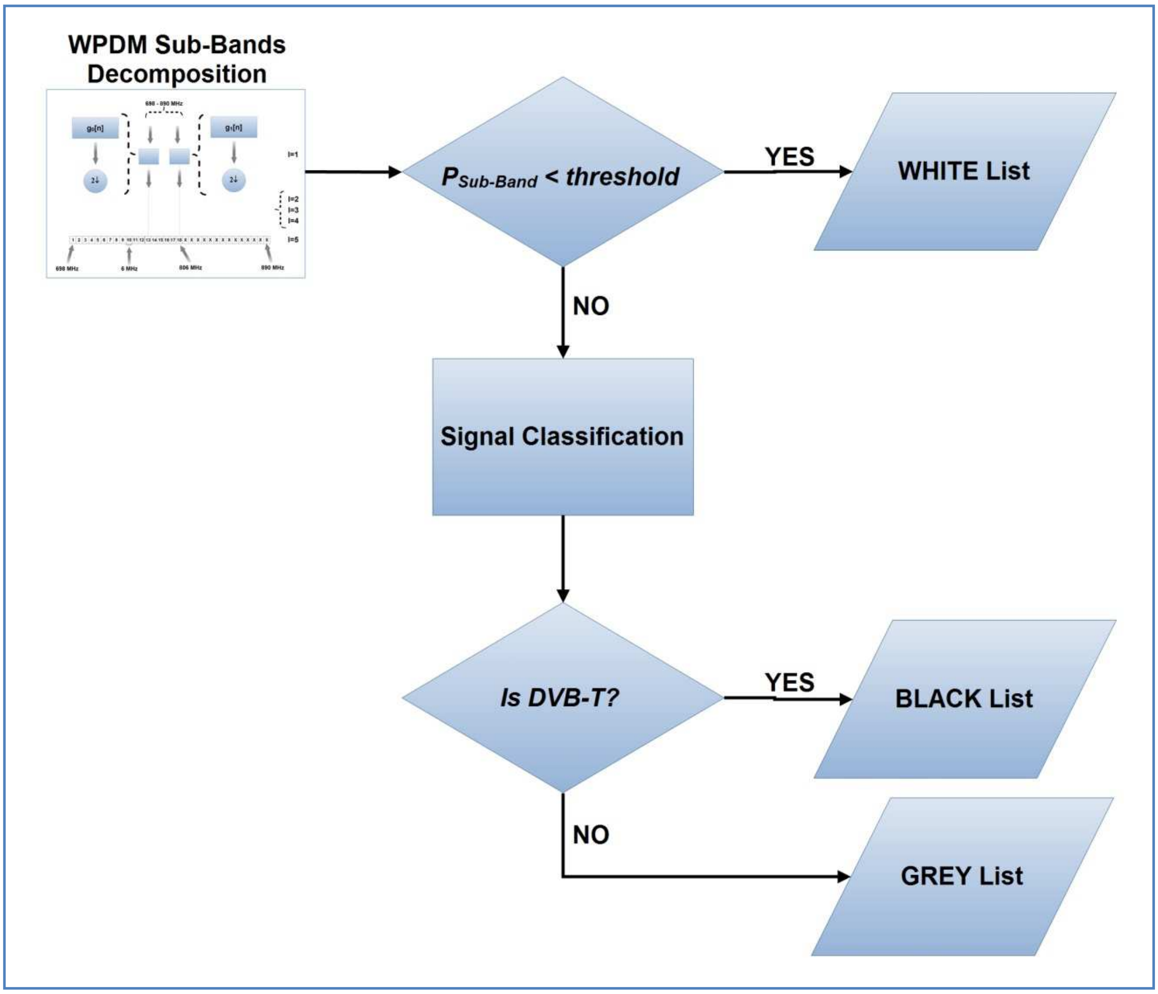

Figure 4 Flowchart of the two-stage spectrum-sensing scheme in the DVB-T UHF band.

Furthermore, the wavelet transformation has to be performed only once for both the two stages of the spectrum sensing scheme, the coefficients used for energy detection and signal classification being the same. A schematic of the proposed two-stage spectrum sensing method performing in the DVB.T band can be seen in figure 4.

2.1.3 Software Simulation

The proposed spectrum sensing method is implemented using a two-stage algorithm in which an energy detection based on discrete wavelet packets sub-bands analysis followed by a feature detection stage is performed, as shown in section 2.1.2.

The algorithm was implemented in Simulink / Matlab. Simulink (Simulation Link) is a toolbox of the popular mathematical software Matlab for modeling, simulating and analyzing of dynamic systems. Through a graphical interface models can be created in the form of block diagrams, thanks to a rich library of built-in components (input signals, linear and non-linear components, connectors, outputs etc.). After creating a model, a simulations can be performed by changing various parameters and the results can be seen in real time or stored in the MATLAB Workspace to rework them..

Simulink has a rich library of various DSP components as signal generators, filters, lines and transmission channels, modulators, transformation blocks and also a toolbox for both continuous and discrete Wavelet transformation. Other important components are the Simulink toolbox for rapid prototyping and implementation of signal processors (Infineon, Texas Instruments, Freescale) and platforms (FPGA Xilinx and Altera).

In this considered algorithm the coefficients in the sub-bands are generated using two-channel Butterworth IIR polyphase filters, which have a complexity in the order of $3(M \log_2 M)$, M being the number of the samples of the original signal. If the number of DWPT levels is considerably lower than the number of samples in the initial signal, as it is in our case here for 5 DWPT levels ($L = 5$), the complexity can be reduced further to the order of $3ML$. In analyzing the feature detection complexity the first goal is to show how the mean score can be calculated as in (3) with a simple algorithm. In every step the *i-th* component of the process x_i is multiplied by the correspondent normalized histogram $p(x_i)$ and this value updates the mean score. This operation cycle is called N times (N is the number of wavelet coefficients in a single sub-band) and during the whole execution we compute $2N$ operations (N for sum and N for multiplication).

The second goal is to calculate the variance of the DWPT, as shown in (11). During the whole execution we compute $(2N + n + 4)$ operations ($2N$ for the first sum and N for the second one). The channels marked as "black" are not suitable for transmission and therefore, after the first energy and feature detection, we have to consider only the "grey" and "white" channels, reducing furthermore the number of operations.

The test signals for the system's functionality were generated using the Agilent SystemVue Software: is a focused electronic design automation (EDA) environment for electronic system-level (ESL) design. It enables system architects and algorithm developers to innovate the physical layer (PHY) of wireless and aerospace/defense communications systems and provides unique value to RF, DSP, and FPGA/ASIC implementers. As a dedicated platform for ESL design and signal processing realization, SystemVue replaces general-purpose digital, analog, and math environments.

8 signals, spaced evenly at 8 MHz on 7.61 MHz wide channels, with constant additive white Gaussian noise (AWGN), were modulated on carrier in the upper UHF band in order to simulate the behavior of a real terrestrial DVB-T system. Figure 5 depicts one of the test signals.

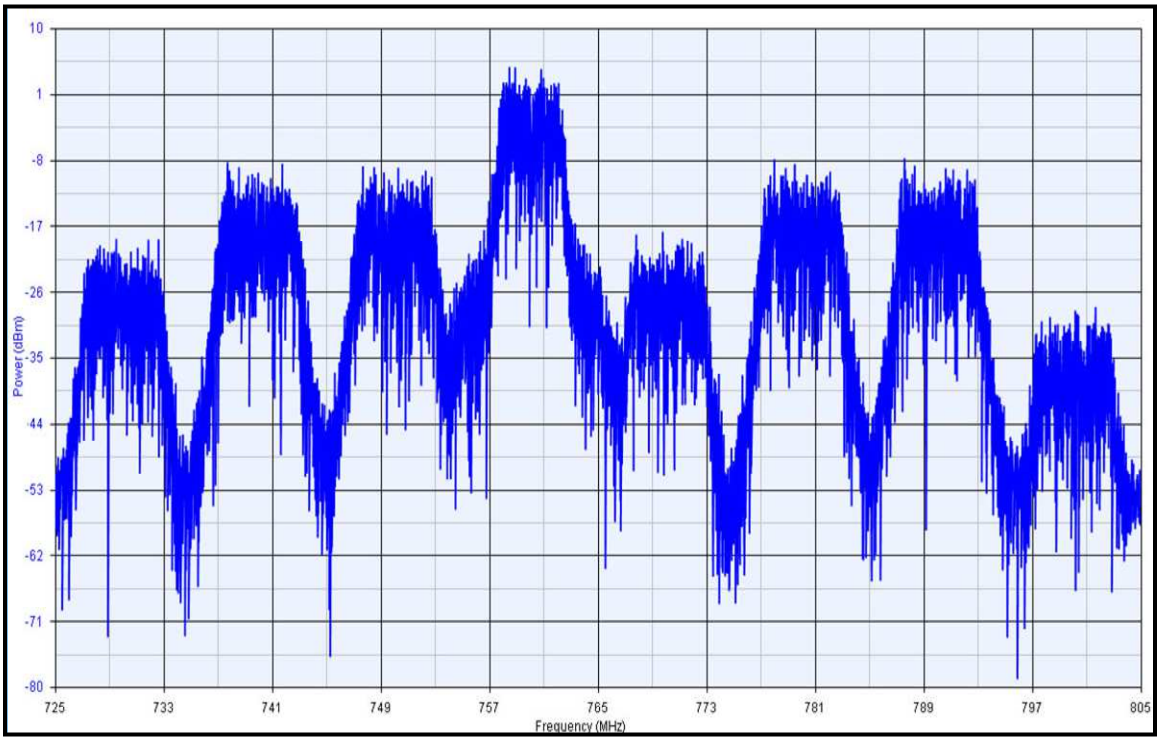

Figure 5 Test signal composed by 8 DVB-T signals with different standard modulations.

Different modulation schemes were chosen even for adjacent signals in order to test the capacity of the system to correctly compute the threshold values needed for the signal classification.

The first step consisted in the calculation of the threshold of the energy detection stage based also on the results from [43]. The next step implied calculating the reference thresholds for the modulation classifier based on the simulated input signals with known modulation type and signal to noise ratios (SNR). Based on these thresholds, pre-set in the simulator, we tested the reliability of the proposed application scenario. A series of test consisting in changing the amplitude of the signals, their SNR and the modulation type has been performed. A total set of 200 different test signals has been fed to the simulator. For SNR values higher than 5 dB and specifically for the signals in the 700 MHz band, the proposed method equaled the best methods presented in the literature [20,21]: for the typical DVB-T standard modulations the signal classifier had an identification percentage of 96.5 %.

2.1.4 Hardware Set-Up

After testing the functionality of the software implementation and calculating the appropriate threshold values for both the energy detector and the modulation classifier, we validated these results with real DVB-T signals acquired using RF hardware. The hardware set-up consisted of USRP2 software defined radio (SDR) boards equipped with WBX wideband daughterboards covering a spectrum range from 50 MHz to 2.2 GHz. The SDRs were connected to a PC running a Simulink model that commands the RF hardware and implements the entire baseband processing.

Appropriate antennas for the frequency band of interest were used during the tests. The measurements on the power of the DVB-T signals and on their modulation type were crosschecked using as reference the Agilent EXA9020A Vector Signal Analyzer, the 89600VSA software and the instrument’s onboard software (figure 6). In next sub-sections the USRP2 SDR and the Agilent EXA9020A VSA.

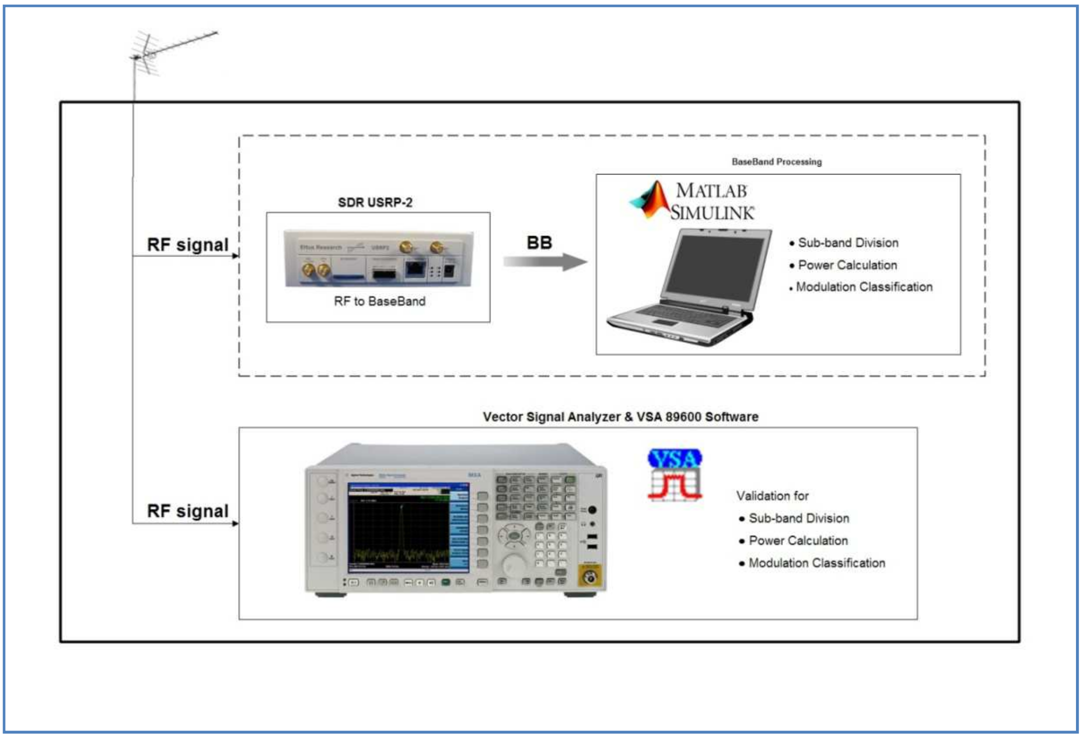

Figure 6 Flowchart of the functionality of the proposed feature detection method

2.1.4.1 USRP2 Software Define Radio

A SDR system is made up of a SDR hardware platform and its associated software framework and functionality. The term software defined radio was coined in [44]. Mitola introduces the concept of applying digital signal processing (DSP) on general purpose hardware and using digital to analog converters (DAC) to build digital communications systems. GNU Radio founder Eric Blossom, states in [45] that SDR is the technique of getting code as close to the antenna as possible. The concept is to turn radio hardware problems into software problems which are more flexible and manageable. SDRs generate, modulate / demodulate the transmitted /received waveforms, contrary to most radios, which do their processing through analog or combined analog and digital circuitry. To sum up, a SDR or frequency-agile radio, module is capable of reconfiguring and switching to newly-selected frequency bands. It can be programmed to tune to and operate on specific frequency bands over a wide range of spectrum [46].

The USRP2 (figure 7) consists of a motherboards containing an FPGA for high-speed signal processing and interchangeable daughterboards that cover different frequency ranges. Together, they bridge between bits in a host computer and one or more antennas. The USRP2 even contains:

- Gigabit Ethernet interface.
- Two 100 MS/s, 14-bit, analog-to-digital converters.
- Two 400 MS/s, 16-bit, digital-to-analog converters.
- Secure Digital (SD) card reader.
- Fully coherent multi-channel systems (MIMO capable) with up to 8 antennas.
- Modular architecture supports a wide variety of RF daughterboards.
- 2 Gbps high-speed serial interface for expansion.

Figure 7 Universal Software Radio Peripheral 2 (USRP2) SDR.

2.1.4.2 Agilent EXA9020A Vector Signal Analyzer

Analog, swept-tuned spectrum analyzers use superheterodyne technology to cover wide frequency ranges; from audio, through microwave, to millimeter frequencies. FFT analyzers use DSP to provide high-resolution spectrum and network analysis, but are limited to low frequencies due to the limits of analog-to-digital conversion (ADC) and signal processing technologies. Today’s wide-bandwidth, vector-modulated (also called complex or digitally modulated), time-varying signals benefit greatly from the capabilities of FFT analysis and other DSP techniques. VSAs combine superheterodyne technology with high speed ADCs and other DSP technologies to offer fast, high-resolution spectrum measurements, demodulation, and advanced time-domain analysis. A VSA is especially useful for characterizing complex signals such as burst, transient, or modulated signals used in communications, video, broadcast, sonar, and ultrasound imaging applications.

Figure 8 Agilent EXA 9020A Vector Signal Analyzer.

The Agilent EXA9020A VSA, in figure 8, implements a very different measurement approach than traditional swept analyzers; the analog IF section is replaced by a digital IF section incorporating FFT technology and digital signal processing. The traditional swept-tuned spectrum analyzer is an analog system; the VSA is fundamentally a digital system that uses digital data and mathematical algorithms to perform data analysis. For example, most traditional hardware functions, such as mixing, filtering, and demodulation, are accomplished digitally, as are many measurement operations. The FFT algorithm is used for spectrum analysis, and the demodulator algorithms are used for vector analysis applications.

A significant characteristic of the VSA is that it is designed to measure and manipulate complex data. In fact, it is called a vector signal analyzer because it has the ability to vector detect an input signal (measure the magnitude and phase of the input signal). Similar to an FFT analyzer, VSAs cover RF and microwave ranges, plus additional modulation-domain analysis capability. These advancements are made possible through digital technologies such as analog-to-digital conversion and DSP that include digital intermediate frequency (IF) techniques and fast Fourier transform (FFT) analysis. Because the signals that people must analyze are growing more complex, the latest generations of spectrum analyzers have moved to a digital architecture and often include many of the vector signal analysis capabilities previously found only in VSAs.

Some analyzers digitize the signal at the instrument input, after some amplification, or after one or more downconverter stages. In any of these cases, phase as well as magnitude is preserved in order to perform true vector measurements. Capabilities are then determined by the digital signal processing capability inherent in the spectrum analyzer firmware or available as add-on software running either internally (measurement personalities) or externally (vector signal analysis software) on a computer connected to the analyzer.

A traditional swept-spectrum analyzer1, in effect, sweeps a narrowband filter across a range of frequencies, sequentially measuring one frequency at a time. Unfortunately, sweeping the input works well for stable or repetitive signals, but will not accurately represent signals that change during the sweep. Also, this technique only provides scalar (magnitude only) information, though some other signal characteristics can be derived by further analysis of spectrum measurements

The VSA measurement process simulates a parallel bank of filters and overcomes swept limitations by taking a “snapshot,” or time-record, of the signal; then processing all frequencies simultaneously. For example, if the input is a transient signal, the entire signal event is captured (meaning all aspects of the signal at that moment in time are digitized and captured); then used by the FFT to compute the “instantaneous” complex spectra versus frequency. This process can be performed in real-time, that is, without missing any part of the input signal. For these reasons, the VSA is sometimes referred to as a “dynamic signal analyzer” or a “real-time signal analyzer”. The VSA’s ability to track a fast-changing signal isn’t unlimited but depends on its computational capability.

The use of DSP also yields additional benefits providing time, frequency, modulation, and code domain measurement analysis in one instrument. Having these capabilities it improves the quality of a measurements. FFT analysis allowing easy and accurate views of both time and frequency domain data. Although the VSA clearly provides important benefits, the conventional analog swept-tuned analyzers can provide higher frequency coverage and increased dynamic range capability.

2.1.5 Results

A set of 50 real DVB-T signals, each one 30 seconds long, with different signal characteristics (modulation, symbol rate, FEC, SNR) were recorded to the Matlab environment using the RF hardware and an appropriate antenna. The signals were contemporary fed to the Agilent Vector Signal Analyzer for identifying their features.

The Simulink / Matlab set-up presented in sections 2.1.3 and 2.1.4 was tested with the real recorded signals in terms of detection reliability.

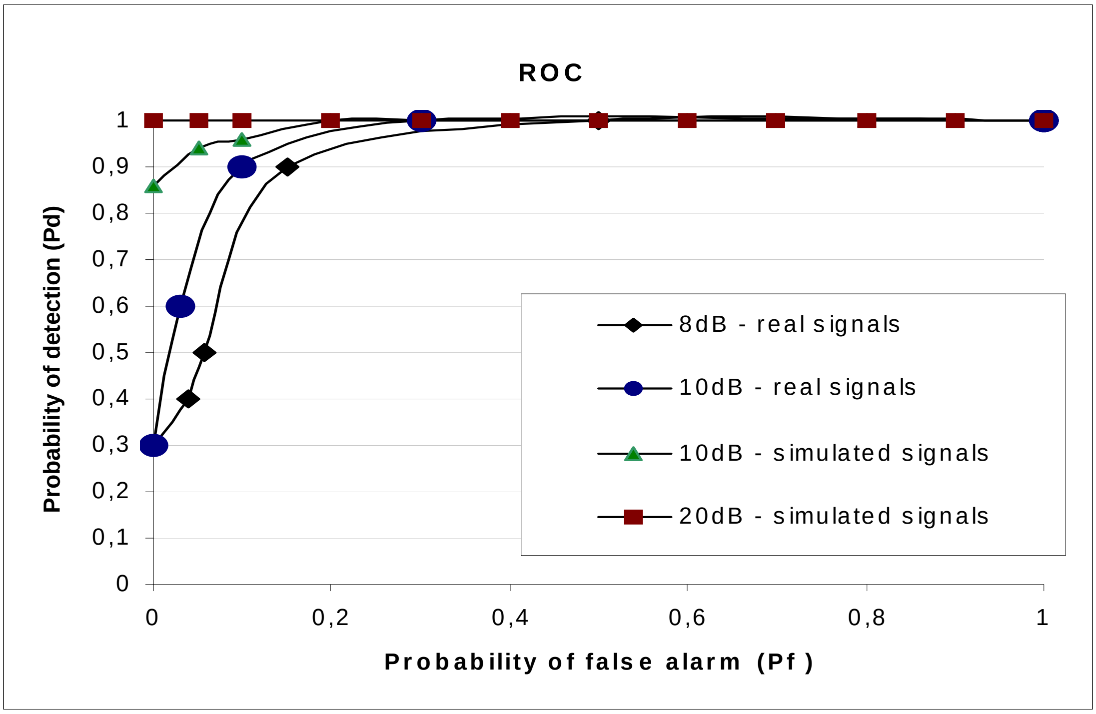

Figure 9 Receiver operation characteristics for the proposed two-stage spectrum sensing method.

Figure 9 presents the receiver operating characteristics (ROCs) of our combined spectrum sensing approach, for both simulated and real DTT signals. While the system performed well for simulated signals with a SNR as low as 10 dB, we noticed a degradation of the detection curve for real signals. It can be seen that the ROC for a real signal with a 10 dB SNR is worse than the ROC curve for simulated signals with the same SNR. The discrepancy is due to the calculation of the initial thresholds values of the feature detection stage, done based on simulated signals.

2.2 Cooperative Spectrum Sensing for Geo-Location Databases

Another possible approach could be the implementation of a cooperative spectrum sensing architecture [22], based on sensor networks. This scenario is applicable both for outdoor and indoor applications. Cooperative spectrum sensing is typically divided into operational networks, handling cognitive transmissions, and sensing networks. The latter would involve a set of sensors deployed in an area of interest, which would sense the spectrum and would relay the process' results to a Cognitive Radio Controller (CRC) [47, 48]. The CRC further processes the collected data and sends the sensed area of interest's spectrum occupancy information to a GL-DB, to which it is connected, in a transparent way, through Future Internet typical infrastructure [49].

The database centralizes all the sensing information from its attached CRCs and serves as a general register that SUs, who no longer require their own dedicated sensing equipment, can inquire for accessing sensing information for their particular area of interest. The focus of this paper is a proof-of-concept on the use of spectrum sensing for populating a GL-DB by implementing and deploying a sensor network – based sensing architecture and extending the functionality of the GL-DB towards human users. This approach features the concepts of cluster radio mapping and natural sensing information perception through 3D Virtual Reality (VR) representations of the GL-DB relevant information for the benefit of a spectrum manager or developer.

Radio Mapping techniques are employed in an attempt to predict and graphically represent network coverage on the basis of a number of connection measurements from locations in an area of interest. A cluster is defined by an area where there is an active CRC and a number of deployed spectrum-sensing sensors. This translates into a real-time electromagnetic profile of the specific area where the sensing sensors are deployed. This profile serves for the design and development of radio architectures over the considered area, and reveals such data as optimum transmission pathways, radio propagation obstacles and, especially, sensing information.

The idea was to implement an architecture able to centralize the real time statistical sensing information, normally intended for secondary cognitive transmitting users who no longer perform the sensing stage, from different areas of interest, in a GL-DB. Also, the next goal was to employ novel perceptual representation in order to provide a radio spectrum manager with a way of perceiving and assimilating this statistical information in a natural and efficient way.

2.2.1 *Conceptual Application Implementation*

The sensing sensor network employed for the functional implementation of the conceptual application is a Crossbow ZigBee Wireless Sensor Network (WSN) that uses wireless sensor nodes know as MICAz Motes [50]. Although it is limited to central frequencies between 2.405 and 2.485 GHz, with low throughput, ZigBee does have sixteen 5 MHz channels that we used for testing the sensing algorithm. In other words, our testing scenario involves limiting the concept of radio frequency spectrum to the 2.405 GHz - 2.485 GHz domain, and its 16 channels. All the sensors of the WSN have in their transmission stream's frames a Received Signal Strength Indicator (RSSI) slot, which reveals a numerical value of the gateway's signal power as perceived by that particular network node, which we can interpret as a power measurement, equivalent to the energy detection spectrum sensing method. The RSSI is a naturally available resource when dealing with wireless nodes, and can be used to implement obstacle and position detection and estimation algorithms, in dealing with both primary and secondary users of a CR Network [51].

The total number of utilized wireless nodes is 192. The area of interest is split into 1.5 m side squares, disposed as 16 in length and 12 in width. Each square is the sensing area of a specific sensor, positioned in the middles of the square at 0.6 meters from the floor. The position of each node represents an increment of the measurement step, of 1.5 meters. Theoretical values of the detected signal power (and implicitly of the sensed signal RSSI) can be found out by utilizing the logarithmic correlation between received signal strength and distance as was previously done in [52].

It is at this point that we will consider a theoretical division of the WSN Gateway into two distinct functional entities. The first will be considered as an entity that gathers the sensing information from the WSN nodes, and therefore, also performs the CRC characteristic functionality of GL-DB update, while the other will handle the WSN Gateway's transmission and will be considered a typical CR primary transmitting user, using one of the typical ZigBee channels. To sum up, the measurement and validation scenario enforces the following suppositions:

- the radio spectrum is the ZigBee standard frequency domain with its 16 channels;
- the WSN Gateway is a primary transmitter;
- the sensors are secondary users who employ energy detection sensing (RSSI);

- the WSN Gateway’s data gathering and GL-DB update is transparent.

The primary user (WSN Gateway) is placed in the corner correspondent to row 0 and column 0 of the sensors grid in the area of interest, at 0.6 m from floor level. All the sensing information gathered by the sensing sensors is real-time processed and forwarded by the WSN Gateway entity, playing the CRC role, towards the GLDB, to be made available for secondary users or spectrum managers.

As previously stated in the definition of the concept, our functional implementation aims at modeling and developing a real-time natural perception and interaction GUI that brings additional functional uses for the GL-DB concept. The data, contained in the GL-DB, that was originally intended for cognitive users can be employed by spectrum and network managers in order to better understand, develop and utilize available channels and spectrum resources. For perceptually representing the gathered GL-DB data, the authors implemented a 3D VR Environment build upon traditional desktop equipment, which portrays the available sensed information. Inside the GUI, along with information perception, the user can interact with relays and switches that control actuators from the area of interest, in so enabling the reconfiguration of the sensing architecture to better suit the user’s informational needs. The consequence of the interaction inside the GUI and its implicit sensing sensor pattern reconfiguration is a real-time change in the sensed information and accordingly in its representation. Also inside the 3D GUI, there is a navigation menu that allows the user to move inside the virtual environment in order to gain better perspective and perception of the relevant information. The deployed 3D Virtual Environment is supported by the VR Media’s XVR virtual reality framework [53]. The virtual environment is a 3D replica of the real world area of interest, starting from the RSSI information interpretation, upon which, obstacle and position detection and estimation algorithms were based, can be implemented.

2.2.2 Results

A view of the 3D representation of the gathered data is presented in figure 10. The graphic representation describes a Cognitive Radio Network primary user’s (WSN Gateway) signal power distribution as received by a sensing WSN. This radio signal is on a typical ZigBee frequency channel, having 5 MHz of bandwidth. The represented values are expressed in [dBm] and they are subject to the propagation constraints provided by typical electromagnetic indoor obstacles, disposed in the area of interest.

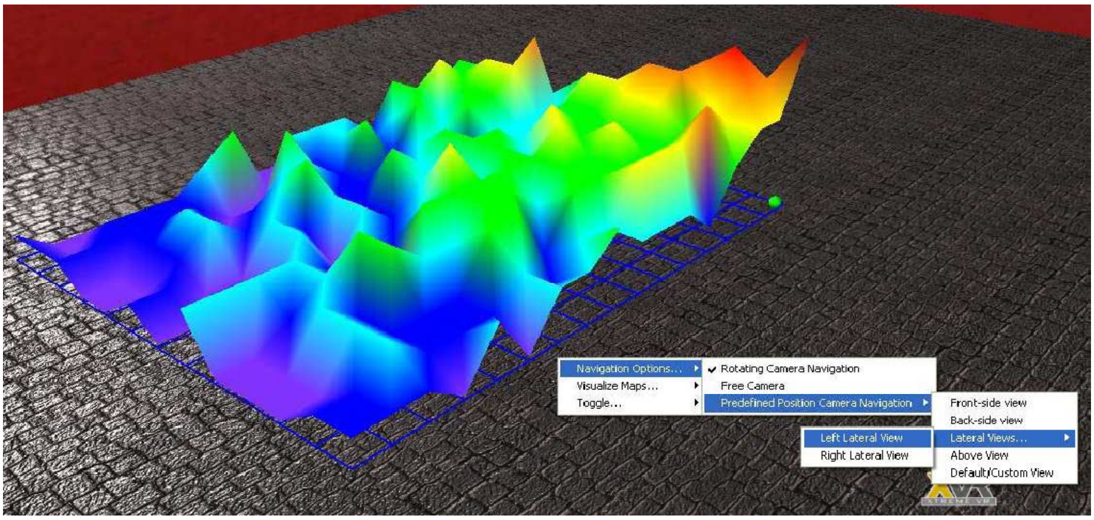

Figure 10 Radio Map representation of the signal power distribution with smooth transition between colors, inside the area of interest (form Red the highest value to Violet the lowest); The green sphere represents the WSN Gateway primary user.

The highest RSSI values are color-coded red, and are given a high value on the Y axis (the orthogonal direction from the wireless sensor node arrangement geometry represented as a blue grid plane), in the representation, while the lowest are color-coded violet, and have a value of 0 (null) on the Y axis. Between the two extremes the values are interpolated, for a smooth transition. The green sphere marks the location of the transmitting primary user, and, as expected, has the highest RSSI value. While the signal power distribution profile is loosely consistent with Friis' model equations, the inherent anomalies signify electromagnetic obstacles, typical to indoor environments. The measured Gateway RSSI values were in between a -60 dBm and -100 dBm. The WSN's PER (Packet Error Rate) was established to be 3.4%.

The main result is the added value derived from the hybrid implementation of the Radio Spectrum Management field with Virtual Reality representation and multimodal interaction methodologies. The first tests, performed in order to validate the proof-of-concept application, using a single frequency, showed that merging exponentially developing domains such as Virtual Reality and its characteristic techniques and devices with the field of spectrum sensing and, generally, dynamic spectrum management, results in added functionality and significant added value for the latter. The idea is to continue these initial tests by analyzing a more extended range of frequencies and by implying more intelligent sensor nodes, for example software-defined radios.

Coordinated Techniques that involve CRCs, if operational networks would be implemented on top of sensing networks (collocated) and additional functionality (from the point of view of the transmission and processing power) would be passed from the CR Controller to the sensor nodes, which can be implemented by employing SDR platforms (USRP2) [54]. This is not an evolution of the Sensing sensor networks approach but rather a parallel alternative for a better-suited purpose scenario, both collocated and separated architectures approach having their pros and cons.

Because of the immersive nature, high interactivity and powerful sense of presence, the authors' 3D GUI complies perfectly with the 3D Internet [55] component of the Future Internet that offers users an augmented interaction and navigation metaphor. Also, the wireless nodes network features a functionality that emulates Internet of Things specific scenarios, while the whole conceptual application offers a radio spectrum management service particular to the Internet of Services.

The VR environment could be further developed by employing advanced visualization, sound and haptic devices specific to immersive VR applications (i.e. CAVE [56]). The first tests, performed in order to validate the proof-of-concept application, using a single frequency, showed that merging exponentially developing domains such as Virtual Reality and its characteristic techniques and devices with the field of spectrum sensing and, generally, dynamic spectrum management, results in added functionality and significant added value for the latter. These initial tests will be continued by analyzing a more extended range of frequencies and by implying more intelligent sensor nodes, for example software-defined radios.

Chapter 3

A Real Cognitive Radio System in the TVWS

The evolution of wireless communication systems and networks in recent years has been explosive. This trend had an enormous impact also on short-range indoor consumer applications. Today's TV broadcasting industry is rapidly facing new challenges to chase the technological progress if compared to the previous fifty years of its existence [57]. The analog to digital migration of the broadcasting technologies, has allowed broadcasters offering interactive services and tailored applications to users which include interactivity, different levels of personalization, and innovative location-based, as well as context-aware, services [58]. Recently, several new means for delivering services, such as TV video streaming over IP (IPTV) based either on XDSL or in the forthcoming near future on WiMAX, LTE or LTE-A access are arising beside traditional terrestrial and satellite systems [59]. All these new access techniques are providing broadband services, enabling the streaming of high definition video and audio information [60]. The new generation set-top boxes are provided with the multiple access feature being able to decode heterogeneous TV input signals (e.g., DVB-T, DVB-S, IPTV) whereas the promise of multi-room digital video recording (DVR), as well as the ability to deliver commercial content to more devices within the same domestic environment, excites both consumers and service providers. Within this context, the Digital Living Network Alliance (DLNA) has developed a robust set of technical guidelines for high-quality streaming of multimedia content over both wireless and wired network connections between home entertainment and mobile devices [59]. The DLNA guidelines provide for a homogeneous and universal infrastructure through Wi-Fi 802.11 for wireless connectivity and Multimedia over Coax Alliance (MoCA) for wired connections. MoCA uses an infrastructure based on coaxial cable for providing reliable distribution of video content [61].

On the other hand, wireless connectivity through Wi-Fi spots raises overcrowding issues. The significant advances and the growing interest in wireless technologies have resulted in a wide range of standards and applications, especially the ones operating in the unlicensed 2.4 GHz Industrial Scientific and Medical (ISM) band. The overcrowding of the ISM band is becoming in fact a serious challenge for the development of the next-generation networks operating in these bands (e.g., ad-hoc, low-power networks). These problems are even more accentuated in urban morphologies such as dense cities with near multiple floor buildings. In the EU, for instance, the proliferation of indoor Wi-Fi networks operating in the ISM band, has led to a situation in which every flat has its own Wi-Fi spot, leading to complex coexistence problems.

In order to limit this congestion, especially for indoor applications, the first proposed solution was the use of the currently non-congested 5 GHz band. Unfortunately, working at such high frequencies does not allow indoor systems to provide very high data rates and adequate coverage in indoor environment such as multi-floor houses. Therefore, a valid alternative would be to use lower frequencies (below 1 GHz),for which the signal propagation in indoor environment improves, avoiding phenomena related to the presence of objects, walls and other obstacles, even in big buildings with multiple floors.

Worldwide, lots of countries have already finished or are in the process of switching off analog TV broadcasting in favor of DTT broadcasting systems [7]. Even after the redistribution of the digital TV channels, the problem of an efficient utilization of the allocated frequencies is still far from being solved. For example, there are still large territorial areas on which, although allocated, the TV channels result unused, due to coverage problems. In these conditions a transmitter operating at a low antenna height and a low power level such as for a typical indoor application, could reasonably operate without causing existing interference to TV services, due to its much restrained service and interference range. To dynamically exploit the nominated spectral opportunities (i.e., TVWS), such a device should have the capability of monitoring its own radio environment and adapt accordingly. These capabilities are typical for CRs.

In the TV bands specifically, the presence of PUs (e.g. TV broadcasters) can be revealed both performing a local survey of the occupied spectrum (the “spectrum sensing” operation) and considering the information provided by the external GL-DB if available. In the United States, the FCC has already named several operators and performed first field tests with such GL accessible to CR devices at no operational cost. As already seen the database provides, for a certain location, the list of the free TV channels and the allowable maximum effective isotropic radiated power (EIRP) for transmitting without harmful interference to incumbent users [17]. In other countries such as the UK the management of Program Making and Special Events (PMSE) band already makes extensive use of similar databases to license radio microphones and in-ear monitor (IEMs) users within the UHF band. The drawback of using GL-DBs, even upgraded on a daily basis, resides in the values corresponding to a specific geographical point that are still the results of calculations based on a certain signal propagation model and estimated power level. Due to this static (for short term at least) approach, the provided data might be inaccurate for different reasons such as variable atmospheric conditions o 'and fading phenomena. Furthermore, GL based on the exact position of a cognitive device, which especially for indoor applications may not be accurate [17]. The BBC conducted a study [62] on compatibility problems for broadcasting networks and devices operating in the DTT band. The study identified the joint use of spectrum sensing techniques, GL-DBs and EIRP control as a possible way to effective safe communications. This conclusion is being supported also by a research conducted by the Electronic Communication Committee (ECC) [17] and is implemented by the first worldwide TVWS cognitive radio standard, the IEEE 802.22 WRAN [18, 19]. By the light of that, TVWS in the UHF bands, with respect to certain limited low power application, could be candidate to reduce the congestion in the 2.4 GHz band for typical consumer indoor applications.

For all this reasons we decided to implement an unlicensed indoor short-range distribution system for the wireless retransmission of high definition (HD) DTT-compliant contents in the TVWS, with straightforward implementations as home entertainment system. The HDTV content can be both free-to-air (FTA) and pay channels received by either DTT/SAT or cable TV, IPTV, sources as well as auxiliary content originating external inputs (A/V devices, infotainment content, closed circuit cameras etc.). The DTT receivers do not require auxiliary hardware, but a conditional access module (CAM) nowadays commonly incorporated in consumer equipment. A potential consumer application scenario is indoor broadcasting of HD DTT contents, redirecting several channels which may be acquired from different sources (DTT, SAT, IPTV, cable TV etc.). Unauthorized access is prevented by employing digital rights management (DRM) scrambling techniques [63] implemented on a common interface (CI) card to be inserted in the CAM slot of the DTT receiver. The system relies on the exclusive joint use of GL-DBs and spectrum sensing. We focused on real transmitting constraints such as the Adjacent Channel Interference (ACI) issues, the potential direct radiation into the TV receiver and the presence similar systems within the same coverage range. To assess the feasibility of the proposed system, extended measurements were performed in real indoor environments with respect to the protection of the existing broadcasting TV services which verify the suitability for multi-floor environments.

The rest of the chapter is organized as follows. Section 2.1 describes the design of the proposed technical solution and section 2.2 presents the actual implementation. Section 2.3 describes the test-bed, the performed measurement campaign together with the results of the hardware implementation, to illustrate the system's feasibility. Finally section 2.4 illustrates some application scenarios.

3.1 System Description

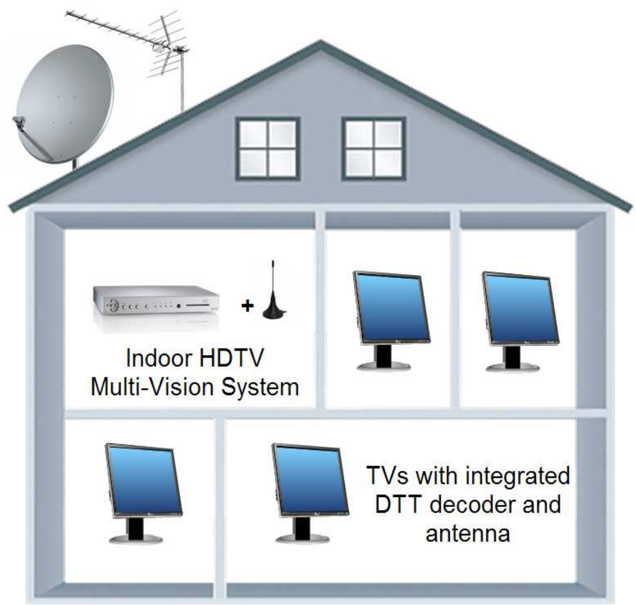

Figure 11 General view of the indoor system.

Before starting with the description of the system, the concepts of multiplex and transponder for digital television transmissions need to be restated. A multiplex (MUX), also called virtual sub-channel in the USA, is a group of several TV channels mixed together (multiplexed) and broadcasted over a DTT frequency. Many PPV TV broadcasters offer to their subscribers several MUX packages (i.e. a dedicated MUX for sport events, movies etc.). Depending on the regional DTT broadcast standards, a single MUX is able to broadcast up to 16 TV channels with a total transmission rate up to 40 Mbps (for example the European DVB-T2 standard [23]). This data rate is divided between HDTV, Standard Definition Television (SDTV), radio and additional information channels. Similar to the terrestrial MUX, the satellite transponder includes several video and audio channels on a single wideband carrier. A typical transponder has a bandwidth between 27 Mbps and 50 Mbps (DVB-S2 standard [64]). This data rate is also divided between HDTV, SDTV, radio and additional information channels.

The main idea is to use the TVWS to redirect several TV MUXs/transponders, originating from terrestrial or satellite transmissions, to a range of authorized users in an indoor environment. Additional contents from DVD/PC/mobile/camcorders or IPTV devices can be shared for home entertainment use or for infotainment architectures (resorts, hotels, airports, malls etc.). Besides the active use of GL-DBs (encouraged both by European and US regulation boards and IEEE standards), the proposed system also implements spectrum sensing as an additional resource. Sensing is used for validating the local unused or underused channel information read from the standard database and, in case, refining the terms of its use (e.g. EIRP control).

This indoor multi-vision system is based on a central cognitive device acting as a server and in charge for receiving TV content and retransmitting it at low power to end devices that, in this case, are commercial TV sets with onboard DTT decoders (figure 11). The system is assumed to be connected to a GL-DB which provides information on the unused channels available in a particular location and, thanks to the spectrum sensing approach, is able to validate the result of this query in an exclusive manner [14]. The four main tasks performed by the central device are illustrated in figure 12.

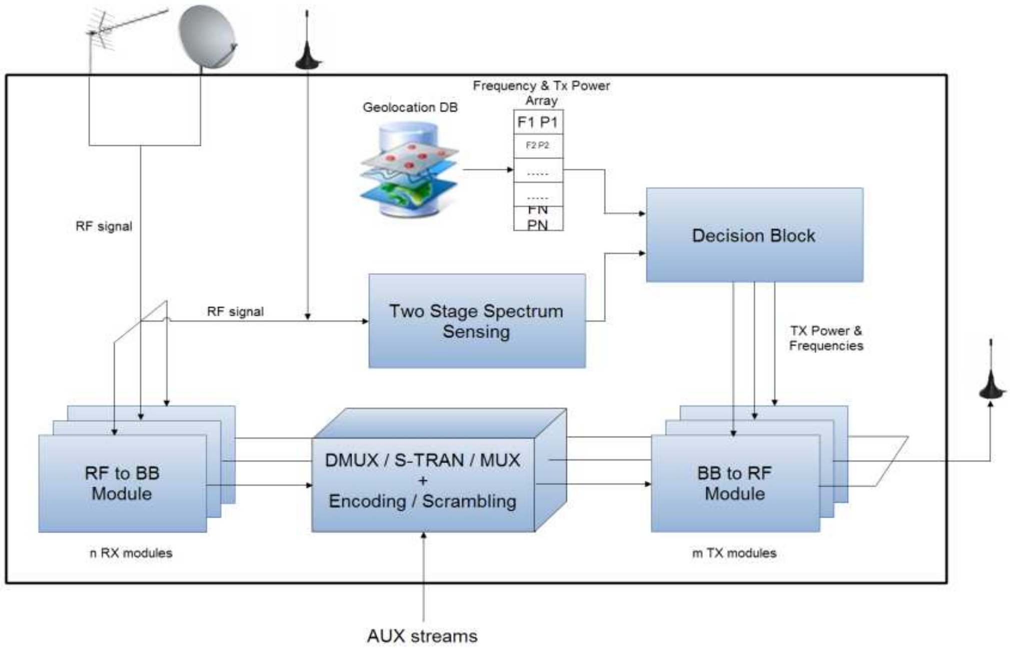

Figure 12 General view of the indoor HDTV multi-vision system.

The first task is to receive digital broadcasting content and to translate it from radio frequencies to baseband (RF/BB modules). Each of the n modules can handle the TV programs contained in one DTT MUX or Satellite Transponder. Additional modules are needed for simultaneously receiving more MUXs or transponders in order to allow the users to build up a list of desired TV channels.

Based on this list, the central block (DMUX/S-TRAN/MUX) handles the n received digital contents and bundles the chosen channels into one or more MUXs/transponders compliant to the opportune standard. The number m of generated MUXs/Transponders depends on the number of the desired channels and their characteristics (SDTV, HDTV, radio etc.). The central block has also the possibility to redirect additional contents from external DVD/PC/mobile/camcorders or IPTV devices (AUX streams) in the detected spectral opportunities, as one or more channels within a MUX.

Prior to the distribution, the TV content is encoded/scrambled by a proprietary Digital Rights Management (DRM) - compliant system [65, 66], thus preventing streaming by unauthorized users. Only the TV sets equipped with a dedicated Conditional Access Module (CAM) paired to the central device will be enabled to decode and to view the retransmitted contents.

The decision block takes into consideration possible inconsistencies between the GL-DBs and the output of the sensing stage: for example, if the spectrum sensing stage detects no broadcasting services or PMSE signals, but the database shows one or more channels used by broadcasting services or PMSE, these channels will not be used until both content is congruous. In the other case, if the spectrum sensing stage detects signals of broadcast services or PMSE, but the database shows no used channels, the incriminated channels are discarded too [67]. The validation analysis provides the optimal frequencies and the maximum transmission power values to be used by the m BB/RF modules, based on an algorithm which will be presented in next section.

The last task implies the m BB/RF modules in the effective over-the-air DTT compliant retransmission of the digital contents on the previously chosen frequencies, using power levels as to avoid interferences with the incumbent services.

3.2 System Design

The proposed system involves the knowledge of the channel occupancy for a particular location to calculate the allowable maximum EIRP useful to transmit without providing harmful interference to adjacent channels. Real transmitting device constraints as potential direct radiation into TV receivers, adjacent channel Interference (ACI) issues and the existence of similar devices need to be taken into account in order to find exhaustive values.

3.2.1 Adjacent Channel Interference

For indoor environments the distance between an interference device and a DTT receiver is relatively short and intermodulation effects can occur. The tolerance of DTT receivers to ACI has been quantified in several studies [67, 68], revealing that transmission on adjacent channels can cause harmful interference if the output power of the transmission exceeds the maximum received interference power tolerable by the DTT receiver, especially for indoor environments where the distance between the interference device and a DTT receiver is short and intermodulation effects can occur.

In [68] further measurements have been made on a wider range of receivers (including some newer silicon tuner based designs). The wanted TV signal and the interference signal were put together using a directional coupler and a combiner. The useful signal (C) versus interference (I) protection ratios C/I obtained are shown in figure 9. The protection ratio is the minimum value of the signal-to-interference ratio required to obtain a specified reception quality under specified conditions at the receiver input [69]. For these measurements, the reception quality was quantified using subjective evaluation criteria, i.e. the absence of a picture failure (PF) [70, 71], during a minimum observation time of 30 seconds [72].

The first two curves (labeled “Si Tuner” and “CAN Tuner”) in figure 13 clearly show how the power of an interfering DTT signal does not decay gradually on both sides starting with the adjacent channel. Depending on the quality of the receiver, the fifth and especially the ninth channel can create interference problems, particularly for the older, so-called “CAN” tuners. Most of the current TV sets use newer “silicon” tuners having a much smoother and predictable protection ratio than CAN tuners across all channels and do not suffer from the ninth image channel weakness in protection ratio [68].

All these measures found in literature have been performed by coupling the useful and interferer signals directly, using directional couplers. Instead, real DTT systems implement over-the-air transmissions. Starting from this consideration, we decided to validate the results in an ideal radio environment using antennas for the transmission of the wanted TV and interference signal as described in section 2.2.2.

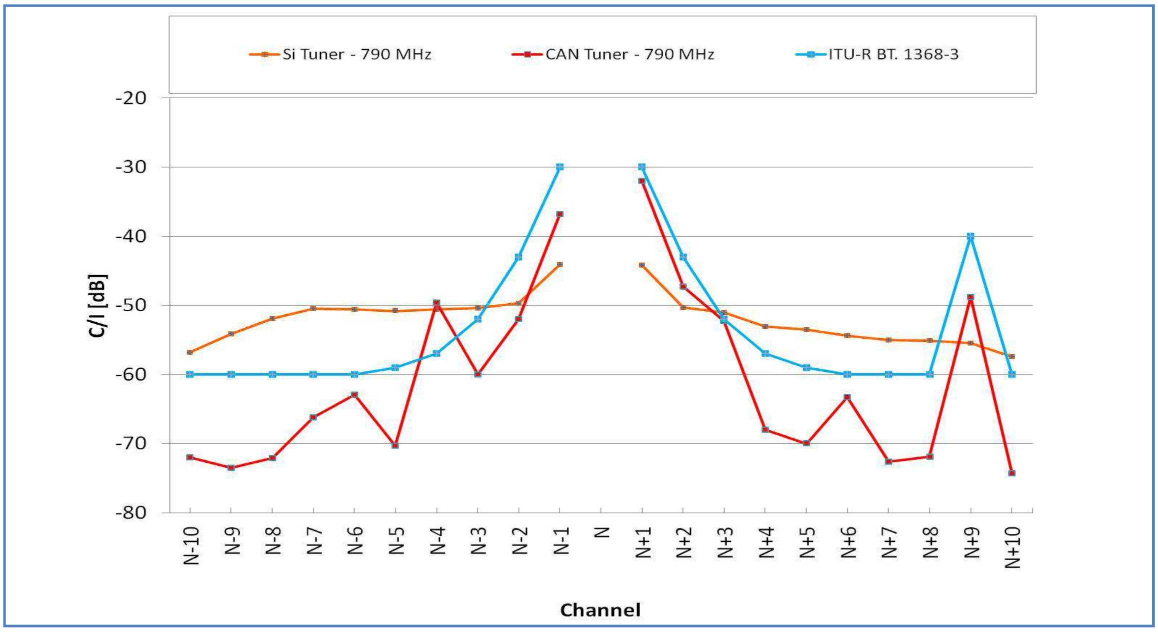

Figure 13 DTT into DTT protection ratio (DVB-T signal, 8K 64QAM 2/3 FEC) with C = -73 dBm for literature references.

3.2.2 Anechoic Chamber Measurements

The measurements were performed in the anechoic chamber of the Department of Electrical and Electronic Engineering of the University of Cagliari in Italy. It is a room insulated from exterior sources of noise, designed to stop reflections of electromagnetic waves and consists of an outer casing of galvanized steel, which allows creating an effective shield in order to make as much as possible insensitive to electromagnetic interference that may be present in the environment. The combination of both aspects means it simulates a quiet open-space of infinite dimension, which is useful when exterior influences would otherwise give false results. We tested three commercial DTT flat-screen TV receivers. A PC running GNU radio software was in charge to generate the wanted TV signal that was successively transmitted by an USRP2 SDR board covering the entire UHF band and connected to a CBL6143 indoor stub antenna. The TV sets were connected to a PCB WA5VJB log-periodic antenna. The DTT-compliant interference signal was generated with an Agilent N5183A (figure 14) signal generator using a Sirio SD 1300N discone antenna.

Figure 14 Agilent N5183A Vector Signal Generator.

The transmitted and received signal power was analyzed using an Agilent N9010A EXA Signal Analyzer. The main characteristics of the antennas are summarized in table I.

TABLE I
CHARACTERISTIC OF THE ANTENNAS USED IN THE MEASUREMENTS

MODEL	POLARIZATION	TYPE	FREQ. RANGE [MHz]	TX-GAIN RANGE [dBi]	RX-GAIN RANGE [dBi]
PCB WA5VJB	Vertical	PCB logperiodic	400 - 1000	0.2 - 4.2	0.06 - 2.5
Schaffner CBL6143	Vertical	X-Wing BiLog	30 - 3000	6 - 8	6 - 8
Sirio SD 1300N	Vertical	Discone	25 - 1300	0 - 5.5	0 - 6
BAF 121XSA2A	Vertical	Stub	470 - 870	0 - 2	0 - 2

The N5183A MXG microwave analog signal generator delivers the performance needed for broadband component manufacturing. This instrument provides ≤ 900 μs frequency switching (≤600 μs typically) to improve test times for applications like antenna test and manufacturing. All the antennas were properly placed in the anechoic chamber at a height of 1.5 m, in order to avoid antenna coupling (figure 15).

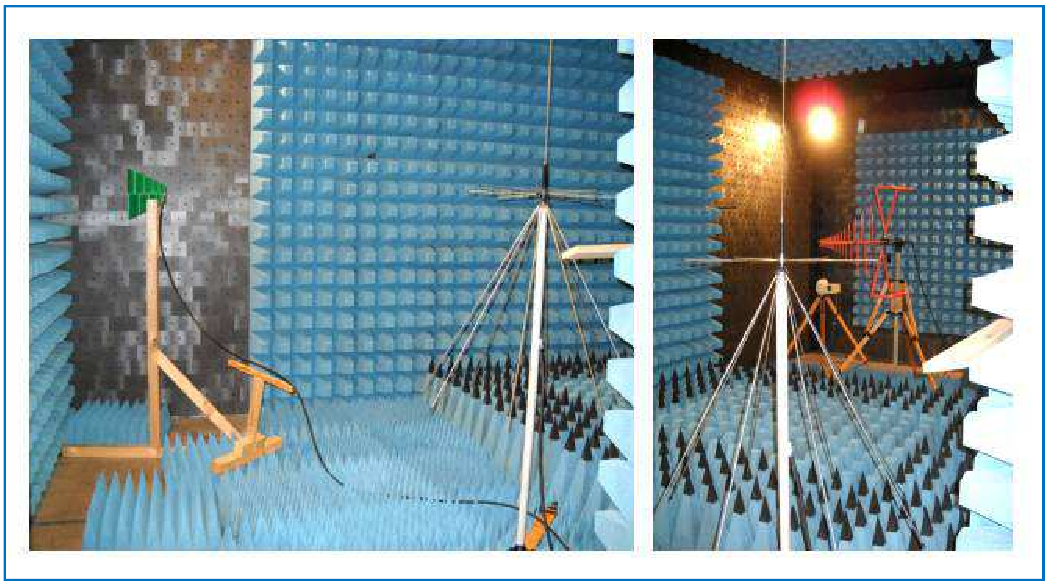

Figure 15 Antennas disposition during measurements in the Anechoic Chamber.

Optical fiber cables were used to connect the antennas to the generators, vector analyzer and DTT receivers placed outside the chamber Using the guidelines found in the literature [67] and the ITU Recommendation 1368-3 [72] (fixed C, variable I) the following test procedure was used to measure the C/I protection ratios:

1) For each of the three DTT tested receivers we measured their sensibility finding an average level of -73 dBm. Thus the wanted channel power level C was set to -73 dBm. This can be considered the worst operative case.
2) The wanted channel power level was measured using the Agilent N9010A Vector Signal Analyzer (VSA) with a channel bandwidth of 7.61 MHz.
3) The signal generator transmitting the interfering DTT signal was initially set to a power level of -20 dB below the noise floor of the tested receiver.
4) The signal level of the DTT interference was then adjusted at the output of the signal generator to achieve the required degradation (PF point) of the received and decoded MPEG signal.
5) The RMS power level of the interferer was measured in the channel bandwidth of the receiver.
6) The C/I protection ratio was calculated from steps 2 to 5.
7) Steps 2 to 6 were repeated for each of the channels from $N-9$ to $N+9$.

The protection ratio for the DTT receiver tested (Anechoic 790 MHz) and used in the implementation of the system is shown in figure 16.

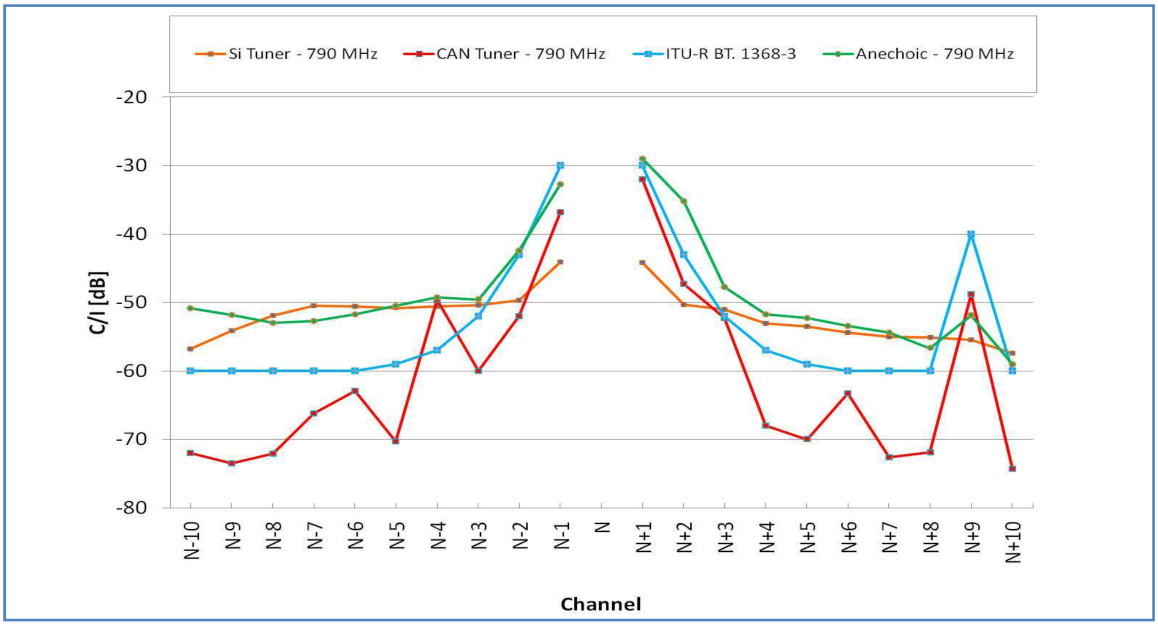

Figure 16 DTT into DTT protection ratio (DVB-T signal, 8K 64QAM 2/3 FEC) with C = -73 dBm for literature references (Si Tuner, CAN Tuner and ITU curves) and measurements performed in the anechoic chamber.

The results demonstrate that, even in real over-the-air transmission, the receivers under test can be considered as having typical operating performance for silicon receivers, more susceptible to DTT interference on the N-1, N+1 and N+9 channels. The reference results found in the literature for both silicon and can tuners were obtained considering a central frequency of 790 MHz (channel 61). For this reason we chose the same centre frequency for obtaining consistent values.

The protection ratios were obtained taking into account the characteristics of all antennas and cables used in the measure setup. The measurements in the anechoic chamber present a higher C/I ratio than the previous studies, due to the fact that the values were obtained in different conditions implying over-the-air transmission.

3.2.3 Spectrum Sensing Method

Spectrum sensing in the TVWS needs to detect the presence of different types of signals such as DTT or wireless microphone (WM) in a particular TV channel. As known, spectrum sensing techniques mainly focus on primary transmitter detection. The present system uses the two-stage spectrum sensing algorithm previously described in section 2.1.

The first stage performs an energy detection deploying filter banks for sub-band division and FFT for calculating signal power levels in each sub-bands. The resulting values are compared to DTT and WM specific thresholds values to mark the channels as free (“white”) or occupied. The second performs the signal classification: for all the channels that previously were identified as not “white” it analyzes if they are occupied by PU or SU using a modulation classifier.

The modulations for DTT (QPSK, 16QAM, 64QAM etc.) and WM (FM) signals are known, so a signal classifier for these typical modulation schemes can be used. Based on the signal classification stage, the channels are completely discarded or added to the previously built “white list” of TVWS.

3.2.4 Protection Ratio Mask

As described in section 2.2.1, in the proposed system a central cognitive device is in charge of transmitting at low power on the free channels in the UHF bands to DTT TV sets, without disturbing existing transmissions. These free channels have to be considered as interferers to all DTT receivers present both in the home environment as in the nearby environment (for example neighbor apartments of a house). Thanks to the previous measurements we obtained information of how DTT receivers can be interfered by active transmission over their adjacent channels.

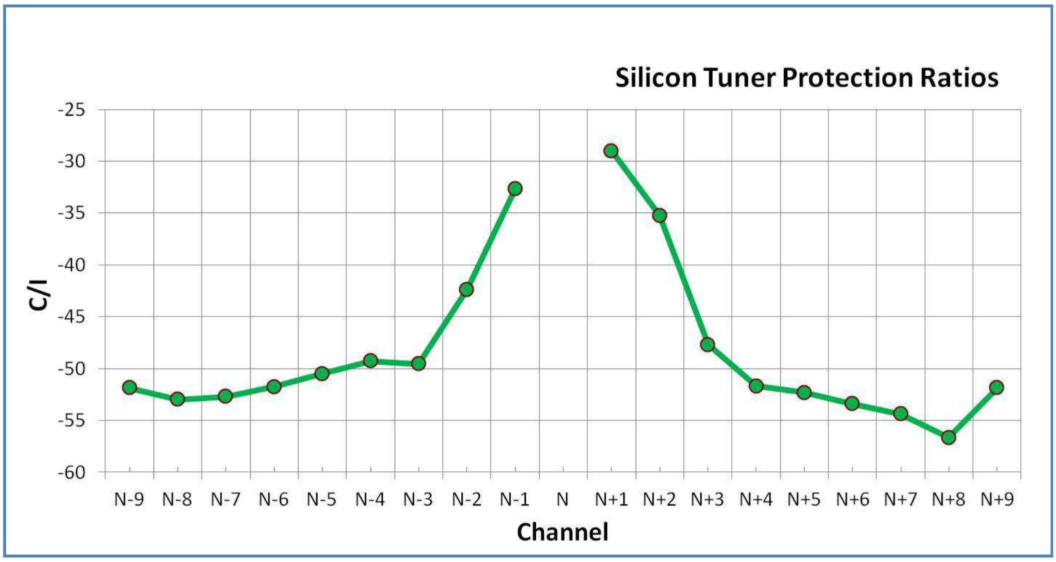

Figure 17 Silicon tuner protection Ratio.

From the point of view of a potential transmitter operating in one of these adjacent channels, the C/I protection ratio in figure 17 can be turned into a mask to be used for calculating the allowed transmission power. The superior adjacent channels of a receiver represent inherently the inferior adjacent channels of a potential transmitter (figure18).

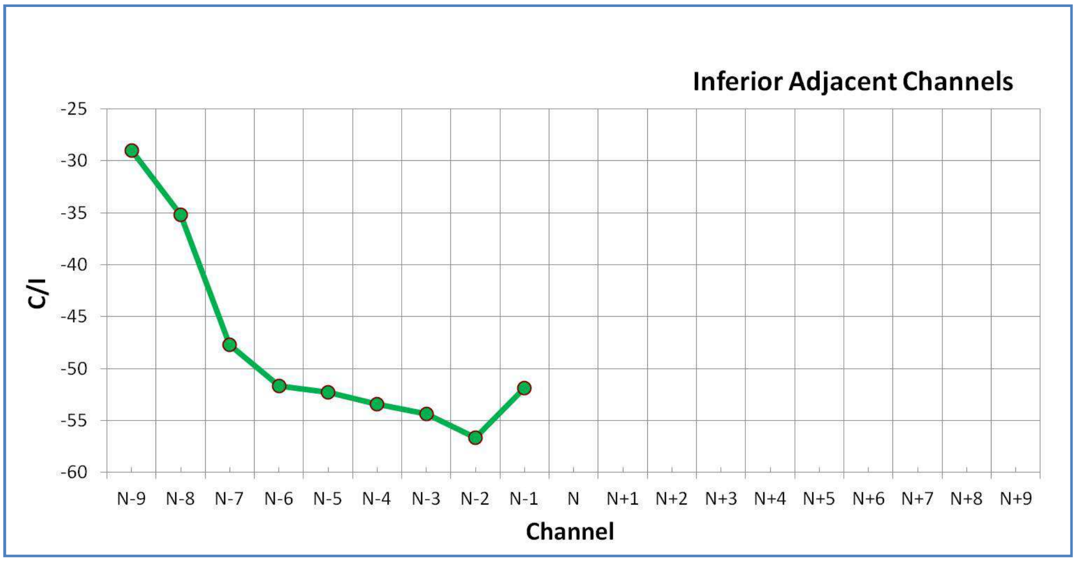

Figure 18 Inferior adjacent channels of a potential transmitter.

At the same way, considering the Protection Ratio curve, the inferior adjacent channels of a receiver represent the superior adjacent channels of a potential transmitter. The new obtained curve is shown in figure 19 representing the protection ratio curve of a potential transmitter.

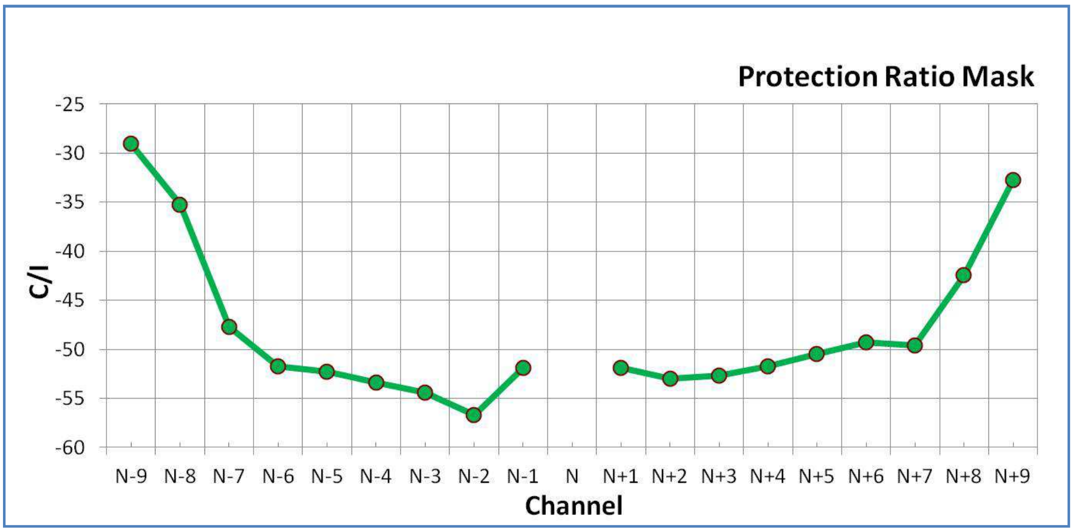

Figure 19 Protection Ratio for a potential transmitter.

This mask is the reversed representation of the protection ratios of figure 17. For a potential transmitter operating in the adjacent channels, the protection ratio can be turned into a mask to be used for calculating the allowed transmission power.

3.2.5 Adjacent Decision Algorithm

For dynamically choosing the best TVWS, in order to avoid interference to the adjacent active channels, we implemented a particular algorithm called Adjacent Decision Algorithm (ADA). The algorithm uses as input are the occupancy data (the list of available channels obtained from the joint exclusive use of GL-DB and a spectrum sensing method), the channel power values in the UHF band (two-stage spectrum sensing of section 2.1), the number of channels to be used (from the DMUX/S –TRAN/MUX block) and the adjacent channel protection ratio mask (ADA Mask) shown in figure 20, in order to obtain a list of available TVWS and their corresponding transmission powers.

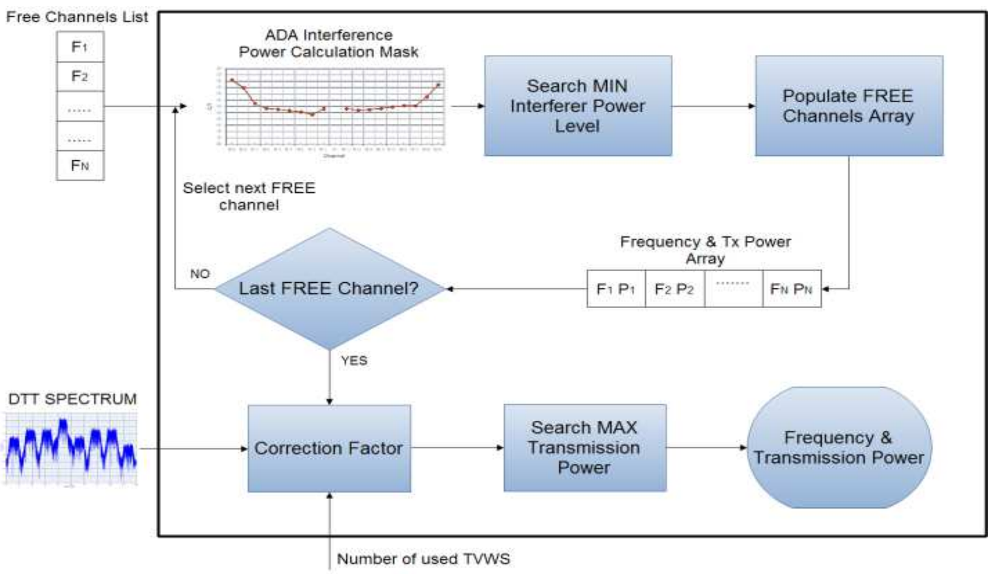

Figure 20 Schematic of the Adjacent Decision Algorithm.

We assume that a number of N free channels can be detected. The N^{Th} available channel can be seen as a potential interferer by its 18 adjacent channels (from $N-9$ to $N+9$ channels). At the same way, a generic $(N \pm x)^{Th}$ channel (with x from 1 to 9) sees the N^{Th} free channel as its $(N \mp x)^{Th}$ adjacent channel. Based on the knowledge of both the received power of all the 18 adjacent channels and the ADA Mask Protection Ratio (figure 18) the algorithm estimates 18 different potential transmission power values for the N^{Th} free channel. Only the minimum value of these 18 power levels guarantees an active transmission that does not generate interferences.

For example, for a generic N^{Th} free channel, considering one of its 18 adjacent channels characterized by a power level $C/I = -52\ dBm$ and a $C/I = -52\ dB$, the algorithm calculates the allowed transmission power for the considered adjacent channel as $I = C - C/I = -4.5\ dBm$. Recursively, the allowed transmission power levels are calculated for all the remaining adjacent channels and the minimum power level is chosen. This procedure is repeated for all the N free channels.

Multiple low-power secondary transmissions behave as a single high-power user when they all are using the same frequency. Nevertheless, in a realistic indoor scenario with more than one secondary user, simultaneous secondary transmissions will have inherently different transmit powers and will operate in different frequencies. Thus, their aggregated transmit powers cannot be simply summed up and treated as a single high-power interference. Measurement results [73] showed how the tolerable interference level in a particular adjacent channel decreases when multiple devices access different adjacent channels at the same time. Based on the number of channels used to retransmit the selected HDTV contents and a specific correction factor [73], ADA is able to find the TVWS with the highest potential transmission power level, for incrementing the performance of the indoor system in terms of coverage (distance) between a transmitting and a receiving device.

As shown in section 3.2.2, the protection ratios have been computed from measurements under ideal conditions. Taking into account that, for a fixed channel power level C, the signal level I of a DTT interference in a real environment will always be lower than the signal level in an ideal environment due to propagation effects, we can consider the obtained protection ratios curve as a worst-case scenario. For this reason, based on the protection mask obtained from the measurement previously shown, the ADA can perform in a real scenario, without having its performance affected.

3.3 Measurements and Results

This section is dedicated to explain the investigation for experimentally determining the conditions under which the co-existence of short-range DTT receivers and transmitters is feasible for indoor environments. We investigated the coverage of the central device, performing a DTT MUX retransmission , considering a fixed transmission power level obtained by using the described ADA algorithm in real environment.

3.3.1 Set-up

The set-up for the measurement campaign consisted of a broadband vertically polarized omni-directional discone antenna “Sirio SD 1300N” connected to a DTT compliant TV set, and two USRP2 SDR boards connected to two PC running a software model that commands the RF hardware implement the entire baseband processing. Each board is connected to a vertically polarized off-the-shelf omni-directional indoor antenna (BAF-121XSA2A). One of the boards is used as the main central cognitive device, while the second one, placed in an adjacent room, plays the role of another multi system transmitting continuously for simulating the aggregate interference scenario.

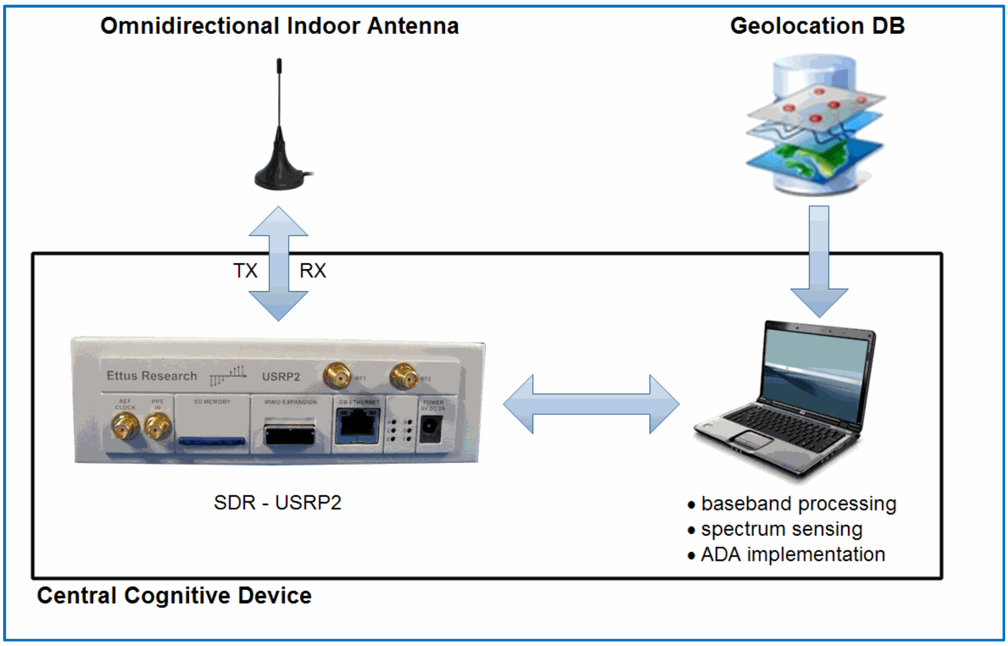

Figure 21 Schematic of the hardware set-up for the central device.

The central device of the proposed system, illustrated in figure 21, is performing following tasks:

- Running a decision algorithm (ADA) taking into account all adjacent channel interferences for choosing the optimal transmission frequencies and power levels;

- Transmitting a DTT signal using the selected frequencies.

The indoor measurements were performed inside the Department of Electric and Electronic Engineering (DIEE) located in Cagliari, Italy, using the 474 - 858 MHz frequency range (Italian DTT spectrum). The central device is considered to be fixed in location during all the tests, while the receiving TV set has a variable position. Receiving a channel with a low power level C implies that the useful power level to transmit a signal in an adjacent channel needs to be lower in order to respect the protection ratio values C/I For operating in a worst-case scenario, we investigated the received power channel levels in different locations of the department in order to find the worst conditions, before selecting the final position of the central device.

The central cognitive device, using the ADA, calculated the maximum available transmission power for the selected best TVWS. By initially placing and operating a TV set close (more than 1.5 m to avoid antenna coupling) to the central cognitive device, we checked for interference with the received existing transmissions, ensuring the correct functionality of the ADA.

From this moment the only variable during the measurement campaign was the distance between the central device and the receiving TV set. For the investigated worst-case scenario a transmission power of -22 dBm for the central device, operating on channel 46 (674 MHz), was calculated by ADA in order to not disturb a receiver in proximity of the central device and to avoid effects of aggregated interferences with another multi-vision system. This power level is the output power level of the central device, prior to the antenna used for the effective transmission.

3.3.2 Measurements

Initially we considered the TV set on the same floor (ground floor) with the central device. We started by positioning the TV set in the neighbor room of the central device reaching a distance of 7 meters (TV1 in figure 22).

Incrementing the distance from the central device we found two position of the coverage boundary corresponding to the TV2 and TV3 positions in figure 22. The slight difference in linear distance (23 meters vs. 25.5 meters) is motivated by the presence of a different number of walls in the two links, specifically the presence of one supplementary wall for the TV set positioned at 23 meters from the central device. Subsequently we positioned the TV set in different positions on the first floor of the building (figure 23), keeping the same position and transmission power for the central device as in the previous scenario.

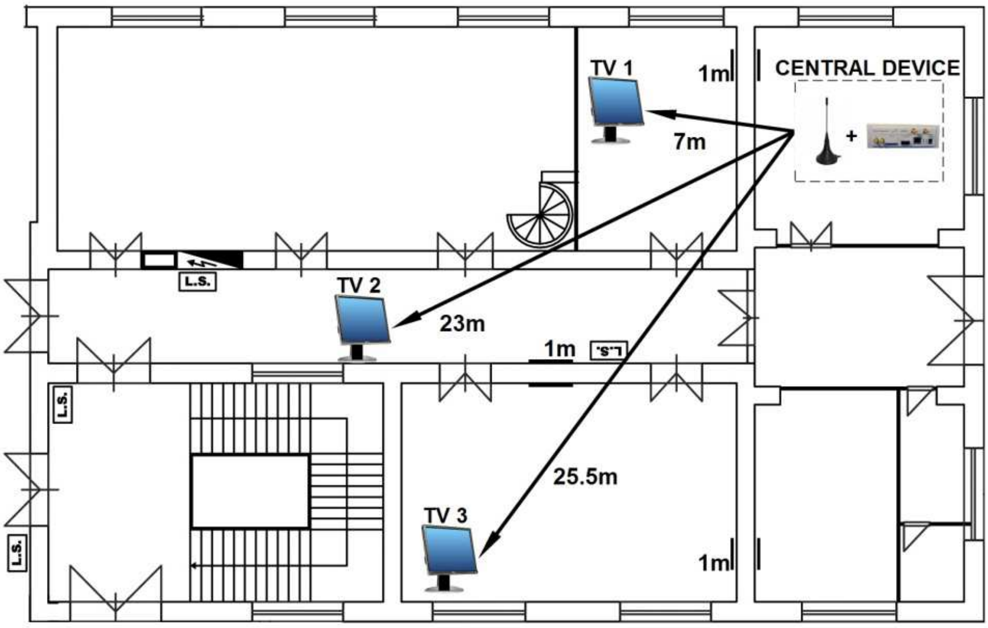

Figure 22 First indoor scenarios: the central device broadcasts a DTT signal to three TV sets situated on the same floor.

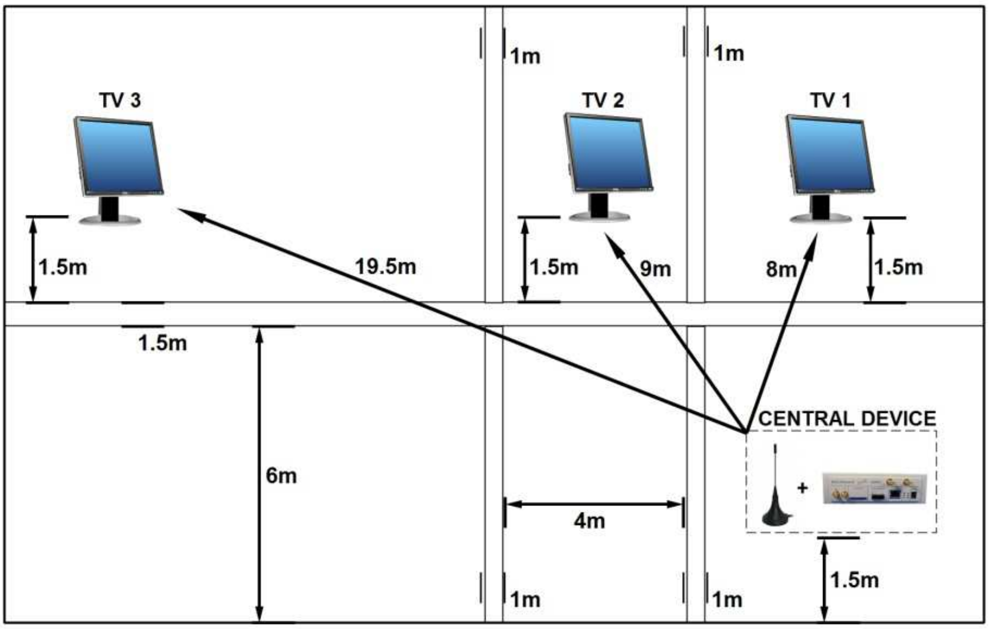

Figure 23 Second indoor scenarios: the central device broadcasts a DTT signal to three TV sets situated on a different floor.

We changed the TV position until reaching the coverage limit using the same subjective evaluation criteria, the absence of a PF. We started by positioning the TV set in the room directly above the central device reaching a distance of 8 meters (TV1 in figure 23). By incrementing the distance from the central device we found that the position of the coverage boundary, corresponding to the TV3 position in figure 22, is about 19.5 meters.The environment where the measurement campaign was performed has some peculiar characteristics: the height of the ceiling (6 m) is bigger than for normal residential environments and the thickness of the walls (1 m) is also at least three times bigger than usual internal walls. The propagation characteristics for the test environment are therefore implicitly worse than for a residential environment. For these reasons, we can conclude that the coverage of the presented system is optimal for the extent of a normal two-floor house.

The transmission power of the central cognitive device respects the previously measured protection ratios, not disturbing a receiver placed close to it. Thus, by maintaining this fixed transmission power level, no other receivers, placed in a more distant position, can be disturbed by a new transmission.

3.4 Application Scenarios

In this section different application scenarios for the multi-vision system described in the previous sections is presented.

3.4.1 DTT Contents Redistribution

The first scenario is an indoor short-range distribution system for the wireless retransmission of free-to-air and PPV DTT contents, redirecting several PPV channels from different DTT MUXs in a centralized manner, with only a central device and subscription. The great advantage to existing systems as for example MoCA, is that the end TV devices do not require any changes or additional set top boxes. The central cognitive device will enable users watching their PPV contents all over their desired environment.

3.4.2 *Satellite Contents Redistribution*

The second scenario is similar to the previous one: an indoor short-range distribution system for the wireless retransmission of satellite contents received by the cognitive HD decoder. The central cognitive device receives the contents of m satellite transponders instead of m DTT MUXs.

Additionally to the first scenario, dedicated exclusively to the indoor redistribution of PPV DTT contents, the satellite version can enable DTT-enabled TV sets to view also satellite contents (free-to-air and PPV) without any supplementary hardware components.

3.4.3 *Auxiliary and Mixed Content Redistribution*

The previous application scenarios can be approached also in a combined manner, for example by mixing satellite and/or DTT TV contents The appropriate RF/BB modules can be randomly combined and replicated in order to meet any particular scenario. Furthermore, additional contents from external DVD/PC/mobile/camcorders or IPTV devices can be fed into the central device and combined with the mixed content, for enhancing flexibility of the system and making it feasible for a wide variety of consumer applications. This approach can be deployed for home entertainment use or in infotainment architectures (resorts, hotels, airports, malls etc.).

We need to underline that unauthorized access can be prevented in all the presented scenarios by employing DRM scrambling techniques using the CI slot of the TV receivers[74]. The hardware design of the central cognitive device is implicitly more complex with respect to a normal DVB-T decoder. From a consumer point of view, an enough versatile commercial implementation should contain at least two satellite and two DTT receivers that can be implemented in a hardware design with new generation System-on-a-Chip SoC decoders. The scrambler, multiplexer and the decision block can be easily fit onto a powerful FPGA platform connected to one or more RF modulators. Based on these considerations, the price of a mass-produced hardware device appropriate for the presented application scenarios should be in an accessible range, even though the hardware design is implicitly more complex with respect to a normal DTT decoder. For scalable semi-professional solutions more RF demodulators and modulators could be managed by a more powerful FPGA core.

Chapter 4

Hidden Node Margin and Man-Made Noise Measurements

The UHF band is mainly allocated for terrestrial broadcasting.. This is the primary service over the frequency range from 470 MHz to 860 MHz, with Mobile Service for broadcasting auxiliary as secondary service. Additionally, a few Fixed Service Allocation cases exist in the range from 790 to 862 MHz.

The channel bandwidth allocation to each TV RF channel depends on the ITU-R Region. In Europe the allocation bandwidth is 8 MHz. Once the allotments and assignments have been made in a certain area and to certain TV services, the frequency management of the band in that country is rather static. The usual approach to plan terrestrial broadcast systems in a certain area is to select a number of channels amongst and use these frequencies to provide the TV service. In this scenario, there will be a number of channels that will not be available for broadcast service use within the target area, because they are being used for other TV transmitters in neighbor zones (usual Multiple Frequency Channel planning). In a majority of locations of the area under study, those frequencies being used in neighboring zones appear as empty channels, or at least with negligible power received from transmitters covering those neighboring areas. These empty channels are the “white spaces” of the area under study. These empty or almost empty channels could be used as spectral resources for low power applications, provided their power does not disturb the broadcast services that use those same frequencies in neighboring areas.

The objective of the study described in this third chapter was to carry out an analysis of the UHF band to obtain realistic empirical values of the parameters upon which CR operation is based. Consistent values from a carefully planned measurement campaign are provided in next sessions. These empirical data has been recorded in different locations of Spain and Italy during 2011 and 2012. In concrete, two key areas for cognitive operation were studied: on one hand, the study will cover current values of UHF radio noise and perform comparison with realistic receiver noise figures in relation to occupancy decision thresholds. On the other hand it will study the statistics of the so-called “Hidden Node Margin” (HNM) [16].

4.1 Hidden Node Margin

The so called Hidden Node (HN) problem is typical of spectrum sensing techniques. For a sharing scenario between CR operating in the TVWS (White Spaces Device - WSD) and DTT systems the HN problem is graphically described in figure 24. A rooftop mounted DTT receiver is in Line of Sight (LOS) conditions with respect to the DTT transmitter (path 1). Nearby a WSD is attempting to detect the DTT signal at street level, but it is shielded by the surrounding buildings (path 2). The WSD could then erroneously conclude that the specific sensed DTT channel is available and hence it might cause harmful interference (path 3) to the DTT receiver.

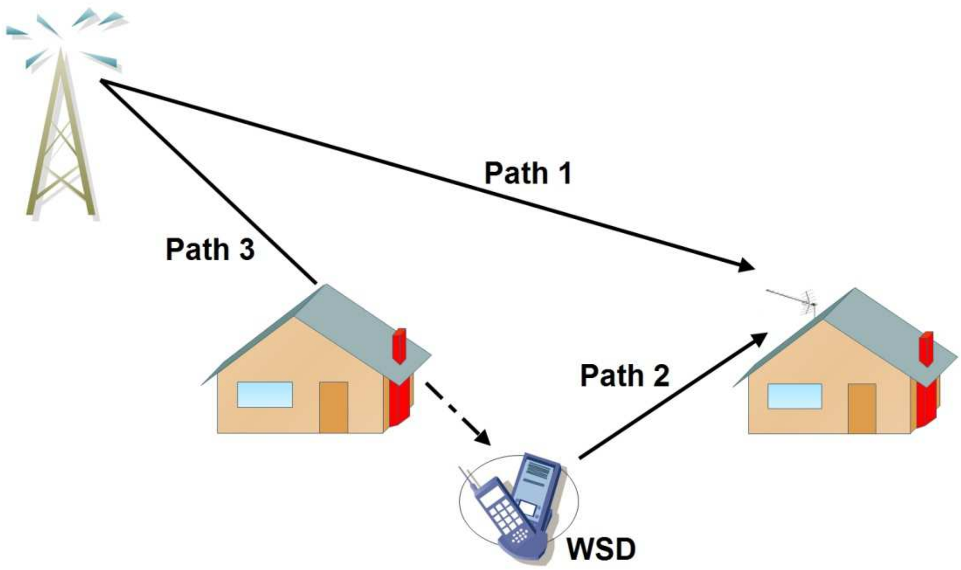

Figure 24 Representation of the Hidden Node Problem.

A CR generally need to detect a DTT signal at a height of 1.5 m using allow gain omni-directional antenna, whereas DTT reception is usually planned on the basis of a directional high gain antenna at a typical height of 10 m. The difference signal strength at 10 m and 1.5m is referred to as the hidden node margin and its value is important as it determines CR detection sensitivity.

Decision thresholds are a critical parameter for protecting Broadcast Services in a scenario where WSD would be operating. There are cases where the approach based on Geolocation Spectrum Occupancy Databases might not be available, either because the database does not exist for that area (for example in non densely populated areas) or in the case that access to the database is not possible (deep indoor operation, low populated areas etc.). Several studies [15] have suggested that radio noise has increased significantly over the last decades and consequently the assumptions about decision thresholds and interference protection ratios might be outdated.

In order to mitigate the impact of the HN problem, WSD sensing thresholds have to be properly set, considering a specific additional margin. The HNM is a parameter that quantifies the difference between the potential interfered signal values at the location where it is measured or estimated by the cognitive device, and the actual value at the location where the receiving antenna for this signal is located. HNM is a key parameter to define the protection requirements that cognitive devices must comply in order not to create any harmful interference to broadcast receiving systems.

It depends on different parameters such as DTT reception modes (e.g. fixed rooftop, portable indoor, portable outdoor, mobile TV) and the environment scenario (e.g. urban, rural). Different approaches can be adopted for its estimation. The HNM can be evaluated considering either deterministic or statistical propagation models; experimental measurements may be used to validate the simulation results. The values of the HNM should be derived in order to assure adequate protection of primary services in worst case scenarios.

The two methods proposed in [17] are based on deterministic propagation prediction models (ray-tracing) and statistical propagation prediction models (ITU-R P.1546) respectively:

- The deterministic approach is based on ray tracing simulations performed in several environments (e.g. dense urban, urban). The HNM is calculated as the difference between field strength levels at the DTT receiver location (for different heights) and field strength levels at the WSD location (for different heights). Simulations provide statistics for HNM values, which are employed to obtain the wanted protection of the DTT service, typically99 % and 99.9 % of cases.
- The statistic approach is based on the ITU-R P.1546 [75] statistical model. According to this methodology the HNM is calculated as the difference between the median field strength received at different heights corresponding to DTT receiver and WSD locations. This difference is then modified with a proper Gaussian location correction factor, in order to guarantee an adequate protection to the DTT service (primary

service); in equation 16 the formulation is reported for the case of 99.9% protection of the primary service:

$$HNM = E_{med,DTT} - E_{med,WSD} + \mu_{99\%}\sigma \qquad (16)$$

The previous work on this topic can be found in [16, 76, 77, 78, 79]. A short project was previously undertaken by ERA to determine indicative values of the HNM through direct measurement. This trial estimated that the average HNM for a CR to successfully detect a DTT signal at 1.5 m, for approximately 90% of all locations, was about 25 dB but in some situations a margin of 30 dB or greater could be required.

A theoretical study from the BBC [16] has proposed a reference value of 40 dB for outdoor HNM (10 m to 1.5 m margin) and an additional 20 dB attenuation for the indoor case. Other studies have obtained values that range from 16.6 dB to 33 dB on channel 22. Additional work has based the results on the field strength simulated values provided by different algorithms, including results with 3D ray tracing and conventional UHF empirical and semi empirical methods (ITU-R P.1546). In this case, the values range from 4 to 46 dB.

4.2 Man Maid Noise

The background noise level of the electromagnetic spectrum in the 40 MHz to 3 GHz region is dominated by MMN produced by a wide variety of equipment. Electric motors, car ignition systems, neon lights and many other devices produce sparks as part of their normal mode of operation. These spark discharges radiate across a wide frequency range and can interfere with radio receivers; the effects worsening as receiver bandwidth is increased. As well as these impulsive noise sources, there are also a great many (intentional and unintentional) sources of narrowband signals. Television viewers and radio listeners regularly experience the effects of MMN, although they don’t always recognize it as such.

Measuring the level of the MMN activity can give useful information to receiver designers, researchers and to those concerned with allocating the RF spectrum. Currently the levels of MMN are documented in the ITU-R recommendation [80]. The graphs in that document are based on measurements made in the 1970s and earlier using narrowband equipment in the United States. Because technology has moved on considerably since then and because Electromagnetic Compatibility (EMC) regulations have changed, there is concern that the [80] document may now be out-of-date and even misleading. Such concerns can only be addressed by measuring today's MMN levels in the UK. A feasibility study in 2001 looked at the state of MMN research and identified a way forward. That study [81] reported that [80] should be updated and that, in order to do so, a new, wider bandwidth measurement system could be built.

The MMN which affects radio communication and radar systems is of a type generally termed impulsive, and although the average noise level tends to decrease with an increase in the frequency of measurement. The impact of MMN on digital terrestrial transmission needs to be considered when planning new broadcast networks or designing powerful receivers. The extent of MMN heavily depends on the considered channel, as the different sources of man-made noise typically emit distortions only in a particular range of the frequency spectrum.

The intensity of MMN has been extensively analyzed during the last decades in several studies [82, 83]. Besides a dependency on the location and the corresponding environment of interferers, it has been reported that the characteristics in the same frequency band at the same location have significantly increased over the recent years due to technological advances [84]. One example for this development is the increasing amount of electronic devices that are used in office buildings as well as private households.

Apart from the particular characteristics of the MMN distortions, the performance of communication systems, which are affected by MMN, further depends on the used modulation scheme. An example is the application of orthogonal frequency division multiplex (OFDM). This scheme is used in most state-of-the-art broadcast systems as DVB-T or DVB-T2, but is known to be sensitive against impulsive noise distortions [85]. Such impulsive noise events have durations of few μs with very high noise levels that may significantly exceed the receiver's input level of the payload signal. Whilst this would cause only few disturbed bits using single-carrier modulation, the so-called noise bucket effect [86] spreads the disturbance over the complete OFDM symbol in the OFDM case. Hence, a single impulse may severely disturb the data within one complete OFDM symbol, which may lead to decoding failures if the Forward Error Correction (FEC) scheme is not able to handle long error bursts. Due to the missing time-interleaver in DVB-T (which would normally distribute burst errors into many single errors that can be corrected more easily by the FEC) this standard is known to be quite vulnerable against impulsive noise. In contrast, the sophisticated time-interleaver concept of DVB-T2 offers a higher level of robustness against impulsive noise.

Besides the selection of a particular transmission system, the effects of MMN further depend on the actual implementation of the receiver algorithms, since e.g. several algorithms for combating impulsive noise distortions in OFDM systems are known [87].

4.3 Measurements Methodology and Scenarios

This section describes the methodology used to obtain the empirical database used as the basis for this study. The general principle has been to obtain reference values of the power received at the roof level. These values were obtained for all the DTV channels available at each building location. Subsequently, the received power on all UHF channels (occupied and unoccupied) was measured in different rooms for each floor of the building. By comparing both sets of measurements, we were able to estimate the HNM values. Considering that the measurements include void channels, the measurements have also been considered for man-made noise level estimations. At certain locations, the street level outdoor values were also measured.

4.3.1 Scenarios

The first step of this survey was to elaborate an environment classification that would allow extrapolation of the measurement results and conclusions to a number of real cases as wide as possible. The study is based on two measurement campaigns carried out in Spain and Italy. The measurements in Spain were carried out in urban, suburban and rural environments around city of Bilbao. The measurements in Italy were carried out in Sardinia, in different urban areas of the city of Cagliari and surrounding suburban spots as well as a rural location 50 km west of the city. The measurement methodology was the same in both scenarios. Table II summarizes the main characteristics of the measurement sites.

Outdoor roof and indoor measurements were carried out in the three environments. Indoor measurements were performed in each floor of the building under tests, using a dipole antenna at 1.5 m. above the ground level.

TABLE II
CHARACTERISTICS OF THE MEASUREMENT SITES

	Floor Number	Environment
BI-00	4	Urban
BI-01	7	Urban
BI-02	2	Rural
BI-03	2	Suburban
CA-00	2	Urban
CA-01	2	Suburban
CA-02	1	Rural
CA-03	4	Urban

4.3.2 Methodology

The measurements consisted of three rounds of power measurements over the entire UHF band using different channel widths in order to obtain a picture of the received levels across the band with three sensitivity thresholds. The first round gathered Root Mean Square (RMS) power values using a filter channel equivalent to an 8 MHz bandwidth, specific for the digital terrestrial channels. The second and third round included measurements with 1 MHz and 100 kHz respectively, in order to benefit from a lower equipment noise floor.

The measurement system was composed of two antennas, a log-periodic calibrated antenna and a dipole. The measurement equipment was a field strength meter in Bilbao and a vector signal analyzer in Cagliari. The equipment noise floor was similar in both cases. Table III shows the antenna gain values and equipment noise floor data.

TABLE III
MEASUREMENT SYSTEM FEATURES

	Bilbao	Cagliari
Log-Periodic Antenna Factor (avg)	17	21
Dipole Antenna Factor (avg)	25	-
Discone Antenna Factor (avg)	-	22
Field Meter Noise Floor (dBm,1 Hz)	150	-
Vector Signal Analyzer Noise Floor (dBm,1 Hz)	- 155	-149

This work has not considered potential changes on the propagation conditions and the number of measurements at each frequency has been limited to a minimum of 20 seconds. Further analysis of the data proved the correctness of this hypothesis.

4.4 Data Processing and Detection Thresholds

The measurement files were first inspected to detect possible errors during the data capture. After this first file cleaning process, the data sets were normalized using the antenna calibration data. The data was analyzed to obtain the threshold value that will be used for deciding if an 8 MHz channel is occupied or free. The procedure to obtain this threshold depends strongly on the filter bandwidth used for the measurements, the larger the bandwidth.

For every location we selected three channels across the UHF band for which we had the guarantee that they were free, based on the official occupancy data. Subsequently we evaluated the man-made noise for the three different frequencies to determinate the channel occupancy decision threshold. We noticed that the values for man-made noise for the selected channels range up to 3 dB over the instrumentation noise level.

Therefore, based on this consideration and on other research [78], we considered a threshold of 5 dB over the noise floor, i.e. -75 dBm. After obtaining the reference noise value, for the channels that are within a range of ± 1 dB of the 5 dB threshold we crosschecked the measurements performed with a bandwidth of 8 MHz with a second measurement round. The supplementary measurements were carried out for the channels in doubt using a 100 kHz resolution bandwidth in order to benefit from a much lower instrumentation noise floor and to obtain more accurate data.

4.4.1 Database Description

The complete dataset has been arranged on a database with the basic structure described in Table IV. This database provides information to easily calculate:

- Hidden Node Margin Values and associated statistics;
- TV Channel Occupancy;
- Man Made Noise Upper Limit.

The database is composed of three different data sets, each one associated to one of the measurement bandwidths and resolutions: 8 MHz, 1 MHz and 100 kHz. The 8 MHz bandwidth measurements provide the typical spectral information that a potential cognitive device could achieve by typical spectral sensing techniques. The results in this paper focus on the spectral analysis and the accuracy limits that can be achieved using this measurement bandwidth by cognitive devices.

The accuracy of the Hidden Node Margin calculations will be directly related to this cognitive device behavior. The 1 MHz and 100 kHz measurements, not feasible for typical cognitive radio implementations, have been carried out having in mind further spectral analysis of the UHF band as well as a crosscheck benchmark for correctly evaluating the 8 MHz results.

TABLE IV
DATABASE STRUCTURE

Locations		CH21				.	CH69			
		Median Power	Max. Value	Min Value	Std. Deviation		Median Power	Max. Value	Min Value	Std. Deviation
Location 1	Roof									
	Floor X									
	…									
	Ground									
…										
Location N	Roof									
	Floor X									
	…									
	Ground									

4.5 Results

4.5.1 Spectral Occupancy

Table V summarizes the results obtained for spectral occupancy and standard deviation, providing different data associated to the different measurement scenarios and reception environments. The overall occupancy calculations show that the UHF band occupation in Cagliari is on average twice as high as the one for Bilbao. The result is an expected one and is motivated by the differences between the Italian and the Spanish TV market: the presence of numerous private TV broadcasters offering both free-to-air and pay per view services, increases the use of the spectrum in Italy.

TABLE V
MEAN SPECTRAL OCCUPANCY (%)/ STANDARD DEVIATION

	Bilbao			Cagliari		
Site	Rural	Suburban	Urban	Rural	Suburban	Urban
Roof	27.0/5.7	32.5/0,2	28.2/4.5	83.3/50.5	62.0/29.2	54.2/21.4
4th floor	-	-	21.5/11.2	-	-	-
3rd floor	-	-	26.7/6	-	-	54,2/21.4
2nd floor	18.0/14.7	17.5/15.2	25.07.7	-	39.6/6.8	51.7/18.9
1st floor	20.0/12.7	20.0/12.7	25.0/7.7	39.6/6.8	20.8/11.9	50.0/17.2
Street	-	22.2/10.5	-	-	20.8/11.9	47.9/15.1
Basement	-	3.00/29.7	7.50/25.2	-	-	-

For both the Spanish and Italian case the spectral occupancy in urban environments decays gradually, as expected, from the roof of the buildings to the bottom. For the suburban scenario, the rooftop occupancy is bigger than for the urban scenario, due to better propagation conditions. The difference between the occupancy measured on the roof and the various floors is more accentuated than for the urban scenario. The rural scenario revealed a good occupancy on the roof with a significant decay for the indoor measurements, due to the intersection of different coverage areas.

The variation of the spectrum occupancy in Italy is proportionally similar to those obtained in Spain, especially for the urban and suburban scenarios. The most relevant differences can be noted for the rural scenario for which the rooftop values obtained in Italy represent more than double the occupancy measured inside a rural home. These values can be explained taking into consideration the topology of the analyzed Italian rural scenario, with large open spaces allowing the reception with rooftop antennas of signals from more than one broadcast repeater.

4.5.2 Hidden Node Margin Calculation

The Hidden Node Margin parameter accounts for the fact that the primary service of the band uses mainly roof top antennas for receiving TV signals and the potentially interfering cognitive device is analyzing the spectrum picture not at roof top level but at street level. If the cognitive device is operating in an indoor environment, the situation is even less optimistic. This means that an existing primary service might not be detected by the sensing device (even if it is effectively present at the antenna) and using this false unoccupied channel might cause interference to the primary service.

The HNM has been calculated as the difference of the signal power measured at the roof and all the power values measured in each floor. The average values of the HNM are between 8 and 38 dB. There is a considerable variation of the obtained values depending on each one of the buildings, the floor number and the receiving environment. Table VI summarizes the results.

TABLE VI
HIDDEN NODE MARGIN

	Bilbao			Cagliari		
Site	Rural	Suburban	Urban	Rural	Suburban	Urban
4th floor	-	-	17.53	-	-	12.64
3rd floor	-	-	8.21	-		12.80
2nd floor	17.14	16.30	8.85	-	19	15.44
1st floor	23.50	15.76	12.35	30.13	24	17.32
Street	-	17.91	-	-	26	18.31
Basement	-	28.86	38.34	-	-	-

As for the mean spectral occupancy, the HNM for an urban environment decays gradually with the distance from the roof, for each floor of the buildings where the measurements have been performed. For the Italian scenarios, the HNM values are generally bigger than the ones measured in Spain.

We observed a smoother variation for the HNM in the urban area than for the variations in the suburban and rural areas which can be explained by the topology of the dense urban environment populated with tall buildings leading to an important amount of attenuation for all the urban scenarios.

The HNM varies with the channel on which the measurements were performed in the range of ±5 and does not present any variation rule as a function of frequency.

4.5.3 Man Made Noise Limits

The measurements in void channels have provided information about the upper limit of the Man-Made Noise levels within the UHF band.

The results should not be interpreted as definitive noise data, as the measurement system was not specifically designed for measuring noise levels. The values provided here can be considered as an upper limit of the current levels. As it could be expected, in most cases, the measured levels in void channels correspond to the internal noise floor of the receiver, which in the case of 8 and 1 MHz is relevant as previously shown on Table III.

The frequencies where the noise has been evaluated differ from place to place, as the empty channels are different in different measurement areas. Table VII summarizes the frequencies where noise values have been obtained and the noise level statistics are shown in Table VIII.

TABLE VII
FREQUENCIES FOR NOISE ANALYSIS (MHZ)

	Rural	Suburban	Urban
Bilbao	408,520	408,520	408,520
Cagliari	466, 658, 842	466, 658, 842	570, 666, 834

TABLE VIII
UPPER NOISE LIMITS (MAXIMUM VALUES) FOR 8 MHZ MEASUREMENTS

	Rural			**Suburban**			**Urban**		
Frequency	500	600	800	500	600	800	500	600	800
Bilbao (outdoor)	-81.9	-80.8	-80.6	-81.5	-81.8	-80.7	-79.1	-78.2	-79.4
Bilbao (lower floors)	-81.7	-81.1	-80.7	-81.5	-81.8	-80.7	-78.5	-79.1	-79.7
Bilbao (upper floors)	-	-	-	-81.5	-81.8	-80.7	-81.5	-81.8	-80.7
Cagliari (outdoor)	-81.7	-80.2	-81.2	-81.5	-81.8	-80.7	-78.2	-78.1	-77.6
Cagliari (lower floors)	-81.5	-81	-80.7	-81.5	-81.8	-80.7	-81.5	-81.8	-80.7
Cagliari (upper floors)	-	-	-	-	-	-	-79.7	-79.8	-78.9

As it can be seen, for the most of the analyzed scenarios, the values obtained do not vary with frequency and are close to the noise threshold of the measurement system, leading to the conclusion that noise is well below the equipment performance. This conclusion is confirmed by the measurements we performed on the free channels using a filter bandwidth of 1 MHz and 100 kHz, for which the noise level was still in the same range of the equipment noise, -90 dBm and -100 dBm respectively.

The only scenarios where the upper noise limits exceed the noise threshold of the equipment are the urban spots, where the man-made noise is around 3 dB higher than the equipment threshold, more accentuated at lower floors and street level.

Chapter 5

Performance evaluation of IEEE 802.22 Standard in the TV Bands

5.1 International Standardization of CRs

Due to very large interest in the CRs, its standardization is currently performed on all levels, including the ITU, IEEE, ETSI, and ECMA. In the ITU, ITU-R WPs 1B and 5A are currently preparing reports describing the CRS concept and the regulatory measures required to introduce the CRS. In the IEEE several Working Groups (WG) in Standards Coordination Committee (SCC) 41 on Dynamic Spectrum Access Networks and the 802 LAN/MAN Standards Committee are standardizing CRs and their components. In ETSI, Technical Committee (TC) on Reconfigurable Radio Systems (RRS) has been developing reports describing different components of the CRS, as well as reports on the CRS concept and the regulatory aspects of the CRS. In the ECMA, Task Group 1 of Technical Committee 48 has standardized a CRS for TV white space. In next sub-sections the currently IEEE, ETSI, and ECMA standards for CRs performing in the TVWS are presented.

5.1.1 Standardization in the IEEE

IEEE SCC 41 is developing standards related to dynamic spectrum access networks. The focus is on improved use of spectrum, including new techniques and methods of dynamic spectrum access, which requires managing interference and coordination of wireless technologies, and includes network management and information sharing [88]. Currently, the 1900.4 WG is developing two new draft standards:

- P1900.4.1, “Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks”, started in March 2009. P1900.4.1 uses IEEE 1900.4 as a baseline standard. It provides a detailed description of interfaces and service access points defined in IEEE 1900.4.

- P1900.4a, “Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands”, started in March 2009 together with P1900.4.1. P1900.4a amends IEEE 1900.4 to enable mobile wireless access service in white space frequency bands without any limitation on the radio interface to be used.

On March 8, 2010 the ad hoc on white space radio was created within IEEE SCC41. The purpose is to consider interest in, feasibility of, and necessity of developing a standard defining radio interface (media access control and physical layers) for a white space communication system.

5.1.2 Standardization in IEEE 802

The activity to define CRSs is currently performed in the 802.22 and 802.11 WGs, while the activity to specify components of a CRs is currently performed in 802.21, 802.22, and 802.19 WGs [89].

- The draft standard P802.22 is entitled “Draft Standard for Wireless Regional Area Networks Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands”. It specifies the air interface, including the cognitive MAC and PHY, of point-to-multipoint wireless regional area networks, comprised of a professionally installed fixed base station with fixed and portable user terminals operating in the unlicensed VHF/UHF TV broadcast bands between 54 MHz and 862 MHz (TVWS) In section 5.2 can be found a short view of this new standard.
- Draft standard P802.11af is entitled “IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN MAC and PHY Specifications - Amendment: TV White Spaces Operation”. It is an amendment that defines standardized modifications to both the 802.11 physical layers and MAC layer to meet the legal requirements for channel access and coexistence in the TVWS.
- Draft standard P802.22.1 is entitled “Standard to Enhance Harmful Interference Protection for Low Power Licensed Devices Operating in TV Broadcast Bands.” It specifies methods for license-exempt devices to provide enhanced protection to low-

powered licensed devices from harmful interference when they share the same spectrum.

- Draft standard P802.19.1 is entitled “IEEE Standard for Information Technology - Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 19: TV White Space Coexistence Methods”. It specifies radio-technology-independent methods for coexistence among dissimilar or independently operated TV band device networks and dissimilar TV band devices.

5.1.3 Standardization in ETSI TC RRS

In ETSI standardization of the CR is performed in the TC RRS [30] that is currently developing two drafts:

- A draft report titled “Operation in White Space Frequency Bands” will describe how radio networks can operate on a secondary basis in frequency bands assigned to PUs. The topics currently considered are the operation of the CRs in UHF white space frequency bands, the methods for protecting PUs, the system requirements and the use cases.
- A draft technical specification titled “Coexistence Architecture for Cognitive Radio Networks on UHF White Space Frequency Bands” that will define system architecture for spectrum sharing and coexistence between multiple CR networks. The coexistence architecture is targeted to support secondary users in UHF white space frequency bands.

5.1.4 Standardization in ECMA

In ECMA, standardization of the CRs is performed in Task Group 1 of Technical Committee 48. Standard ECMA-392, “MAC and PHY for Operation in TV White Space,” was published in December 2009 [29]. It specifies MAC and physical layers for personal/portable cognitive wireless networks operating in TV bands. Also, ECMA-392 specifies a number of incumbent protection mechanisms that may be used to meet regulatory requirements.

5.2 Overview of IEEE 802.22 WRAN Standard

In this section an overview of the IEEE 802.22 WRAN standard with particular attention to the physical layer is presented. It is the first entirely cognitive standard and is aimed at using CR techniques to allow sharing of geographically unused spectrum allocated to the TV broadcast service, on a non interfering basis, to bring broadband access to hard-to-reach low-population-density areas typical of rural environments, and is therefore timely and has the potential for wide applicability worldwide. IEEE 802.22 WRANs are designed to operate in the TV broadcast bands while ensuring that no harmful interference is caused to the incumbent operation (i.e., digital TV and analog TV broadcasting) and low-power licensed devices such as wireless microphones.

The application for the IEEE 802.22 WRAN standard will be providing wireless broadband access to a rural area of typically 17–30 km or more in radius (up to a maximum of 100 km) from a base station (BS) and serving up to 255 fixed units of customer premises equipment (CPE) with outdoor directional antennas located at nominally 10 m above ground level, similar to a typical VHF/UHF TV receiving installation.

The minimum peak throughput delivered to CPE at the edge of coverage will be equivalent to a T1 rate (1.5 Mb/s) in the downstream (DS) direction (BS to CPE) and 384 kb/s in the upstream (US) direction (CPE to BS), allowing for videoconferencing service. Due to the extended coverage afforded by the use of these lower frequencies, the physical layer (PHY) parameters must be optimized to absorb longer multipath excess delays than accommodated by other 802 wireless standards. An excess delay of up to 37 μs can be absorbed by the OFDM modulation used. Beyond the 30 km for which the PHY layer has been designed, the medium access control (MAC) layer will absorb additional propagation delays for coverage distances of up to 100 km for IEEE 802.22 systems addresses the PHY and MAC layers, and the interfaces to a station management entity (SME) through PHY and MAC layer management entities (MLMEs), as well as to higher layers such as IP, asynchronous transfer mode (ATM), and IEEE 1394 through an IEEE 802.1d compliant convergence sub-layer. At the PHY layer there are three primary functions: the main data communications, the spectrum sensing function (SSF), and the geolocation function, with the latter two providing necessary functionality to support the cognitive abilities of the system. The PHY interfaces with the MAC through the PHY service access point (SAP), as well as to the MLME and the SME through the PHY layer management entity (PLME) and its SAPs.

5.2.1 Physical Layer

IEEE 802.22 compliant WRANs will provide broadband access similar to asymmetrical DSL (ADSL) and cable modems, but will support more economical deployment over sparsely populated areas. The frequency range used in the VHF/UHF TV broadcast bands extends from 54 to 862 MHz depending on the various regulatory domains around the world.

IEEE 802.22 will define a single air interface based on 2048- carrier orthogonal frequency-division multiple access (OFDMA) to provide a reliable end-toend link suitable for NLOS operation. A general description of OFDMA is easily found in the literature [83]. Since it is not always possible to have paired TV channels available, IEEE 802.22 is initially defining a single time-domain duplex (TDD) mode, with plans to define a frequency-division duplex (FDD) mode as a future amendment to the standard.

To support the various TV channel bandwidths in use in the world (6, 7, and 8 MHz channels), the sampling frequency, carrier spacing, symbol duration, signal bandwidth, and data rates will be scaled by the channel bandwidth for worldwide operation. IEEE 802.22 systems will use a common oversampling factor and the same frame/symbol structure, coding schemes, interleaving, and so on.

Four different lengths of cyclic prefix are defined as 1/4, 1/8, 1/16, and 1/32 of symbol duration to allow for different channel delay spreads while utilizing the spectrum efficiently. Due to the physical size of antenna structures at these lower frequencies, IEEE 802.22 will not support multiple-antenna techniques such as multiple-input multiple-output (MIMO) or beamforming.

Since WRAN systems are for fixed operation, transmission channels are expected to change very slowly, so there is little time diversity gain to be achieved through burst allocation across different symbols. Therefore, the downstream bursts in IEEE 802.22 will be allocated progressively across subchannels in the frequency domain, as depicted in figure 24, to minimize overhead by simplifying the downstream map. This will also contribute to reducing decoding latency. The upstream bursts will be allocated progressively across symbols to minimize the number of subchannels used by CPE, hence reducing the instantaneous effective isotropic radiated power (EIRP) to mitigate interference to incumbent systems. The upstream bursts can also be mapped on a 7-symbol column basis, as shown in figure 25.

The physical subcarriers in each subchannel in IEEE 802.22 are distributed across the channel to increase frequency diversity. Transmitting a cluster of adjacent subcarriers is not supported in the IEEE 802.22 standard because it would increase the potential for harmful interference to narrowband wireless microphones.

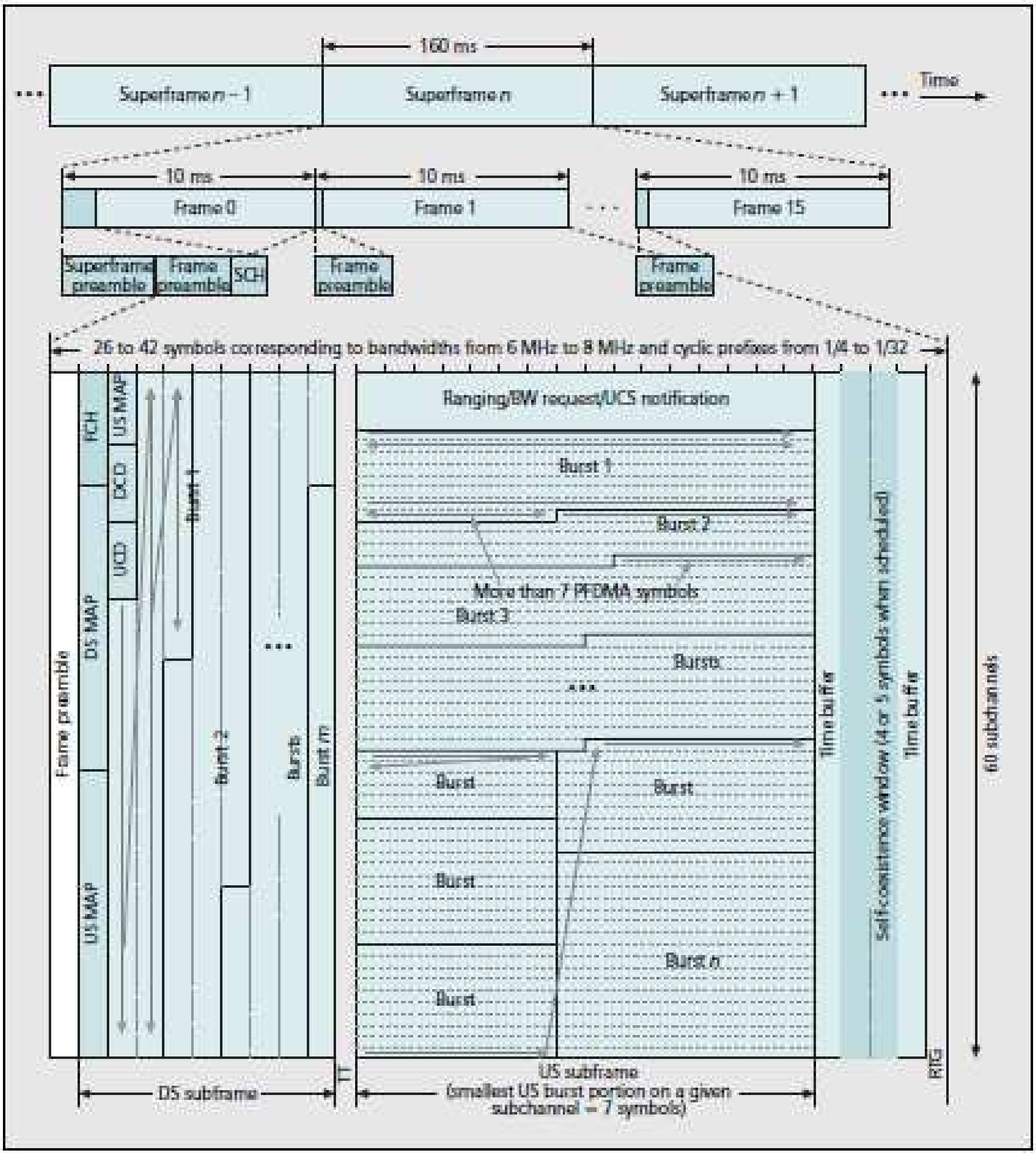

Figure 25 Superframe and Frame Structure.

5.2.1.1 Adaptive Modulation and Coding

IEEE 802.22 defines 12 combinations of three modulations (quaternary phase shift keying [QPSK], 16-quadrature amplitude modulation [QAM], 64-QAM) and four coding rates (1/2, 2/3, 3/4, 5/6) for data communications that can be flexibly chosen among to achieve various trade-offs of data rate and robustness, depending on channel and interference conditions.

TABLE IX
PHY MODES AND THEIR RELATED MODULATIONS, CODING RATES AND DATA RATES FOR TCP = TFFT/16

PHY Mode	Modulation	Coding Rate	Data Rate (Mb/s)	Spectral Efficiency (for 6 MHz bandwidth)
1	BPSK	Uncoded	-	-
2	QPSK	½ Repetition 4	-	-
3	QPSK	½ Repetition 3	-	-
4	QPSK	½ Repetition 2	-	-
5	QPSK	1/2	4.54	0.76
6	QPSK	2/3	6.05	1.01
7	QPSK	3/4	6.81	1.13
8	QPSK	5/6	7.56	1.26
9	16-QAM	1/2	9.08	1.51
10	16-QAM	2/3	12.10	2.02
11	16-QAM	3/4	13.61	2.27
12	16-QAM	5/6	15.13	2.52
13	64-QAM	1/2	13.61	2.27
14	64-QAM	2/3	18.15	3.03
15	64-QAM	3/4	20.42	3.40
16	64-QAM	5/6	22.69	3.78

As shown in Table IX, a total of 16 transmission modes are supported in IEEE 802.22. Modes 3–14 are used for data communications; mode 1 is used for transmission of code-division multiple access (CDMA) ranging/bandwidth (BW) request message/urgent coexistence situation (UCS) notification; and mode 2 is used for the coexistence beacon protocol (CBP). The peak data rate and spectrum efficiency shown are for a single TV channel with BW 6 MHz. For other BWs such as 7 MHz or 8 MHz, the numbers will scale up proportionally. Convolutional coding is the only mandatory mode of forward error control (FEC) coding defined in IEEE 802.22. The data burst is encoded using a rate 1/2 binary convolutional encoder with constraint length 7. Different coding rates are obtained by puncturing the output of the convolutional coder. Three optional advanced FEC modes are included to provide better performance, but at the price of increased decoding latency and complexity: two variants of turbo codes, duo-binary convolutional turbo code (CTC) and shortened block turbo codes (SBTC), and low density parity check (LDPC) codes. It is worthwhile mentioning that the bit interleaving process after FEC is a departure from other IEEE standards such as 802.16 or 802.11. The block interleaving algorithm is a turbobased structure using an interleaving unit integrated in an iterative structure. Interleaving parameters are selected to optimize the interleaving spreading between adjacent samples and separated samples in order to achieve better frequency diversity.

5.2.1.2 Preamble, pilot pattern and Channelization

There are three types of preamble defined in WRAN: superframe preamble, frame preamble, and CBP preamble, in order to facilitate burst detection, synchronization, and channel estimation. All three preambles are one OFDM symbol long in time with 1/4 cyclic prefix. All CPEs synchronize to a BS, in time and frequency, using the superframe preamble, which consists of four repetitions of a short training sequence (STS) following the cyclic prefix. The frame preamble is used for synchronization, channel estimation, frequency offset estimation, and received power estimation. It consists of two repetitions of a long training sequence (LTS). The CBP preamble is used for CBP detection, synchronization, frequency offset estimation, and CBP channel estimation. It has the same structure as the superframe preamble but uses a different STS to be distinct from the superframe preamble with low cross-correlation. In order to obtain robust channel estimation and good tracking ability for frequency offset and phase noise, one pilot is placed on every seventh useful subcarrier in the frequency domain, and the pilot positions are changed from symbol to symbol to ensure that every subcarrier has been used as a pilot over the period of seven OFDM symbols. The basic tiling is one subcarrier by seven symbols for both downstream and upstream. The repletion unit of the pilot pattern is shown in figure 26.

The elementary unit for resource allocation is the subchannel, which consists of 28 subcarriers with 24 data subcarriers and 4 pilot subcarriers. There are a total of 60 subchannels in each OFDM symbol. In the downstream, all data subcarriers in the 60 subchannels will be interleaved with block size 1440 (24 × 60) before transmission to exploit frequency diversity. In the upstream, two subchannels will be reserved for ranging, bandwidth request message, or UCS notification. The remaining subchannels will be interleaved with block size 1624 (28 × 58), including both pilot and data. The frequency interleaving algorithms for upstream and downstream are the same as the bit interleaving algorithm, but with different parameters. The inclusion of pilots in the interleaving process in the upstream direction is to ensure that every CPE burst that arrives at the BS will have one pilot on each subcarrier over the period of seven OFDMA symbols, which is the minimum upstream burst length. On the other hand, the exclusion of pilots in the interleaving process in the downstream is to allow fast channel estimation (using fewer than seven OFDM symbols) at CPEs to allow for delay-sensitive applications.

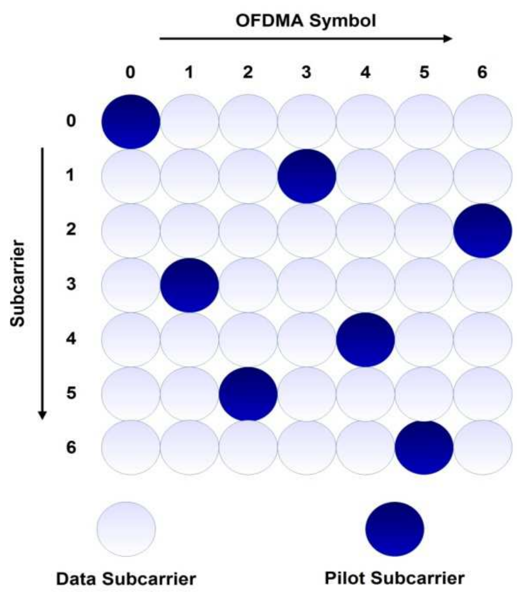

Figure 26 Repetition Unit of the Pilot Pattern

5.2.1.3 Cognitive Functions

In order to operate in TV broadcast bands without affecting digital TV, analog TV, and licensed wireless microphones operated by TV broadcasters and other eligible licensees, 802.22 systems will have to be cognizant of all incumbent operations in their vicinity. The necessary tools are being included in the standard to fulfill these cognitive functions. First, the location of each BS and CPE unit will be accurately established. This is described in detail in section 5.2.1.5 below. The second tool is access to a channel availability database that will provide reliable information on channel availability for WRAN use at any given location. The third tool is the sensing capability included in the standard to sense the presence and identify the type of incumbent signals in channels of interest. These capabilities will, by allowing the BS to control channel usage and CPE maximum EIRP, constitute the set of cognitive functions needed to allow operation of 802.22 systems in the TV broadcast bands on a noninterference basis with the incumbents.

5.2.1.4 Spectrum Manager

The spectrum manager is the cognitive function at the BS that will use the inputs from the spectrum sensing function (SSF), geolocation, and the incumbent database to decide on the TV channel to be used by the WRAN cell as well as the EIRP limits imposed on the specific WRAN devices. This entity is to be conceptually located at the MAC sublayer in the BS and will work closely with the data path MAC to communicate with the CPE, and will interface with the PLME to control the local sensing and geolocation functions, and with the SME to access the incumbent database and for any local override. Various steps need to be taken by the SM to declare that a channel may be used for operation. Sensing has to be done on the operating channel (N) and adjacent channels (N ± 1) to make sure that no incumbent (digital or analog TV or licensed wireless microphone) is present. Verification of the distance to the protected contour will need to be done through access to the TV incumbent database. If it is established that WRAN operation on channel N may create interference to a broadcast incumbent operating on a related channel, the SM will have the following four options:

- Reduce the EIRP of the CPE by placing a limit on the transmit power control (TPC) range to eliminate the interference in their local area.
- If such a decrease in CPE EIRP renders the service unsustainable, disallow these CPE units (i.e., these CPE units need to seek service on another channel from the same or a different service provider).
- Reduce the EIRP of the BS transmission to eliminate the potential interference.
- In many cases a reduction in the BS EIRP will no longer allow proper WRAN operation with distant CPE, and the SM will need to initiate a channel move (to its first backup channel) involving the BS and all of its associated CPE.

There will always be a manual override at the BS in the unlikely event that an unexpected interference situation occurs. It is assumed that the WRAN operator will have the ultimate responsibility for avoiding interference to incumbents. Any special event will be handled on a case-by-case basis to avoid interference.

5.2.1.4 Geolocation and Databases

The IEEE 802.22 standard requires all devices in the network to be installed in a fixed location and the BS is required to know its location and the location of all of its associated CPE. The location of the BS must be known to within a 15 m radius while the location of CPE must be known to within a 100 m radius. In order to meet this location requirement all devices in the network are equipped with satellite-based geolocation technology (GPS, Galileo, etc.). During the initialization procedure of any new CPE on the network, the geolocation unit in the CPE must successfully lock to the necessary number of satellites; and, in doing so, the CPE must accurately determine its location before it can transmit. After the CPE determines its own location, it can then attempt to associate to the BS. Another requirement of the 802.22 standard is that the BS must have access to an incumbent database service. This service provides accurate and up-to-date information describing protected broadcast operation in the area. It is expected that the BS accesses through the incumbent database service not only a database detailing protected television operations and a database detailing low-power licensed auxiliary operations in the area, but also a database detailing other IEEE 802.22 operations in the area. When a new CPE attempts to associate with a BS during initialization, the CPE sends its location coordinates to the BS. The BS then uses the location information for the new CPE to query the database. The latitude and longitude for the CPE gets passed to the higher layers at the BS. Other parameters for the CPE, input from the higher layers, such as antenna pattern, height, and EIRP, can be provided along with these coordinates so that the incumbent database service can determine the expected area over which the CPE could potentially interfere. A list of available channels and their respective maximum EIRP at which the CPE can operate without potentially causing interference to the protected incumbent service is generated and returned to the BS. An 802.22 network is prohibited from operating on any channel not on this resultant list of available channels or above the maximum EIRP level specified for any available channel.

5.2.1.6 Spectrum Sensing

Spectrum sensing involves observing the radio frequency spectrum and processing the observations to determine if a channel is occupied by a licensed transmission. Spectrum sensing is included as a mandatory feature within IEEE 802.22.

In IEEE 802.22, both the BS and CPE sense the spectrum for three different licensed transmissions: analog television, digital television, and licensed low-power auxiliary devices such as wireless microphones. In addition to these signals, the Working Group is developing a standard for a self-organizing network of beacon devices (being standardized as IEEE 802.22.1) which is intended to give additional protection for low-power licensed uses. The sensing requirements are summarized in terms of four parameters: sensing receiver sensitivity, channel detection time, probability of detection, and probability of false alarm. All nodes in the 802.22 network will sense licensed transmissions using an antenna with a gain of at least 0 dBi in all directions. The sensing antenna must be outdoors, clear of obstructions as much as possible, and at a minimum height of 10 m above ground level. The sensing receiver reference sensitivity is specified for this 0 dBi antenna gain, and after all losses between the antenna and the input to the receiver have been included. For digital TV, the sensing receiver sensitivity is –116 dBm. For analog TV the sensitivity is –94 dBm, while for wireless microphones the sensitivity is –107 dBm. The channel detection time for all signal types is 2 s. The probability of detection is 0.9, while the probability of false alarm is 0.1 for all signal types.

The 802.22 spectrum sensing framework is built on four pillars:

- Per-channel sensing
- Quiet periods
- Standardized reporting
- Implementation independence

Each television channel is sensed independently. However, the standard will not preclude an implementation that senses multiple channels simultaneously. This architecture was selected to allow a low-cost design that tunes the sensing receiver to a single channel at a time. The second component of the sensing framework is the use of quiet periods. The MAC supports scheduling of quiet periods during which the BS and all CPE temporarily cease transmission. The MAC also includes signaling between nearby BSs that enables these BSs to synchronize their quiet periods. Sensing is performed during these scheduled quiet periods to minimize any interference from the

WRAN systems to the sensing receiver. The third component of the sensing framework is standardized reporting of spectrum sensing. Sensing is performed in both the BS and the CPE, but the final decision on whether a given channel is available for use by the WRAN is made at the BS. Therefore, the results of the spectrum sensing performed at the CPE must be reported to the BS in a standardized way. Also, the spectrum sensing in CPE is controlled by MAC management messages sent from the BS indicating the prioritized lists of channels to be sensed during CPE idle time or specific alternate sensing tasks. The fourth and final pillar in the spectrum sensing framework is spectrum sensing implementation independence. No specific spectrum sensing technique will be mandatory in the standard. Designers will be free to implement whatever spectrum sensing technique they choose as long as it meets the specified sensing requirements and reports the results in the standardized format. However, descriptions of a number of spectrum sensing techniques that might be used are included as examples in an informative annex within the IEEE 802.22 draft standard. Additional details on spectrum sensing in IEEE 802.22 can be found in [90].

5.3 IEEE 802.22 Simulator

The IEEE 802.22 PHY layer has been modeled in Simulink. Figure 27 shows the schematic of transmission hand of the simulator. In this section the main blocks and their functionalities are explained.

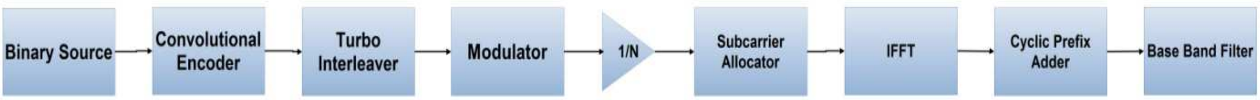

Figure 27 Schematic of the IEEE 802.22 PHY layer Simulink transmission software.

As depicted in figure 1, data bits for simulation are produced by a binary source that is a Bernoulli binary generator block. The data is then coded using convolutional coding, which shall have a native rate of ½ with a constraint length equal to 7. The other code rates can be obtained by puncturing bits.

Coded bits are then delivered to an interleaver. In this standard, a turbo-based algorithm is utilized for interleaving, which uses the interleaving unit $I(k)$ iteratively. The j^{Th} iteration for the algorithm is:

$$I(k)_{p,q}^{(j)} = \left[K - p + q + qp\left[-k - pI(k)_{p,q}^{(j-1)}\right]_K\right]_K \qquad (17)$$

where K presents the number of interleaved bits, p is an integer parameter setting the partition size, q denotes an integer parameter, j presents the iteration number and k is the position index of samples 0, 1, …, K. The operation $[X]_K$, X modulo- K, is defined as the following equation:

$$[X]_K = floor\left(\frac{X}{K}\right), K \qquad (18)$$

The values of the above parameters are listed in TABLE X.

TABLE X
BIT INTERLEAVING PARAMETERS

Coded Block K (bits)	**p**	**q**	**j**
48	16	2	2
336,480, 1056,2016,2112,2304	16	2	3
96, 162,288, 768,1008,1248, 1632, 2208	3	2	3
144, 240, 348, 528, 960, 1344, 1536	6	2	3
432	18	2	1
576, 1152, 1727	36	2	1
672	3	2	2
864, 1824, 1920	48	2	1
1440, 1680	40	2	2

Data bits are mapped to subcarriers after modulation. The multiplier following the modulation block is used to normalize the constellation-mapped data to achieve equal average power. The buffer puts several data bursts together, e.g. 5 bursts, to prepare 1440 data subcarriers. In the US direction, data subcarriers are again interleaved after the pilot subcarriers are inserted. However, in the DS direction interleaving is done before pilot insertion.

The subcarriers interleaving algorithm is similar to bit interleaving. Since there are 60 subchannels each including 24 data subcarriers, we have 60×24=1440 data subcarriers to be interleaved. In the DS direction an optional interleaving algorithm could be performed. This includes three permutation rules, P1, P2, and P3, which are introduced for three consecutive symbols and are repeated periodically, i.e. symbols 1,4 and 7 are interleaved by P1, symbols 2,5and 8 by P2 and symbols 3,6,9 by P3. The interleaving parameters for the permutation rules are shown in TABLE XI.

TABLE XI
SUBCARRIER INTERLEAVING PARAMETERS

Permutations	**K (Subcarriers)**	**p**	**q**	**j**
P1	1440	40	2	2
P2	1440	10	2	3
P3	1440	32	2	3

Static interleaving is used instead of the optional method, using only P1 permutation for all symbols. The latter method is used in our model.

After interleaving, pilots are inserted within the data subcarriers. This standard uses a pilot pattern presented in figure 26 which is repeated after 7 symbols and 7 subcarriers. Utilizing this pattern, all CPEs within a cell can have good channel estimation after waiting for 7 OFDMA symbols. After insertion of pilot, guard and DC subcarriers, the IFFT is operated on them to create OFDM symbol. Finally, the last part of OFDM symbol, as a cyclic prefix, is added to the beginning. After all these operations, the data is ready to be delivered to the channel.

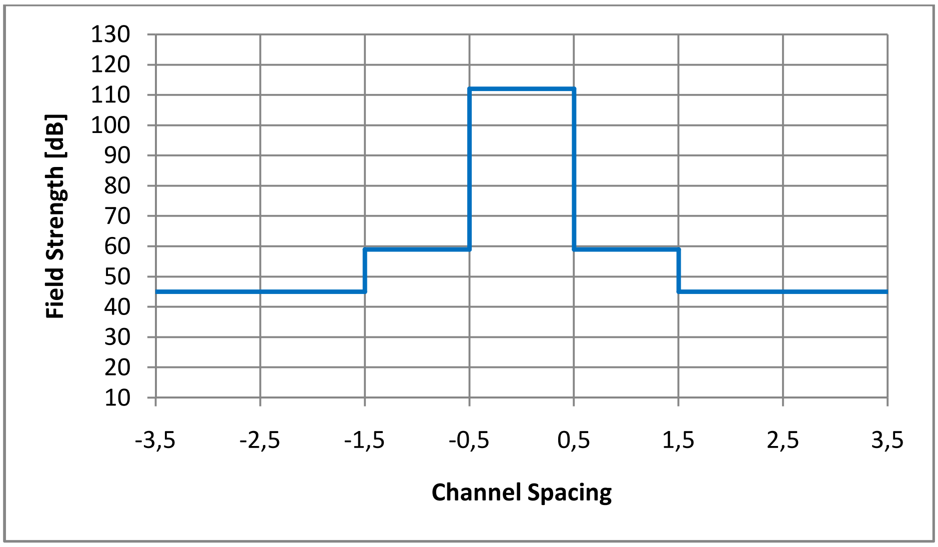

Figure 28 IEEE 802.22 WRAN transmission RF Mask for the USA Channel spacing relative to the TV bandwidth (Symmetrical about the channel center).

The IEEE 802.22 standard specifies the transmit spectrum mask requirements authorized by the various regulatory domains for the different regulatory classes. Figure 28 refers to the appropriate figure which illustrate the RF Masks applicable to the IEEE 802.22 system in the USA. The power spectrum density (PSD) measurement shall be done over a measurement bandwidth of 100 kHz and a video bandwidth of 100 kHz with an average detector. For this reason the last block is a baseband filter.

5.4 Measurement Method and Results

The tolerance of DTT receivers to ACI has been quantified in several studies [67] [68], revealing that transmission on adjacent channels can cause harmful interference if the output power of the transmission exceeds the maximum received interference power tolerable by the DTT receiver. In [68] further measurements have been made on a wider range of receivers (including some newer silicon tuner based designs). The wanted TV signal and the interference signal were put together using a directional coupler and a combiner. The protection ratio is the minimum value of the signal-to-interference ratio required to obtain a specified reception quality under specified conditions at the receiver input [69]. For these measurements, the reception quality was quantified using subjective evaluation criteria, i.e. the absence of a picture failure (PF) [70] [71], during a minimum observation time of 30 seconds [72].

We focused on the co-channel and adjacent channel interference of an 802.22 system operating into the same coverage range of a TV receiver. In order to evaluate the performance of DVB-T / T2 systems interfered by 802.22 transmission, the PF levels has been monitored for different operation modes of the 802.22 standard. The goal of the study was to find the maximum transmission power level and bandwith configuration of an 802.22 signal in the co and adjacent channel of an active DVB-T / T2 system whereas protecting the primary broadcast system.

The wanted TV signal was generated using the X-Stream Dektec software. The IEEE 802.22 PHY layer scheme has been modeled in Matlab/SIMULINK, as described in the previous section, for generating 802.22 signals characterized by different bit rates. The wanted TV signals and the interference signals are combined in the RF band using two DTU-215 multi-standard VHF/UHF Dektect modulators (figure 29) and a 3dB Huber Shuner Hybrid coupler.

Figure 29 Dektect DTU-215 Modulator.

The useful TV signal is received using different DVB-T / T2 receivers. Specifically we used two different DVB-T / T2 receiver: the “Humax HD-Fox T2” receiver and the “Sharp TU-T2 receiver. A simple schematic of the measurement system is shown in figure 30.

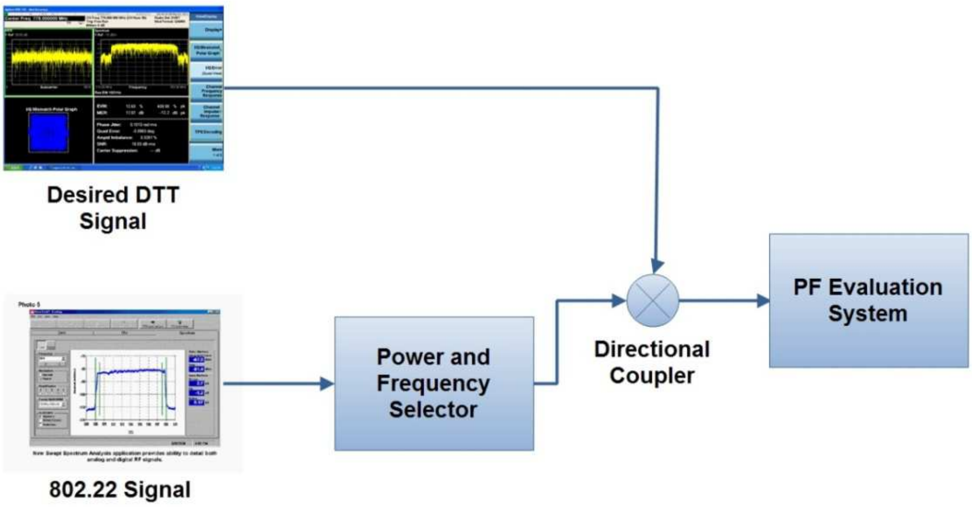

Figure 30 Schematic of the measurement System.

Thanks to the X-Stream Dektec software all the wanted TV signals for all different DVB-T / T2 transmission bandwidth (6, 7 and 8 MHz) were generated. For each of the two tested receivers and transmission bandwidth, the received power level to obtain a modulation error ratio (MER) level of -23 dB was calculated using a Rhode & Schwarz (R&S) EFA40 DVB test Receiver, shown in figure 31. Thus the wanted channel power level C was set to -60 dBm.

Figure 31 R&S EFA40 DVB Test Receiver

EFA's powerful digital signal processing provides fast and thorough analysis of the received DVB signal. Analysis is performed simultaneously with, but independently of, demodulation and decoding. The MPEG2 transport stream is permanently available for decoding as well as for vision and sound reproduction. Thanks to its real-time analysis capability, the high number of measured values necessary for the complex calculation and display processes are made available for subsequent mathematical/statistical processing in an extremely short, as yet unequalled, time.

The maximum transmission power levels of an 802.22 signal transmitting in the co-channel and the first adjacent channel of an active DTT system in order to respect the condition for the minimum PF level of a DTT receiver has been obtained. The transmission frequency of the wanted TV signal is fixed during all the measurements. On the other hand the transmission frequency of the interfering 802.22 signal is initially set to the central wanted TV frequency changing with a frequency step of 500 kHz up to the central frequency of the first adjacent channel. The following test procedure was used to measure the protection ratio of DVB-T and DVB-T2 systems interfered by 802.22 cognitive devices operating in the UHF band:

1. the received power level to obtain a MER level of -23 dB is evaluated for the TV signal using a R&S EFA40 DVB test receiver;
2. the transmitting power level of the interfering 802.22 signal is initially set to a power level of -20 dB below the noise floor of the tested receiver;

3. the signal level of the 802.22 interference is then adjusted to achieve the required degradation (PF point) of the received and decoded TV signal;
4. the RMS power level of the interferer is measured in the considered channel bandwidth using a R&S ESPI test receiver;
5. the C/I protection ratio was calculated from steps 2 to 4;
6. steps 2 to 5 are repeated varying the 802.22 signal frequencies from N to N+1 (N is the considered TV channel) with a step of 500 kHz.

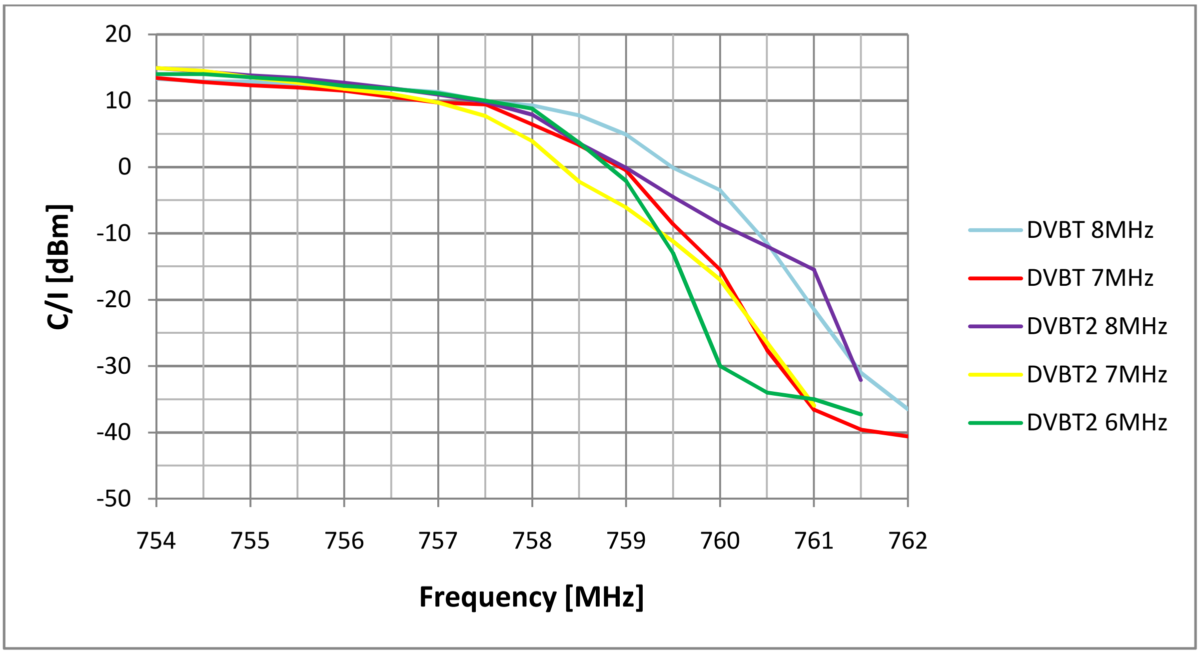

Figure 32 DTT into 802.22 WRAN protection ratio (DVB-T / T-2 signal).

The results (figure 32) demonstrate that the DTT receivers under test are more susceptible to 802.22 interference in the co-channel but already showing a good protection ratio level in proximity of the first adjacent channel. This trend is independent from the signal bandwidth and transmission mode. As it can be seen, the curves obtained for the DVB-T2 standard show a lower Protection Ratio from 757 MHz also reaching differences of 5 dB compared to the case of the DVB-T standard. For this reason the DVB-T2 standard can be considered more robust to 802.22 WRAN adjacent and co-channel transmissions.

Conclusions

This thesis has presented four main topics related to the feasibility of communication cognitive systems operating in the TVWS, considering coexistence as the main operational issue.

The first topic studied new spectrum sensing approaches in order to improve the more critical functionality of CRs. After a short introduction in chapter 1, in chapter 2 the implementation of a new two-stage spectrum sensing method has been described. The system is based on a two-stage spectrum sensing approach for white spaces identification in the 470–790MHz band, combining energy and feature detection methods in the wavelet domain. The current work is specifically adapted for PU signals compliant to the European DVB-T standard. Different from other approaches we looked at the energy detection and signal classification in a combined way, both at system level and at computational level. First we implemented the proposed sensing scheme in a fully software simulator and calculated with these simulated signals the thresholds for both energy detection and the signal classification stages. The simulations validated our design for the next step, i.e. the tests with real DVB-T signals. Our spectrum sensing approach was tested in a functional system consisting of an RF hardware front-end (USRP2 SDR platform) connected to a computer running a Matlab/Simulink model. Real signals were acquired and fed offline to the computational model in order to test the system's behavior in real conditions. The receiver operation characteristics were slightly inferior to those obtained with the simulated signals. The initial tests results and the obtained ROC curves showed the need of improving the reliability of the sensing method for much lower SNR. The first step will be the calculation of new, more accurate threshold values using a large set of real DVB-T signals with various characteristics. Further steps will also include tests with different wavelet filters.

In the second part of chapter 2 a new cooperative spectrum sensing architecture based on sensor networks has been described. Sensing sensor networks can be extended to the paradigm of Centralized Coordinated Techniques that involve CRCs, if operational networks would be implemented on top of sensing networks (collocated) and additional functionality (from the point of view of the transmission and processing power) would be passed from the CR Controller to the sensor nodes, which can be implemented by employing SDR platforms (USRP2). This is not an evolution of the Sensing sensor networks approach but rather a parallel alternative for a better-suited purpose scenario, both collocated and separated architectures approach having their pros and cons. Because of the immersive nature, high interactivity and powerful sense of presence, the authors' 3D GUI complies perfectly with the 3D Internet [13] component of the Future Internet that offers users an augmented interaction and navigation metaphor. Also, the wireless nodes network features a functionality that emulates Internet of Things specific scenarios, while the whole conceptual application offers a radio spectrum management service particular to the Internet of Services. The VR environment could be further developed by employing advanced visualization, sound and haptic devices specific to immersive VR applications (i.e. CAVE).

The first tests, performed in order to validate the proof-of-concept application, using a single frequency, showed that merging exponentially developing domains such as Virtual Reality and its characteristic techniques and devices with the field of spectrum sensing and, generally, dynamic spectrum management, results in added functionality and significant added value for the latter. These initial tests will be continued by analyzing a more extended range of frequencies and by implying more intelligent sensor nodes, for example software-defined radios.

For the second main topic of this thesis an indoor short-range distribution system for the wireless retransmission of SD and HD DTT-compliant contents in the free TV channels has been proposed in chapter 3. A central device can simultaneously and independently distribute the TV contents to several TV sets located in different areas of a building. The system architecture is based on a joint use of GL-DBs, two stage spectrum sensing and EIRP control techniques to provide accurate protection to incumbents. Communication between server and clients is performed over the identified free TV channels using the existing DTT standards. Unauthorized access can be prevented by using DRM scrambling techniques via the CI slot of the TV receivers. To obtain a valid proof-of-concept for the proposed system we first investigated the issues related to the allowable maximum EIRP useful to transmit without providing harmful interference (ACI) and quantified them not only for the first adjacent channel. Starting from already performed investigations on commercial DTT receivers, we conducted our own measurement campaign with newer receiver types and in real working conditions, over-the-air transmission. These tests were performed in an anechoic chamber using antennas for the transmission of the wanted TV and interference signal. We obtained the protection ratios for over-the-air DTT transmissions, revealing a slightly higher C/I ratio than the previous studies. For dynamically choosing the best free channel, in order to avoid interference to the adjacent active channels, we designed a particular algorithm called ADA. The algorithm uses as input the occupancy data obtained from the Agilent VSA and the adjacent channel protection ratio mask, in order to obtain a list of useful frequencies and transmission powers.

Based on these transmitting power values calculated using the ADA algorithm, we used the second part of our research study to experimentally determine the conditions under which the co-existence of DTT receivers and short-range transmitters is feasible for indoor environments. Taking into account all the elements related to the presence of typical attenuation phenomena for an indoor environment, we investigated the coverage distance between the central device and a DTT receiver, using a fixed transmission power level. The implemented hardware test-bed is based on commercial TV sets with integrated DTT tuners and off-the-shelf antennas in combination with SDR hardware devices on which the system prototype has been implemented.

The results of the indoor measurement campaign revealed an extended coverage of the wireless system suitable for a normal two-floor house. We ensured that no other receiver can be disturbed by a new transmission by respecting the transmission protection ratio in order to firstly not disturb the potential receivers in proximity of the central device. By implementing a functional prototype of the proposed system and performing an extended indoor measurement campaign we delivered the proof-of-concept of the proposed indoor short-range distribution system for the wireless retransmission in the free TV channels of DTT-compliant contents. The measurements and assumptions were made using always the worst-case scenario which nevertheless delivered first satisfactory results. Future work will include the possibility to enhance the system's coverage by improving transmission protection ratio using different modulation techniques and different antenna polarization.

The third topic of this thesis was about a particular database developed in order to provide information to easily calculate HNM values and associated statistics, TV Channel Occupancy and Man Made Noise Upper Limits. Chapter 4 presented an extended study on the spectral occupancy, the hidden node margin and the manmade noise of the UHF band allocated for TV broadcasting through real measurements performed in urban, suburban and rural locations in and around the cities of Bilbao (Spain) and Cagliari (Italy). The measurement methodology was the same in both scenarios.

Results have shown that a top occupancy of 84% of the bandwidth can be achieved with rooftop antennas in rural areas, where the coverage areas from different repeaters overlaps based on the lack of obstacles. The mean occupancy for both cities is 32% with a standard deviation of 18. The hidden node margin obtained range from 8 to 38 dB depending on the environment. The measurements of the man-made noise in the UHF TV bands have shown that noise is below the equipment performances with the exception of the urban scenarios where the presence of noise could be measured. From this point of view we can conclude that further measurements are required to have a statistically meaningful set of data.

The overall conclusion is potential that cognitive communication in the UHF TV band needs to make a joint use of geolocation databases and spectrum sensing techniques in order to avoid harmful interference to the primaries services of the broadcasters. Future work will be focused on extending the measurements in the various scenarios and on further in-depth statistical analysis of the results.

In the last topic we focused on the IEEE 802.22 WRAN standard. The objective was to evaluate the performance of an 802.22 system operating into the same coverage range of a DTT receiver. We performed extended measurements for evaluating the protection of the existing broadcasting services. In order to evaluate the performance of DTT systems interfered by 802.22 transmissions in the co-channel and adjacent channel, the reception quality was quantified evaluating the absence of a picture failure (PF) during a minimum observation time of 30 seconds. The goal of the study, shown in chapter 5, was to find the maximum transmission power level and bandwith configuration of an 802.22 signal in an adjacent channel of an active DVB-T / T2 system whereas protecting the primary broadcast system. From the obtained results the DVB-T2 standard can be considered more robust to 802.22 WRAN transmissions in the adjacent and co-channel frequencies.

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