REM DESIGN FOR COGNITIVE RADIO NETWORKS IN TV BAND

A Degree's Thesis

Submitted to the Faculty of the

Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona

Universitat Politècnica de Catalunya

by

Marc Darné Marí

In partial fulfilment

of the requirements for the degree in

TELECOMMUNICATIONS SYSTEMS ENGINEERING

Advisor: Anna Umbert Juliana

Barcelona, June 2014

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

telecom BCN

Abstract

Recent studies have demonstrated a clearly visible fact in our environment: The boom of wireless networks traffic has made raise the need of more bandwidth, due to an increment of the usage of wireless resources; every time with more and more different devices. Otherwise, other studies show an inefficient occupation of radio electric spectrum inside commercial bands; that is, not all assigned channels are currently in use by their operators. UHF TV band is an example of this situation, compounded after analogue TV switching off.

Putting two previous scopes together have induced a new evolution of wireless networks: Deploying a certain kind of devices able to operate at empty channels of commercial bands. This thesis shows a way for these wireless devices to find out empty channels of a certain band and geographical location. The way has been tried out at *ETSETB TelecomBCN UPC Campus Nord* facilities with successful expected results.

Resum

Estudis recents han demostrat un fet clarament visible en el nostre entorn: L'increment de tràfic de les xarxes sense fils ha fet augmentar la necessitat de més ample de banda, degut a un increment de l'ús dels recursos ràdio; cada vegada amb més dispositius diferents. D'altra banda, altres estudis mostren una ocupació de l'espectre radioelèctric ineficient dins les bandes comercials; amb altres paraules, no tots els canals assignats estan actualment en ús pels seus operadors. La banda UHF de televisió és un exemple d'aquesta situació.

Ajuntar els dos àmbits anteriors ha provocat una nova evolució de les xarxes sense fils: Desplegar un cert tipus de dispositius capaços d'operar als canals buits de les bandes comercials. Aquesta tesis mostra un mètode per aquests dispositius ràdio de trobar canals buits d'una certa banda i en una ubicació geogràfica. El mètode ha estat provat a les instal·lacions de la *ETSETB TelecomBCN UPC Campus Nord* amb bons resultats esperats.

Resumen

Estudios recientes han demostrado un hecho claramente visible en nuestro entorno: El auge de tráfico de las redes inalámbricas ha hecho aumentar la necesidad de más ancho de banda, debido a un incremento del uso de los recursos radio, cada vez con más dispositivos diferentes. Por otra parte, otros estudios muestran una ocupación del espectro radioeléctrico ineficiente dentro de las bandas comerciales; con otras palabras, no todos los canales asignados están actualmente en uso por sus operadores. La banda UHF de televisión es un ejemplo de esta situación.

Juntar estos dos ámbitos anteriores ha provocado una nueva evolución de las redes inalámbricas: Desplegar un cierto tipo de dispositivos capaces de operar en los canales vacíos de las bandas comerciales. Esta tesis muestra un método para estos dispositivos radio de encontrar canales vacíos de una cierta banda y ubicación geográfica. El método ha sido probado en las instalaciones de la *ETSETB TelecomBCN UPC Campus Nord* con buenos resultados esperados.

Acknowledgements

The author of this thesis appreciates the effort and received help coming from staff members of *Mobile Communications Research Group* (GRCM) and fellow students, with an special gratitude to Oriol Ros Fornells who designed and implemented a *MATLAB* interface to manage directly *Rohde & Schwarz FSL6* spectrum analyser parameters. This interface automatizes most relevant steps in order to optimize time involved doing the measurements.

The project advisor has been involved deeply in the developing process of this thesis, helping just when necessary with fair information. She has contributed to improve the knowledge and the style of writing of this thesis.

Revision history and approval record

Revision	Date	Purpose
0	22/03/2014	Document creation
1	29/05/2014	Document revision by supervisor
2	09/07/2014	Final document revision by supervisor

DOCUMENT DISTRIBUTION LIST

Name	e-mail
Marc Darné Marí	marc.darne@alu-etsetb.upc.edu
Anna Umbert Juliana	annau@tsc.upc.edu

Written by:		Reviewed and approved by:	
Date	22/03/2014	Date	09/07/2014
Name	Marc Darné Marí	Name	Anna Umbert Juliana
Position	Project Author	Position	Project Supervisor

Table of contents

List of Figures

The figures of this document are found in the following table, with the number, a short description and the page where they can be found:

List of Tables

All the needed tables of this document are found in the following table, with the number, a short description and the page where they can be found:

1. Introduction

1.1. Statement of purposes

REM design for Cognitive Radio Networks in TV Band is a project carried out at UPC University in Barcelona; concretely in the *ETSETB Telecom BCN* facilities (*UPC Campus Nord*). The purpose of the project is to design a methodology to measure and count the number of unoccupied channels which can be found in UHF television band. These free channels are called TV white spaces and they can be used locally by a special kind of radio networks, called cognitive radio networks. Cognitive radio networks have the ability to switch to another unoccupied channel if they detect that their current channel gets occupied by a TV broadcaster, the legal user of the channel according to *Comisión Nacional de los Mercados y la Competencia* (CNMC) resolutions in Spain.

Using a spectrum analyser (*FSL6* by *Rohde&Schwarz*) and an omnidirectional antenna covering UHF bands, the TV band spectrum can be analysed to an interested area. Then, the obtained results can be used to build up a map showing the occupied and unoccupied channels throughout this area. This kind of map is called radio environment map (REM).

This project is focused on the design of whatever REM. The obtained results are then checked in *ETSETB Telecom BCN* facilities, a good place to use cognitive radio networks.

As far as the purpose of this project is concerned, the main goals of it are:

1. Search and identify the main characteristics of a cognitive network (what are they, their advantages and disadvantages, use cases, etc).
2. Put together all the legislation that any TV broadcaster must accomplish (mainly maximum and minimum transmission power and channel bandwidth), according to CNMC. Use this information to identify and mark TV channels as TV white spaces in the band.
3. Characterize the parameters of all the measurement equipment (antenna gain, frequency response of all the equipment, etc).
4. Design the methodology of how to make a radio environment map of any area, taking into account that indoor and outdoor environments must be treated different due to propagation phenomena.
5. Test the obtained results in a known area: *ETSETB Telecom BCN* facilities and for a given band: UHF TV band.

This project starts from the scratch; it means that it is not related directly with another project. However, the project is a continuation of a set of projects made in other universities around Europe and the USA. In Spain there are not many projects related with radio environment maps in TV band, so this project can be considered as one of the first.

REM design for Cognitive Radio Networks in TV Band is carried out within *Mobile Communications Research Group* (GRCM), a research group from *Signal Theory and Communications* (TSC) *Department*. Their purpose is to implement an easy way to build radio environment maps from any RF band; so this project is developed following this aim, and tested in the particular case of UHF TV band. The main project initial ideas were provided initially by the supervisor of the project, as spokeswoman of the whole research group. This project will develop a radio environment map in UHF TV band, one good candidate band for cognitive radio networks as most part of the channels are unused here after the switchover from analog to digital television.

1.2. Requirements and specifications

In order to achieve the previous objectives a starting point must be defined. Basically this project is focused on design a methodology of REMs build, so all details that a REM needs are placed here:

- A detailed description of REM contents. Specifically description of the required parameters like received power, thresholds, spatial resolution, etc.
- An initial contribution to the REM made by the TV band occupancy in the *Campus Nord* area.

The previous requirements get achieved in this project after defining the next specifications:

- Omnidirectional antenna, with flat frequency response or, at least, a known frequency response that can be compensated after measurements. The antenna must be omnidirectional in order to receive any desired signal coming from anywhere in a certain point. And it must cover UHF TV band.
- Spectrum analyzer with a high precision for seeing correctly the TV channel frequency spectrum.
- *MathWorks MATLAB* as the mathematic tool for measured data post processing.
- *Forsk Atoll* as the simulation tool to simulate TV channels propagation.

1.3. Final work plan

The next chart shows the work methodology developed in this project:

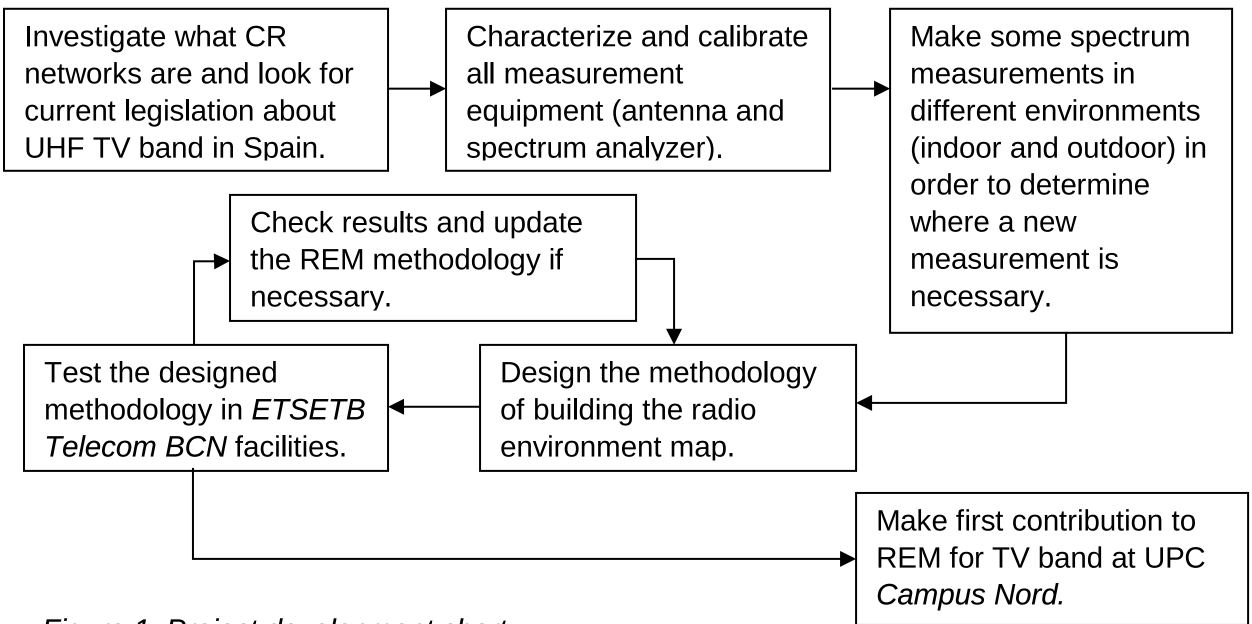


Figure 1: Project development chart.

According to the previous chart, each of the framed objectives is described as a task with multiple subtasks, in some cases. Each task has information about the planned and final start/end date, the name of deliverables (if any) and the delivery date of them.

Project: *REM design for CR Networks in TV Band*	WP ref: 1	
Major constituent: Information search and interpretation	Sheet 1 of 8	
Short description: Investigate what cognitive radio networks are and look for current legislation about UHF TV band in Spain.	Planned start date: 17/03/2014 Planned end date: 31/03/2014 Start event: 24/03/2014 End event: 25/04/2014	
Internal task T1: Look up information about cognitive radio networks, TV white spaces, etc. Internal task T2: Put together all data in a summarized memory.	Deliverables:	Dates:

Table 1: 1st Working Plan reference.

Project: *REM design for CR Networks in TV Band*	WP ref: 2	
Major constituent: Equipment characterization	Sheet 2 of 8	
Short description: Characterize and calibrate all measurement equipment (antenna and spectrum analyzer).	Planned start date: 24/03/2014 Planned end date: 31/03/2014 Start event: 11/04/2014 End event: 25/04/2014	
Internal task T1: Characterize antenna and spectrum analyzer parameters. Internal task T2: Prepare a simple datasheet showing the obtained results.	Deliverables: Critical review	Dates: 28/04/2014

Table 2: 2nd Working Plan reference.

Project: *REM design for CR Networks in TV Band*	WP ref: 3	
Major constituent: Environment characterization	Sheet 3 of 8	
Short description: Make some spectrum measurements in different environments (indoor and outdoor) in order to determine where a new measurement is necessary.	Planned start date: 28/04/2014 Planned end date: 11/05/2014 Start event: 05/05/2014 End event: 09/05/2014	
Internal task T1: Proceed with some measurements in all different environments. Internal task T2: Decide the distance where a new measure is required according to obtained results.	Deliverables:	Dates:

Table 3: 3rd Working Plan reference.

Project: *REM design for CR Networks in TV Band*	WP ref: 4	
Major constituent: REM initial design	Sheet 4 of 8	
Short description: Design the methodology of building the radio environment map.	Planned start date: 28/04/2014 Planned end date: 12/05/2014 Start event: 28/04/2014 End event: 12/05/2014	
Internal task T1: Put together all recollected information. Internal task T2: Prepare a template of a future REM.	Deliverables:	Dates:

Table 4: 4th Working Plan reference.

Project: *REM design for CR Networks in TV Band*	WP ref: 5	
Major constituent: REM design testing	Sheet 5 of 8	
Short description: Test the designed methodology for TV band in *ETSETB Telecom BCN* facilities.	Planned start date: 26/05/2014 Planned end date: 01/06/2014 Start event: 19/05/2014 End event: 06/06/2014	
Internal task T1: Test the design.	Deliverables:	Dates:

Table 5: 5th Working Plan reference.

Project: *REM design for CR Networks in TV Band*	WP ref: 6	
Major constituent: REM design updating	Sheet 6 of 8	
Short description: Check results and update the REM methodology if necessary.	Planned start date: 26/05/2014 Planned end date: 08/06/2014 Start event: 19/05/2014 End event: 13/06/2014	
Internal task T1: Change whatever necessary in REM design. Internal task T2: Check the results and decide the modifications of original design.	Deliverables:	Dates:

Table 6: 6th Working Plan reference.

Project: *REM design for CR Networks in TV Band*	WP ref: 7	
Major constituent: REM final confection	Sheet 7 of 8	
Short description: Make first contribution to REM at *ETSETB Telecom BCN* facilities.	Planned start date: 26/05/2014 Planned end date: 22/06/2014 Start event: 19/05/2014 End event: 20/06/2014	
Internal task T1: Make first contribution to REM for TV band at UPC Campus Nord.	Deliverables:	Dates:

Table 7: 7th Working Plan reference.

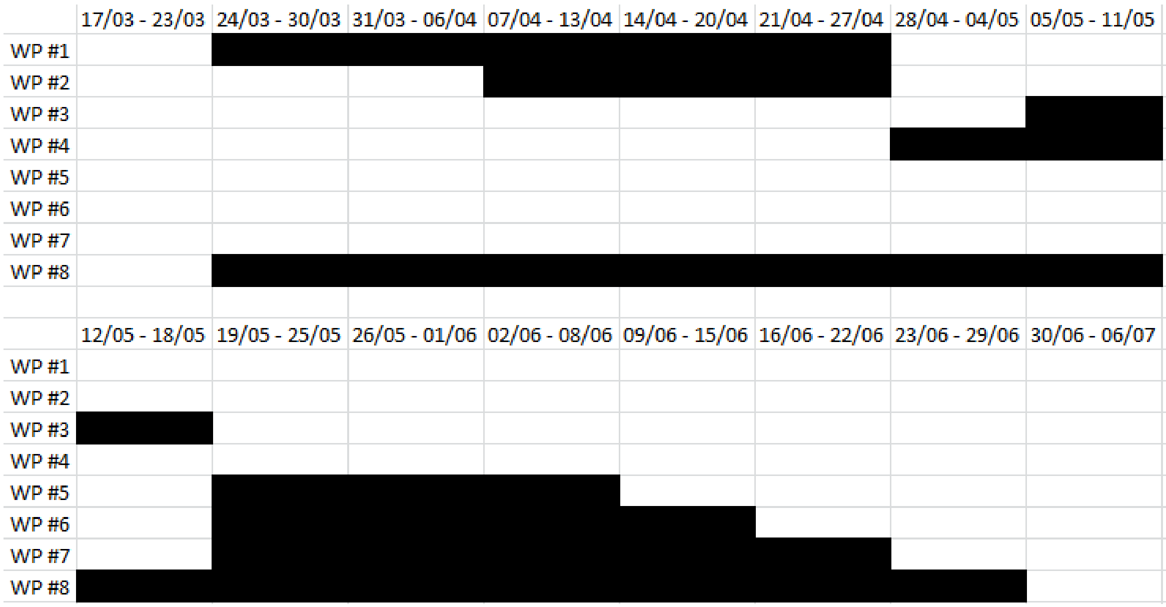
Project: *REM design for CR Networks in TV Band*	WP ref: 8	
Major constituent: TFG final memory preparation	Sheet 8 of 8	
Short description: Prepare the memory of this project.	Planned start date: 31/03/2014 Planned end date: 30/06/2014 Start event: 17/03/2014 End event: 30/06/2014	
Internal task T1: Prepare the memory.	Deliverables: Final review	Dates: 30/06/2014

Table 8: 8th Working Plan reference.

WP#	Task#	Short title	Milestone / deliverable	Date
1	1	Information search and interpretation		31/03/2014
1	2	Information search and interpretation	All clear to start working	25/04/2014
2	1	Equipment characterization		11/04/2014
2	2	Equipment characterization	Equipment characterized	25/04/2014
3	1	Environment characterization		
3	2	Environment characterization	Environment characterized	
4	1	REM initial design		05/05/2014
4	2	REM initial design	Initial REM designed	12/05/2014
5	1	REM design testing		
6	1	REM design updating		
6	2	REM design updating	REM tested in *ETSETB*	
7	1	REM final confection	REM built and tested	
8	1	PFG final memory preparation	Final review	30/06/2014

Table 9: Working Plan summary with milestones and deliverables.

Updated Gantt diagram:



1.4. Incidences and other remarks

The order of tasks, working plans and priorities of this thesis were though and planned to execute in a different order, not in accordance with official advisors order. They usually expect from project author to do first experimental and practical measurements and then move to prepare the final memory. However, the project author with the agreement of his thesis advisor decided to start first the preparation of the final document; looking up all theoretical information, and leaving for the end all measurements. The aim of this change is to build a solid theoretical base about Radio Environment Maps and TV band before planning the characteristics and types of measures needed.

Initially, the Work Plan was planned to execute and finish first and second WP task on March. The amount of information planned to find, add and comment was initially conditioned to a certain maximum number of pages established for thesis of this kind (no longer than 30). This limit will be extended up to 50 pages, making it possible to extend all theoretical information. The required time to end first WP rose up in order to achieve the new objectives.

2. State of the art of the technology used in this thesis

In this section all the ingredients related with one of the main problems nowadays in wireless communications will be put altogether. The problem consists on the need to expand wireless networks beyond the designated bands into the radio spectrum, taking into account the important traffic growing that they have suffered during the past five-ten years. This spectrum expansion cannot be done in whatever unused band, according to the needed bandwidth to support wireless networks for a certain quality of service.

At this point another important factor appears in scene: After analogue TV switch-off, due to an increase of the spectral efficiency in DVB-T emissions, a certain number of channels in TV band were released and nowadays they are empty. These unused channels are assigned to TV broadcasters. However, if any TV broadcaster will not make use of them, unused channels can be assigned to other primary operators by an auction, promoted by *Comisión Nacional de los Mercados y la Competencia* (CNMC) (old CMT) in Spain case. At 40th page of *2012 CMT Sectoral Economic Report* [1], this is proposed as part of the solution of Long Term Evolution (LTE) wireless networks investments promotion at this country. [1] also exposes that the same operation has been done in other European Union countries with expected good results. The reassignment of unused bands to primary wireless networks operators; however, is not the aim of this thesis.

The expected increase in wireless traffic demand will change the current allocation policy, which nowadays establishes fixed spectrum assignments to the desired operator for a long period of time. Recent measurement campaigns have demonstrated that the real occupation of the spectrum is low; so not all users who have assigned spectrum are taking advantage of it. This conclusion has caused a debate on using this non-occupied spectrum by other kind of wireless networks that can operate as secondary users, like cognitive radio networks which can switch automatically among spectrum empty channels if they are available. In parallel, after analogue TV switches off and the imminent result of more freed spectrum, it has been proposed to use UHF TV band as the first one to test those cognitive radio network systems.

Somehow the cognitive radio network must know how the available channels are distributed. At this point, a Radio Environment Map (REM) is crucial because it has all the available empty channels tabulated in a known environment with a really good precision.

The objective of this thesis is to design a methodology for building a REM for cognitive radio networks, leveraging TV white spaces. The REM design must fulfil the EU and Spanish law requirements and must be smart in terms of looking for available TV white spaces at a certain point. As a figure of merit, the REM design is tested by building real REM of UPC Campus Nord facilities.

2.1. A general overview of the situation

In the beginning of the 2000s, Internet was already used for hundreds of million people around the world; more concretely in the countries and continents of the first world. The home or business Internet users accessed to it through wired links basically. They used Ethernet networks or similar protocols for Local Access Networks and other protocols and infrastructures like Dial-Up modems, DSL, etc.

At that time, wired connections were robust and quite useful, but new needs started to rise up. Engineers started to ask questions: Is it possible to get access to the Internet without using wired long cables? Then, if wireless access can be possible at home or business, can also be possible in crossing sites (bars, parks, etc)? Questions like this made appear new ways to connect to the Internet.

In the 2000s, the most extended wireless network was second generation (2G) mobile cellular network. They allowed (and still allow nowadays) a mobile call from one terminal to another one, or between a mobile terminal and a fixed phone anytime and anywhere. The only two requirements were to have enough coverage and battery power in mobile terminals. Exploiting this network already deployed, one of the first wirelesses Internet access was to develop a new protocol able to work with IP packets, but absolutely transparent for physical 2G layer, which were initially designed to work for mobile voice calls. In Europe the protocol was GPRS, which worked perfectly over GSM physical layer.

In parallel, other infrastructures were designed and deployed to allow laptops to be still connected to an Ethernet network without using RJ-45 wires. IEEE 802.11 (Wi-Fi) is the one most used at that time and nowadays. As we can imagine, the great boom of wireless networks made obsolete its initial capacity threshold. An evolution of current technologies and new networks designs solved this problem. Is the case of mobile third generation (3G), a mobile network thought and designed for the first time to support circuit-based (for voice calls) and packet-based (for IP Internet data) links.

However, the continuous wireless traffic growth made also saturated these systems. The wireless traffic grows every year exponentially. It happened in the 2000s era, still happens nowadays and will continue happen next years. A recent study by Cisco [2] predicts a growth of wireless traffic data from the current mean of 1.5 EB per month in 2013 to a mean of 15.9 EB per month by 2018! According to Cisco study, smartphones wireless traffic will pull this growth up to the detriment of non-smartphones wireless traffic, which it will decrease. Next figure shows this traffic growing for different continents:

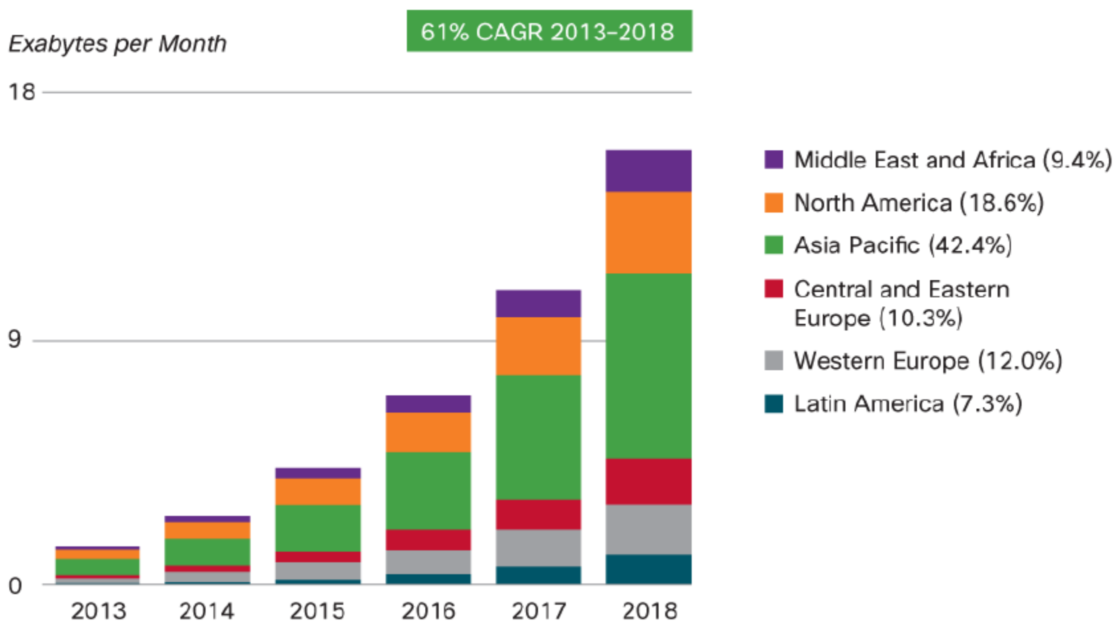


Figure 2: Global mobile data traffic forecast by region, according to Cisco [2].

According to cellular networks; as mobile data, video and TV services are fast becoming an essential part of consumer lives, the study concludes that next-generation mobile networks will require greater services portability and interoperability. Due to wireless networks want to provide experiences formerly only available through wired networks, the next few years will be critical for operators and service providers to plan future network deployments.

Why operators and service providers could have trouble when it is time to plan new wireless networks? There are some reasons but one of the most important ones is the limited bandwidth assigned to wireless networks, either ones assigned to operators (LTE, HSPA, etc) or others deployed without assignment (Wi-Fi, WiMAX, etc).

If we have a look in Spain spectrum distribution, close similar to other European countries, we will see that there are no much bandwidth dedicated to professional wireless networks. Since January 1st, 2015, UHF TV channels from 61 (790 MHz) to 69 (862 MHz) will be released for other wireless telecom services [3]; but it is easy to see that this release is clearly insufficient. Next table summarizes all the bands that could be occupied by wireless networks in Spain nowadays (2014 first semester):

Frequency (MHz)		Band name	Most common operative services in this band
Start	End		
0.1357	0.1378	ITU LF	Amateur band (and other)
0.472	0.479	ITU MF	Amateur band (and other)
1.8	2	ITU MF	Amateur band (and other)
3.5	4	ITU HF	Amateur band (and other)
7	7.1	ITU HF	Amateur band and satellite amateur band
10.1	10.15	ITU HF	Amateur band (and other)
14	14.35	ITU HF	Amateur band
18.9	19.02	ITU HF	Amateur band and satellite amateur band
21	21.45	ITU HF	Amateur band and satellite amateur band
24.89	24.99	ITU HF	Amateur band and satellite amateur band
28	29.7	ITU HF	Amateur band and satellite amateur band
50	54	ITU VHF	Amateur band
144	148	ITU VHF	Amateur band and satellite amateur band
220	225	ITU VHF	Amateur band (and other)
433.05	434.79	ITU UHF	Amateur band (and other)
880	915	900 Band	2G / 3G UMTS/HSPA (uplink) (in the future)
925	960	900 Band	2G / 3G UMTS/HSPA (downlink) (in the future)
1240	1300	ITU UHF	Amateur band (and other)
1710.1	1784.9	1800 Band	4G LTE (uplink)
1805.1	1879.9	1800 Band	4G LTE (downlink)
1900	1980	2100 Band	2G / 3G UMTS/HSPA (FDD and TDD) (in the future)
2110	2170	2100 Band	3G UMTS/HSPA
2400	2500	2.4 GHz	IEEE 802.11 (Wi-Fi), IEEE 802.15 (Bluetooth), IEEE 802.15.4 (ZigBee) IEEE 802.16 (WiMAX) and similar
2500	2690	2600 Band	4G LTE

3300	3400	ITU SHF	Amateur band (and other)
3400	3600	3500 Band	IEEE 802.16 (WiMAX)
5725	5875	5 GHz	IEEE 802.11a (Wi-Fi)
24000	24050	ITU SHF	Amateur band and satellite amateur band
24050	24250	ITU SHF	Amateur band (and other)
47000	47200	ITU EHF	Amateur band and satellite amateur band
76000	81000	ITU EHF	Amateur band and satellite amateur band (and other)
122250	123000	ITU EHF	Amateur band (and other)
134000	136000	ITU EHF	Amateur band and satellite amateur band
241000	250000	ITU EHF	Amateur band and satellite amateur band (and other)

Table 10: Assigned spectrum to wireless networks of any kind. References: [4], [5], [6].

The previous table includes all the cellular mobile networks, the ISM (Industrial, Scientific and Medical) radio bands and also amateur bands; because these last ones can be used by short range wireless networks. However, analysing the obtained results, we can conclude that most important local wireless network (Wi-Fi) only has two bands to operate, causing its used spectrum to be absolutely overused. It is easy to see just having a look of how many Wi-Fi stations are operating together on the same channel. Moreover, 2.4 GHz band is also used for other point-to-point services, causing interferences over Wi-Fi networks. LTE networks perhaps are able to pick some traffic from these networks, but then, LTE will need to expand its operational bandwidth in order to avoid overload in its infrastructure.

2.2. TV band, the opposite world in terms of spectral occupation

Having a look at the above table, if Cisco predictions for wireless traffic by 2018 are going in the right line, the situation is going to be untenable in the future. In urban zones, each channel in 2.4 GHz band can be used at the same time by two, three or even four Wi-Fi networks. More and more Wi-Fi networks in a same channel imply more and more interferences between them. This effect implies a reduction of the quality of service offered; at the end, a reduction of the effective bit rate transmitted and received by each user in the network.

What can be the first solution to solve the problem of Wi-Fi channel overload? Try to switch an unstable/degraded quality Wi-Fi network to an unused channel or, at least, the less used channel. This will partially solve the problem in a local environment, but it is clear that this solution cannot be applied anywhere. Another solution is to move new wireless networks to another band, as nomadic tribes do when they run out of natural resources in a place. But, it has been seen previously that not all bands are free to use. Concretely in Spain, the *Comisión Nacional de los Mercados y la Competencia* (CNMC) decides by auctions which operator will operate any band, following global regulatory criteria. Thus, a solution can be to try to win the desired *CNMC* auction and, finally, be able to operate in that band. *CNMC* band assignment process is a long time process.

Moreover, a regulatory organism does not do every day an auction for any piece of radio spectrum; so that solution is clearly not a good way to solve the problem of overloaded end-to end users' wireless networks (like Wi-Fi).

Regarding to the last proposed solution, it is actually a primary user solution. When a regulatory organism that decides which operator will operate in a channel or a whole band mentions this operator, it is defined as the primary user of some piece of spectrum. However; a piece of spectrum assigned to a specific primary user can be used by another user (called secondary user) if the first one is not using those resources in a certain moment or location? Let's assume from now that it is possible to emit without license in regulated bands. Next section will show more details about bands regulation.

The next step, thus, is to find a band where to place our new wireless network. At this point all military bands must be discarded for obvious reasons, but also amateur bands. Amateur bands usage is very unpredictable; everybody is allowed by law to emit on them anytime, anywhere, and a spontaneous emission of an amateur user could broke down a deployed wireless network link due to interferences. Of course that it can be deployed, but the network will be exposed to a non-clear radio channel, so its stability will be very critical. This fact cannot be assumed in wireless networks used by professional end users, like Wi-Fi or LTE.

Bands located in low or very low frequency ranges can neither be used for that purpose. The needed bit rate for a certain quality of service of any kind of network is automatically related with a given bandwidth. That needed bandwidth can be as large as network bit rate in worst case, so it is difficult to find a piece of unused spectrum by primary users as large as needed bandwidth for wireless network users, the secondary ones. Moreover, the antennas needed to make possible the link must be very large for low frequency bands; perhaps thousands of meters, impossible to manipulate by non-static users.

Taking into account all previous considerations and scrolling up the radio spectrum looking up for unused channels, the band which is close ideal to use for professional wireless networks is UHF TV band. This band is used nowadays for Digital Terrestrial Television (DTT) following the standard Digital Video Broadcasting-Terrestrial (DVB-T). More information about this standard can be found at the next link: http://www.dvb.org/standards/dvb-t2.

In Spain, the UHF TV band is divided in two sub bands [7]: The first one is limited in frequency between 470 MHz and 790 MHz; and it will be from next year the unique dedicated band for TV broadcasting. The second sub band starts at 790 MHz and ends at 862 MHz. It will be used for LTE wireless networks, so it will not be considered as TV band from now in this thesis because its objectives will fall obsolete soon.

According to last reference coming from *Official State Gazette* (BOE in Spanish), the last resolution [7] says that TV band can be used under license by TV broadcasters, following the standard DVB-T. Channelization is limited up to 8 MHz, while other countries use channelization of 5, 6, 7 or also 8 MHz. The requirements specification does not specify an address/separation duplex, thus, any combination of coding rate and guard interval can be assumed. The available bit rates is a function of last two parameters, allowing high definition channels for high bit rates. The information can travel modulated using QAM in combination with COFDM modulation.

In terms of power, the actual legislation determines the emission power of each TV station in the license document so that there is not a minimum absolute transmission power in theory. However, this does not happen on receivers… Royal Decree from the 11th of March, 2011 [8] specifies and regulates how the common telecommunications infrastructures (CTI) must be in order to have a certain quality of service of all those services. From DTT receivers' case, there is a minimum reception power from which a DTT receiver will detect incoming signals and it will be able to demodulate them. There is also a maximum reception power where the receiver will get saturated.

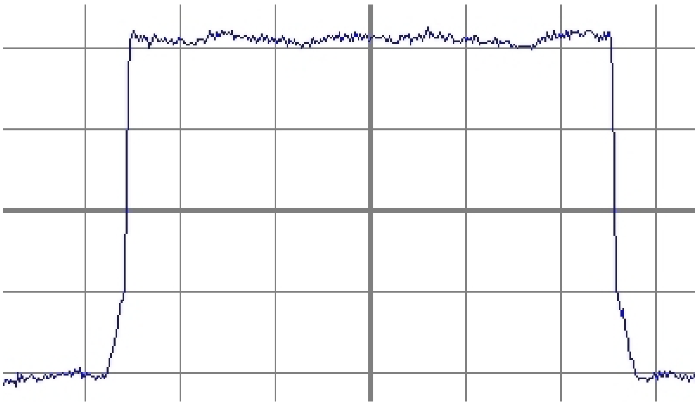


Figure 3: Spectrum of a DVB-T signal of 8 MHz bandwidth.

The CTI regulation specifies the mean of minimum intensity of received electric field $|E_r|$ at receiver input n terms of dBµV/m, it means, voltage value over a resistor of 75 Ω in this case. Expression number 1 shows this value in these terms:

$$20\log|E_r| = 3 + 20\log(f) \quad \left(\frac{dB\mu V}{m}\right) \tag{1}$$

Where f is the DTT channel frequency in MHz and bounded inside TV band specified previously. Expression number 1 can be expressed in terms of received power by computing the equivalent power over this 75 Ω resistor and multiplying the obtained result by the effective area of receiving antenna. According to [8], 75 Ω is the characteristic impedance of all TV coaxial cable infrastructures:

$$10\log P_r = 10\log\left(\frac{|E_r|^2}{75\,\Omega}\right) = D(dB) + 10\log\left(\frac{3}{\pi}\right) - 67 \quad (dBm) \tag{2}$$

Where D is the directivity of the antenna used in reception expressed in logarithmic units. Due to relation between effective area of the antenna and directivity, found in expression (3); putting correctly the units, expression (2) can be achieved.

$$A_{effective} = \frac{\lambda^2}{4\pi}D \quad (m^2) \qquad \text{with} \qquad \lambda = \frac{3*10^8}{f} \quad (m) \tag{3}$$

The previous result can be put in context by comparing it with the emitted power of a certain wireless network deployed in an empty TV channel. If network emission power is lower than previous result (2), it ensures than any DTT receiver will detect this wireless network, causing confusion and some possible errors during its tuning process.

The tables placed in [3] show the current occupation of TV band by all TV broadcasters in Spain. First, channels with full coverage around the country are placed and then each region has a unique table containing local and regional broadcasters. At accessed day the tables also include TV channels placed above 790 MHz, which will be reallocated in principle by 2015. Having a look at the tables a lot of unused channels are found, even if new occupied channels are considered by reallocated broadcasters (most part of them).

At the moment the conclusion that UHF TV band can be a good band to place wireless networks is present, because this band have good propagation conditions; at least better than 2.4 GHz band and comparable with LTE networks low frequency bands conditions. It has emptier than occupied channels and they are strategically spread far enough, making possible its usage for wideband wireless networks. A big amount of information can be placed in 8 MHz spectral bandwidth using most efficient modulations, even multiplying this value by the number of empty channels between two TV broadcasters. The result is comparable with commonly used fast wireless networks nowadays: Exemplary, a TV channel in Spain is a fifth of wideband Wi-Fi channel (IEEE 802.11n) or five half of LTE most wideband channel (considering this LTE channel operating at maximum speed due to very good propagation conditions).

However, these TV channels are assigned to be operated by TV broadcasters and they can only broadcast under a license. But, is this fact an obstacle for other services not related with TV broadcasting?

2.3. <u>The legislation of empty TV channels: TV White Spaces (TVWSs)</u>

The main fact of how to allow other services to operate on TV not-used channels has been started discussing few years ago, more or less when problem of overflowed wireless networks appeared. After discovering the need to use secondary spectrum to allocate them, the importance of regulate these TV white spaces became crucial, in order to avoid its usage like amateur bands; a wild radio electrical environment.

The United States telecom regulatory organism, *Federal Communication Commission* (FCC), was pioneer starting a discussion about this topic. They adopted some rules to allow unlicensed radio transmitters to operate in a broadcast television channel only when that channel is not used by a licensed service; as discussed in previous sections. FCC elaborated a full guide by around 2010, where they are monitoring and giving support to the development and introduction of new possible services operating at a TV White Space (TVWS). The entire guide, including a database of TVWSs containing the power, the frequency band and the geographical location is available here: http://www.fcc.gov/encyclopedia/white-space-database-administration.

In the United Kingdom something similar occurred. In this case was Ofcom regulator organism who elaborated the same guide applicable for the UK. Ofcom is the independent regulator and competition authority for the UK communications industries and its guide is also applicable on TV band. The full guide is available in the next link: http://stakeholders.ofcom.org.uk/spectrum/tv-white-spaces/.

Both guides coincide with the key factor: Unused TV channels can be used by secondary users since one TV broadcaster decides to emit there. The releasing of twice guides was done in parallel with some studies; which are focused on the measure and the situation of TV white spaces in several countries and regions. In this section two of them will be mentioned: one done in North European countries and another one done in Barcelona. The last one will be the basis of research and knowledge of this thesis.

Moreover, apart from those studies whose aim is to have an overview of TVWSs situation, other studies are working on how to take advantage of them somehow by different kinds of wireless networks. In Europe, the COGEU project [9] goes on this line. This project starts showing that the regulatory scenario in Europe is very diverse, and hence innovative solutions to address harmonization and coexistence issues become crucial for the successful exploitation of TVWSs among member states.

The COGEU (COgnitive radio systems for efficient sharing of TV white spaces in EUropean context) project was funded by the European Commission (EU). The basis of this project is to regulate TV band white spaces by dividing the band into two spaces, the first one for commons usage and the second one for secondary spectrum trading. The difference between the two is the Quality of Service (QoS). The common usage band does not require a guaranteed QoS but that is a requirement for secondary trading one. The temporary exclusive rights for operating in the TVWS may be bought from a broker.

The broking method is the basis of COGEU project. In order to avoid interferences between secondary users or between primary and secondary users, a channel assignment method is done; like the auctions made by the authorities who assign licenses to TV broadcasters as primary users. It is like a second-hand market, where unused TV spectrum is the merchandise.

The COGEU project is developed over three challenges of exploiting the TVWSs in the EU exposed all three in the quoted paper. As a summary, the three challenges are:

- The harmonization in the legislation and the allowed usage of a TVWS in all EU countries. Things as cognitive technology, medium access technology, certification and compliance requirements of devices are essential.
- The lag time in terms of exploiting TVWSs, compared with other places as the US.
- The Absence of innovative business models to attract investment in the TVWSs.

Finally, the paper also suggests the way to implement the broker methodology when it is time to assign a TVWS to a user. Figure 4 shows this proposed way.

The paper also suggests that the geo-location database, where all information related with TVWSs is stored as radio environment maps must be decentralized. It means that each EU member has its own database available.

The main issue to deal when a wireless network is operating in a TVWS; despite of thread carefully if the occupied channels are actually not used by primary users is the adjacent-channel interference. The bandwidth of wireless network transceivers must be equal or less than TV channelization of the country where the network is deployed. In addition, if two or more TVWSs are used for a single wideband wireless network, the bandwidth can be extended n times, where n is the number of available TVWSs together.

This statement could sound obvious, but it is actually an upper bound in terms of channel capacity. The reasons are exposed in the first study previously mentioned [10]. It studies the TVWSs distribution in many North-European countries for LTE networks deployment, but taking into account if the adjacent channel emission is allowed or not. The exposed reasons of forbid the emission in a TVWS where it is placed between two primary TV channels are the possible interferences than could be caused over an old TV receiver. By the way, in [10] the criterion of declaring a channel as a TVWS is to use the minimum induced electric field necessary to receive correctly a TV channel as the decision threshold, as exposed in previous section. If the induced electric field is lower than this value, then the channel is declared as a TVWS. In this thesis another criterion exposed in the 3rd chapter will be approached.

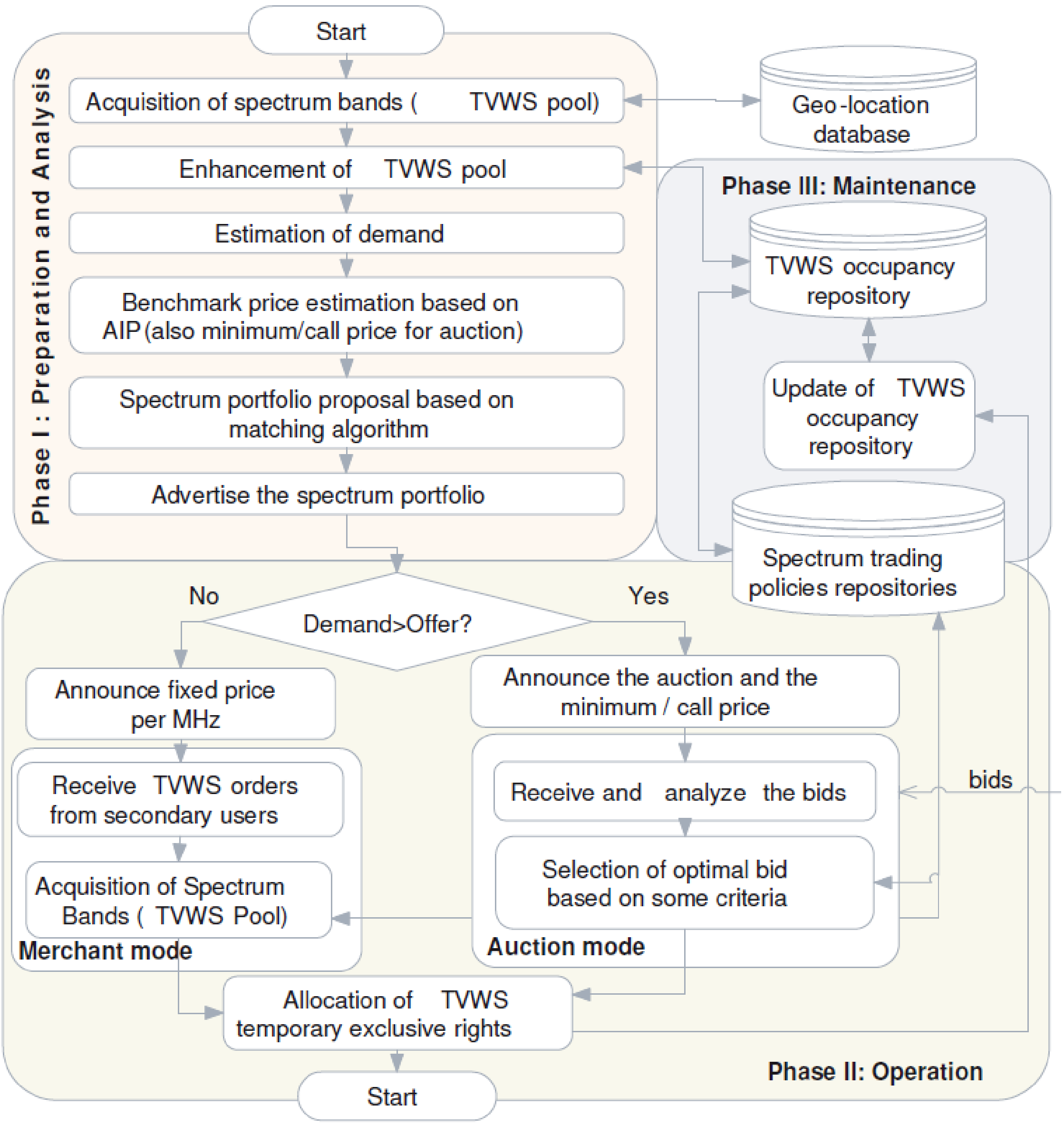


Figure 4: The COGEU broker operation process flow chart extracted from [9].

The next figure, extracted from [10], shows the TVWSs distribution over these countries in two cases: When the adjacent-channel emission is allowed (left picture) and when it is not (right one). The number of total TVWSs is lower in North-Europe than in the USA and they are usually single alone TVWSs between two primary TV channels. These are the main conclusions extracted from [10].

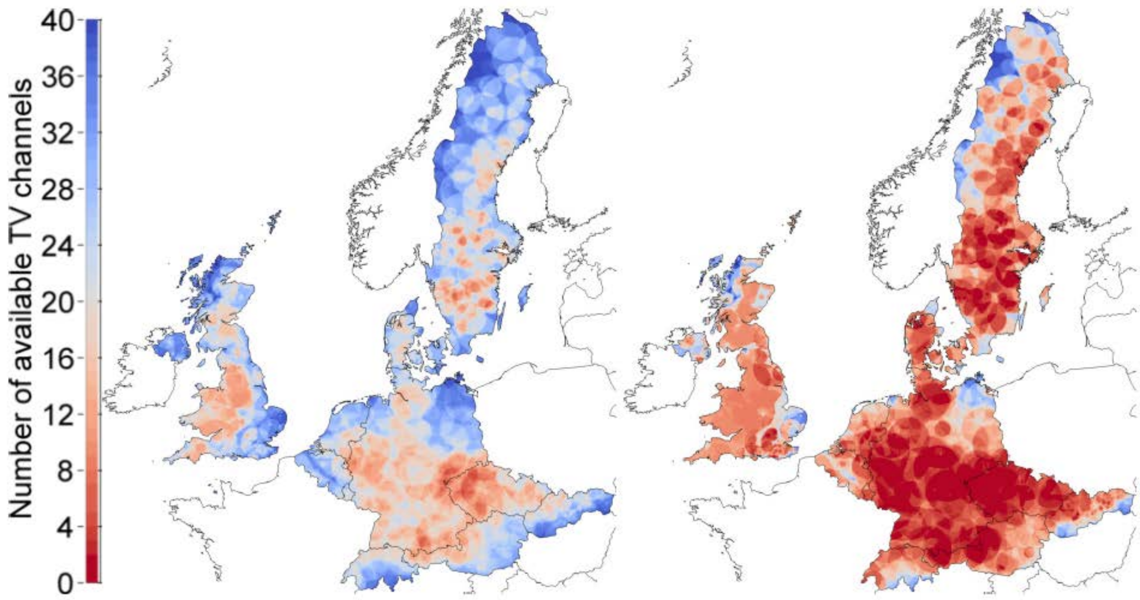


Figure 5: TV white spaces distribution in North-European region (2012) [10].

The study also concludes that TV white spaces are relatively scarce, diminishing, spatially scattered and heterogeneous, as well as rural in nature.

The second paper which will be commented is from the Spanish Telecom Engineers Official College (COET) [11]. The paper looks like an early one which deals with TVWSs legislation and situation in Spain. Actually, it is focused on start the explanation of them as a favourable solution for cognitive radio networks, a special wireless networks topology which have the “intelligence” of knowing somehow the radio electric channel and the kind of its users. As a matter of vocabulary, that paper and the others consulted here calls White Space Devices (WSDs) as the devices that secondary users use to communicate among them using TVWSs. The objective is to differentiate these users and their equipment from primary users and theirs.

Cognitive radio networks will be exposed sooner, in next section. But before going on it, COET paper will be analysed a bit more: Following the same line like [10], it declares a TVWS if the mean received power is lower than a DTT receiver minus a security margin. Moreover, if the WSD could emit secondary spectral lobes in adjacent channels, the received power there is equal plus adjacent channel receiver sensibility; as their figure of merit as higher this value is.

The study referred by COET about TVWSs spectral situation was done in Barcelona in 2008 by the *Mobile Communications Research Group* (GRCM). Thus, they don't take into account the availability of new TVWSs after analogue TV switch off in 2010. However, COET study is concerned on count the available TVWSs in Barcelona and its metropolitan area; but plotting the results as a function of the percentage of municipalities or population who have 1 or 3 TVWSs contiguous, as a function of the available spectrum in MHz. Nowadays, because of the appearance of more contiguous TVWSs rather than in 2008, the blue curve in both figures would be perhaps a little bit closer to the green one. In order to deploy faster wireless networks, the blue curve is more interesting to focus on.

The next figure extracted from [11] is the one which links the TVWSs total available spectrum with the percentage of municipalities. Both figures are similar because of the population distribution quasi uniform in the whole Barcelona metropolitan area.

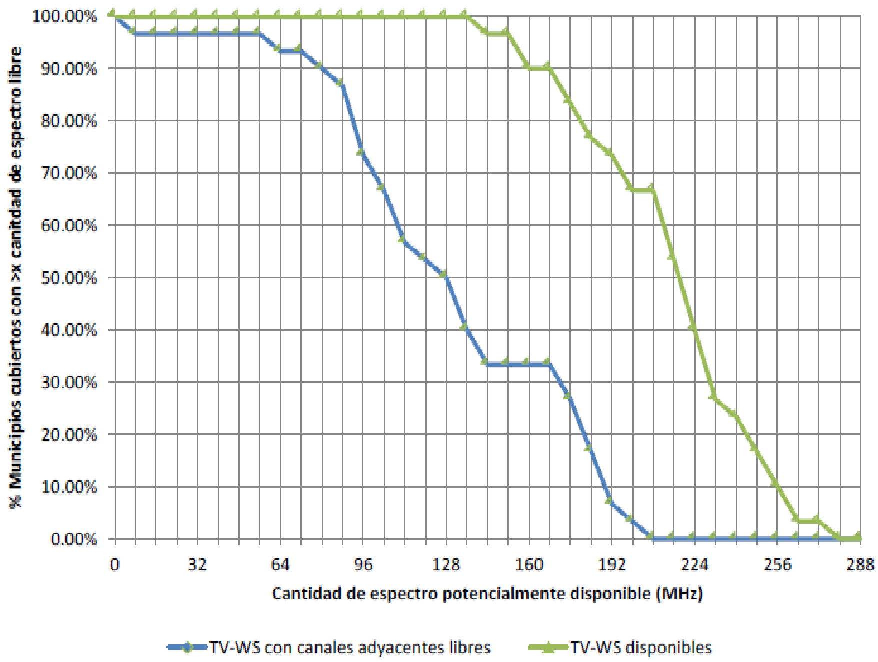


Figure 6: TVWSs spectral availability in Barcelona (2008) [11].

TVWSs are currently under legislation, after the important task done by standardization organisms and recent studies which try to explore and quantize the availability of TVWSs around the world; mostly focused on Europe and the USA. The attractive characteristics of TVWSs also motivated the official standardization of them by IEEE. The final standard is available under IEEE 802.22 name; following IEEE 802 line where all standards related with wireless networks are found. IEEE 802.22 had ended its development in 2011 and it is the basis of Super Wi-Fi technology deployed in the USA. Its typical application is to offer a wideband wireless network up to 512 users on the Internet in rural areas (coverage between 10 km and 30 km); of course using TVWSs as the physical channel for them.

On the same line IEEE is now developing a modification of Wi-Fi standard 802.11, called IEEE 802.11af, which changes physical and MAC layer of the protocol stack in order to provide Wi-Fi systems the availability of accessing to TVWSs spectrum; following legal requirements of coexistence with TV band primary users and other networks. These and other standards will allow in the future the deploying of more kind of "intelligent" wireless networks, taking advantage of TVWSs and overcoming conventional wireless networks. The problem of wireless networks overloading mentioned initially in this thesis seems to be solved by now.

2.4. Cognitive radio networks: Know the channel and its users. Then decide

As mentioned previously here and all consulted references, a cognitive radio network is a kind of wireless network with some added intelligence, whether comparing them with a nominal emitter where the user selects the frequency to emit, the emitted power and the kind of modulation used. Cognitive radio networks are able to decide the most appropriate values as a function of channel availability (unused channels and amount of carrier interference) and users demand. It means that if the farthest user is placed not much far from network access point (AP) in terms of coverage, is not necessary to destine more than necessary power; as it happens with HSPA/LTE networks or Wi-Fi as examples where a closed power control loop is used to maintain a certain QoS.

Actually, the closed power control loop is not the mainstay of cognitive radio networks but its frequency flexibility. A cognitive radio network is able to first listen to the channel seeking for available spaces (using a certain criterion to decide if a channel is clear or not). When the emission channel is decided, then the emission power is controlled by the closed loop and the used modulation for transmission is decided as the best for channel conditions. The cognitive radio network makes some channel predictions in order to decide it.

In addition, a cognitive radio network continuously is reading the channel; it then uses this information to determine the radio frequency environment, channel conditions, link performance, etc. If necessary, it adjusts the radio settings to deliver the required quality of service subject to an appropriate combination of user requirements, operational limitations, and regulatory constraints. Each kind of cognitive radio network will have its own protocol to notify all users those necessary changes.

To use Wi-Fi over TVWSs (IEEE 802.11af) can be explained as one kind of cognitive radio network, because Wi-Fi standard already establishes a closed power control loop between devices and it also has the capability of switching between channels if the access point detects a high level of interference coming from other Wi-Fi stations. This helps to make Wi-Fi band less wild than it would be. Moreover, best propagation conditions for TV band frequencies in comparison with 2.4 GHz band can multiply the cognitive radio coverage twice or more than an IEEE 802.11 standard Wi-Fi network.

Another kind of cognitive radio network could be a machine to machine communication, as a radio link. In addition, if the link is not used continuously but sporadically, a kind of network like this where channel availability is volatile can be the solution. Of course a TVWS can be used by permanent links, like an alternative to ADSL in rural environments where this infrastructure is not deployed or it is not as fast as expected by end users. In this case, some kind of protection against unexpected interferences must be taken into account. Finally, TVWSs can be used by HSPA/LTE cellular networks; whether peaks of traffic need to be absorbed or simply as an extension of coverage. In all cases the good propagation conditions, even among buildings, make feasible their deployment.

Despite of all mentioned previously, when it is time to put in use a cognitive radio network its deployment is not as easy as turning on their access points in a TVWS. Secondary users must follow a regulation in order to prevent a misuse of shared resources with the consequence of converting TV band in a wild jungle. That could happen if cognitive radio networks are leaven to operate into sensing mode; that is, leave them to observe the channel and decide where to operate without any human control. Moreover, TV broadcasters disagree from only use sensing mode, because it is not clear that any cognitive radio network could be able to detect correctly a TVWS. Their received power sensor must be able to detect fewer values than DTT receiver sensitivity to detect appropriately a TVWS.

In order to avoid that serious problem, some basis as guides and standards have been built. The most recent one these days is one report coming from the *Electronic Communications Committee* (ECC), referred in [12], which give us some technical requirements to operate with white space devices like a cognitive radio network into TV band.

The ECC document was elaborated by the *European Conference of Postal and Telecommunications Administrations* (CEPT) just in the beginnings of 2013 with the intention of complement and enhances some findings previously published by the same organism in relation to the geo-location technique of WSDs. The new document contributes with additional technical investigations identified by the CEPT as required to facilitate the development of regulations for WSDs in the TV band.

CEPT specifies that a WSD such as a cognitive radio network must determine first its location of all its coverage area. Then, it must make use of a geo-location database in order to get information on which frequencies are available for itself at its location.

In this report, this regulatory organism wants to give some advices, general principles and basic requirements that a WSD much follow when it operates under the geo-location database. As a summary, the document provides the following specifications for both geo-location database and the WSD:

- Considerations on location accuracy. It is important to deal with the uncertainty in the location of the master WSD (cognitive radio network access point), the slave WSD (cognitive radio network user terminal) and the receiver victim (anybody absolutely external from network, such a DTT receiver). These uncertainties will determine the interference area that a geo-location database will have to consider when looking at the suitable reference and non-reference geometries used by the database to carry out any interference calculations.
- WSD requirements and the master/slave concept. It defines in detail two possible information flows: Between a master WSD and the geo-location database and between a master WSD and all its slaves. Before starting a transmission of a WDS in a country it is mandatory to discover successfully a geo-location database approved by the authorities of that country. The document also specifies the

technical requirements and parameters for first information flow: WSD must communicate to the database the following:

  - Antenna geographical location, height, angular discrimination and polarisation location accuracy.
  - Device and emission class.
  - Technology identifier, device model, device category and device identifier.
  - Selected frequency block, intended transmit power and in some cases the coverage area of the master WSD. These last parameters must be sent after receiving database response.

  On the other hand, the database must communicate to the master WSD some minimum operational parameters:

  - A list of available frequencies.
  - Associated maximum transmit powers for the current WSD location.
  - Limits on the maximum contiguous DTT channels.
  - Total number of DTT channels that WSD can transmit.
  - Time of validity of these parameters for the master and associated slaves.

  The database must also notify the appropriate national/regional database to consult and any information related to spectrum sensing if the latter is required.
- Database management. It includes some considerations about the number of issues including the technical information on services/systems to be protected, the database update delay and update frequency, as well as the translation mechanism.
- Translation process in the geo-location database. All the interchanged information between the database and the WSD must be translated. The competent authorities may pre-calculate the allowed frequencies and associated transmit powers at each location for different WSD types and make this information available. Regarding to the protection of TV broadcasting services, it is provided some develops approaches for calculating in-block and out-of-block emission levels. The key parameters to be used to calculate location specific WSD power levels are:
  - Reference interference geometries.
  - DTT reception modes.
  - Receiving antenna pattern.
  - Location probability and its acceptable degradation.
- Combined sensing and geo-location. Spectrum sensing could be used to support the detection of incumbent radio services conducted using the geo-location database. However, studies have shown that currently the implementation of reliable sensing has a number of challenges, thus some of the potential benefits may not be achievable in practice. This situation may change in the future.

In the report body, all previous data is explained and justified. The EEC document also provides some annexes which clarify technically most part of previously specified decisions. As some examples, they provide DTT interference scenarios (different situations where WSD and a DTT receiver are closer enough having mutual influence), some considerations of degradation of coverage location probability for the determination of maximum WSD EIRP limits, application examples of master/slave concept, trade-off between false TVWSs detection and false occupied detection as a function of increasing detection thresholds, preliminary results on combination of geo-location database and sensing techniques in a real scenario, etc.

Last report contributes a lot on WSDs usage arrangement task, but it is actually a theoretical solution that must be implemented. Nowadays, an available database containing all needed information for cognitive radio networks operation is operative in the USA according to FCC recommendations and under construction in other countries. However, it does not happen everywhere. In those countries where and official database approved by the authorities is not deployed, another halfway solution can be implemented. This other solution can be a Radio Environment Map (REM), which will be exposed as follows.

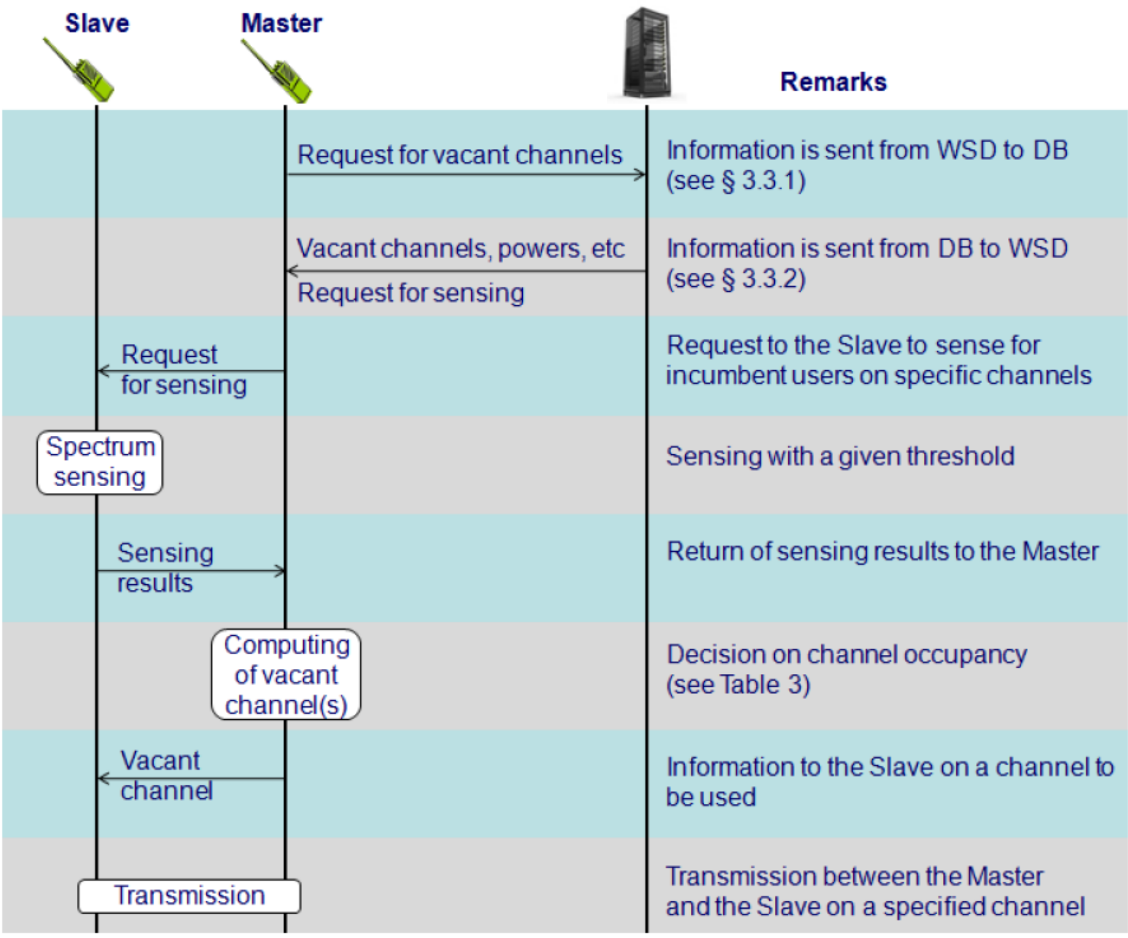


Figure 7: Operational algorithm for combined detection in M/S WSDs [12].

2.5. Radio environment maps as a smart database

All requirements that a cognitive radio networks must fulfil before start its operation in a TVWSs are based on the existence of a public database, which will be looked up by a master WSD. When a database maintained by official country competent authorities is not available, another kind of solution is needed to get used with cognitive radio networks technology. Here is when a Radio Environment Map (REM) comes in.

A radio environment map (REM) [13] is a database which stores information about the radio environment, including basically device locations and their activities, policies and regulations, geographical features and services. The first REM was introduced by the Virginia Tech team after IEEE 802.22 proposal of exploiting TVWSs. A REM is always consulted by intelligent entities such as humans or a cognitive radio network, too.

The concept of building a REM passes through geo-localized measurements of the environment where a cognitive radio network wants to be deployed. Usually a REM store radio spectral measured data and processes it by spatial interpolation (interpolation of measured data between two points closer enough with similar radio spectral conditions). A REM can be static or dynamic. In the first case, the measurements and post processing data is done once; while in dynamic case all actions are doing continuously. A dynamic REM is ideal for bands which are continuously changing its occupation such as all those bands that support radio networks. A dynamic REM stores also information about channel traffic; it helps to plan better a possible secondary use there.

The present case affects TV band, where occupation is not changing every day and it makes no sense to talk about traffic; so the appropriate kind of REM here must be static. The information that it will store is the current TV spectral situation of a certain location with enough precision in order to help deciding a cognitive radio network for its emission channel. The functional architecture must be a bidirectional connection between REM database and the cognitive radio network: the last one asks for the situation of a certain channel and the database provides the requested information. For this case no more additional intermediates are needed.

The built up of a REM also helps to construct a comprehensive map for the cognitive radio network thanks in addition of mixing information coming from geo-location database (if available), characteristics of spectrum usage, geographical terrain models, propagation environments and regulations [14]. In addition, a REM could be able to estimate the state of certain locations where no measurement data is available by estimating the propagation parameters. Moreover, thanks to bidirectional communication between a cognitive radio network and a REM, it is possible to become very simple devices as cognitive devices.

The rest of the remaining section will be devoted to explain some more concepts related on radio environment maps, their stored information and some construction techniques. All the following information has been extracted from [14] and [15] and it will be the basic pillars when it is time to design our own REM.

The essence of the functionality of a REM is to have the interference map for each TV channel in any location of interest. A REM collects spectrum measurements from certain strategic geographic points, called nodes. The geographical position of those nodes is strategically selected properly; close enough, in order to have sufficient information to estimate spectrum data in all points among the nodes. The space complexity of a REM depends on the number of nodes, number of TV channels, and size of network coverage and granularity of REM information. A part from radio environment data, a REM must store information about radio elements (TV emitters in this case) and radio scene (basically the information related with TV band regulation).

Once it is clear what information must be represented in a REM, it is important to bear in mind that efficient representation of information content of the REM is the key to the operation of cognitive radio networks. For master cognitive WSDs, received primary signal levels, location of the measurement, time instance and inspected frequency bands are relevant for them. Moreover, it is better to manage channel signal levels using statistical parameters. When it is time to collect spectrum data at specific nodes during a certain time, received power values will fluctuate between certain margins. In this scenario it is possible to express the results in terms of mean and standard deviation. In addition; received primary signal levels coming from not nodal points will be also expressed in statistical parameters, because their resulting values will come from propagation models computation.

When a WSD receives the results coming from REM point request, it will determine which the appropriate channel to emit is. The basic requirement to emit in a certain channel is to have declared previously that channel as a TVWS. There are two methods for declaring a channel as a TVWS: The first one has been explained previously in this thesis and it is based on a power threshold where a DTT receiver will detect appropriately a TV signal. This method is sometimes not enough restrictive; for example if mean received power plus its standard deviation exceeds that limitation. In these cases, it is more precise to declare a channel as a TVWS if mean received power is below WSD received noise level. The value of second order statistical parameters like standard deviation will determine an outage probability of having a real TVWS or not in this channel.

Due to the essence of REM received data (both mean and standard deviation are statistical parameters) the master cognitive WSD can estimate the probability of having an idle channel and then select the one which have best conditions. Moreover, a REM can also provide its own probabilities in accordance with two previous exposed methods.

As a summary, a REM will provide all statistical values coming from nodal measurements or model computations, accompanying these results with the percent of having a TVWS. Depending on cognitive radio network technology and intelligence, its master device will take these values to decide where to start emitting. After a certain period of time called cognitive cycle, the master WSD will take some spectrum measurements in order to make sure that TVWSs is also available for itself. If the TVWS is no longer available, then the master WSD will search for next TVWS channel; sometimes after a new REM data request.

The best way to build a radio environment map is a kind of based methods called spatial statistics. Spatial statistics based methods take into account the measurements at specific locations and then the rest of REM coverage area is estimated as a function of that measured data. The principles of spatial statistics estimation methods are based on the basic principle that geographically near locations are more related to each other compared to the more distant locations. The literature proposes three estimation techniques: Kriging, Inverse Distance Weighted and Nearest Neighbour Interpolation. All previous methods estimate the values of interest at unexplored locations can be estimated using pondered linear combination of measurements at known data points (nodal points of the REM). The high precision of Kriging method if there are enough available nodal points make this method the most commonly applied technique in the literature.

Kriging method [15], initially developed by Danie G. Krige, is an optimal interpolation based on regression against observer N values of surrounding data points. It estimates the corresponding value of a certain point by an interpolation of weighted measured data points according to spatial covariance values. Near points in space tend to have closer values than farer points. The mean measured power of a certain TV channel in a certain point will be treated as an observed value and it will be used to compute by Kriging method the mean power of a certain TV channel in other non-measured point. The standard deviation of this new computed point will be also provided by the Kriging method, assuming a log-normal distribution very close to statistical distribution that measured nodal points have.

Kriging method can estimate the mean power of a TV channel by using the following expression:

$$\hat{P}(x,y) = \sum_{n=1}^{N} \lambda_n \big(P(x_n,y_n) - \mu(x_n,y_n)\big) + \mu(x,y) \quad (dBm) \tag{4}$$

Where:

- N is the total considered nodal points to be used in Kriging computation. N can be greater; even including the total measured points of the REM. Kriging method will assign less weigh as far as a nodal point is from the point where the mean power of a TV channel is wanted to be computed. After some experiments it is possible to find the optimal N value in order to avoid excessive computational load.
- $P(x_n,y_n)$ corresponds to mean received power of a TV channel in the nodal point (x_n,y_n).
- λ_n is the weighted value which weighs mean measured power of a TV channel (P) at point x_n,y_n minus μ at the same point.
- μ(x,y) is a mean parameter. However, it is not the mean measured power of a TV channel but the mean of the mean taking into account some nodal points or all. Kriging method has three variants; each one differentiates from the others by how this mean μ is considered.

The appropriate Kriging method variant to use in REMs building is the variant called ordinary Kriging. For ordinary kriging, rather than assuming that the mean μ is constant over the entire domain (as it happens with other Kriging variant called simple Kriging), it is assumed that it is constant in the local neighbourhood of each estimation point. This fact is important because a REM will contain nodal points placed both in indoor and outdoor environments. It is known that mean power values of a TV channel in indoor environments can be drastically lower than ones in outdoor environments.

Under this assumption, it is reasonably to forget the unknown local mean (μ(x,y)) by requiring that all kriging weights (λ_n) sum to 1. Expression number 5 shows this result:

$$\hat{P}(x,y) = \sum_{n=1}^{N} \lambda_n P(x_n, y_n) \quad (dBm) \qquad \text{with} \qquad \sum_{n=1}^{N} \lambda_n = 1 \tag{5}$$

The error variance must be optimized using Lagrange method in order to find optimal weigh parameters (λ_n). The entire process is explained well in [15] and other sources; The Kriging error variance is given by (8) and its square root will be treated equal than standard deviation of mean measured power of a TV channel.

The key of Kriging method is covariance function, which must be taken in correspondence with the nature of the problem to solve. The covariance function comes from the kind of semivariogram, the one that defines the dependency between two nodal points value. It is appropriate to take here a spherical covariance function, because electromagnetic field propagation is also spherical. The covariance function has the following expression when the distance between two points is lower than d_{max} and 0 otherwise:

$$C(x,y) = 0.78 * \left(1 - 1.5 * \left(\frac{\sqrt{x^2+y^2}}{d_{max}}\right) + 0.5 * \left(\frac{\sqrt{x^2+y^2}}{d_{max}}\right)^3\right) \tag{6}$$

The value of d_{max} must be selected in accordance with total number of nodal points (N) and the order of magnitude of greatest distance among them. This will determine the correlation between nodal points' value and the separation distance.

The correlation function helps to construct the covariance matrix **C**. This matrix will contain all the covariance values among all N nodal points to be considered. In addition, the matrix will contain and additional row and column with values equal to 1 except the lower right extreme with value equal to 0. Matrix **C**, thus, will be square of N+1 dimension.

The same correlation function helps to construct the covariance vector **c**. This vector will contain all covariance values between the point where mean power of a TV channel wants to be computed and all N nodal points. In addition, it will contain an additional value equal to 1. Vector **c** has N+1 dimension, too.

These last two elements are essential part of the equation system that solves all weigh parameters (λ) and the Lagrange parameter (L). This equation system is found when we try to optimize (4) by minimizing error variance using Lagrange method. The equation system can be found in the following statement:

$$\boldsymbol{C\lambda} = \boldsymbol{c} \tag{7}$$

$$\boldsymbol{C} = \begin{pmatrix} C(x_1-x_1, y_1-y_1) & C(x_2-x_1, y_2-y_1) & \dots & C(x_N-x_1, y_N-y_1) & 1 \\ C(x_1-x_2, y_1-y_2) & C(x_2-x_2, y_2-y_2) & \dots & C(x_N-x_2, y_N-y_2) & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C(x_1-x_N, y_1-y_N) & C(x_2-x_N, y_2-y_N) & \dots & C(x_N-x_N, y_N-y_N) & 1 \\ 1 & 1 & \dots & 1 & 0 \end{pmatrix}$$

$$\boldsymbol{\lambda} = \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_N \\ L \end{pmatrix} \qquad \boldsymbol{c} = \begin{pmatrix} C(x_1 - x, y_1 - y) \\ C(x_2 - x, y_2 - y) \\ \vdots \\ C(x_N - x, y_N - y) \\ 1 \end{pmatrix}$$

In order to avoid an abuse of notation, the couple (x_n,y) corresponds to nodal points; while alone (x,y) corresponds to the point where Kriging method is applying.

Solving last equation system by **λ** matrix all weigh λ factors and Lagrange parameter L are found. Now, the estimated mean received power of a TV channel is able to be found at point (x,y) by computing expression (5).

Kriging error standard deviation can be computed using the following expression:

$$\sigma_{\hat{P}(x,y)} = \sqrt{C(0,0) - \sum_{n=1}^{N} \lambda_n C(x_n - x, y_n - y) - L} \quad (dB) \tag{8}$$

Where:

- C(x,y) is the covariance function, detailed in (5).
- L is the Lagrange parameter used to minimize error variance.

REM quality is a description of how accurate a REM describes the real operation environment. A true REM can be considered; the one that only have values of mean received power of a TV channel of nodal points and an estimated REM, the one that includes smoothing of previous values using Kriging method for example. At this point the estimated REM and the true REM can be compared, as a figure of merit, by using Root Mean Squared Error (RMSE) method. In [14] this study is done by comparing the true REM with some estimated REMs that use different kind of estimation techniques (Kriging as one of them). The constructed REMs are done by transmitter location determination based method; which differentiates from spatial statistics based method in the fact that obtained values are given by applying propagation modelling, instead of obtaining values by measuring radio spectrum at certain nodal points.

Finally, as a conclusion, a REM is a straightforward way to inform a cognitive radio network of all unused channels in a certain point. At this point the amount of known data is enough in order to start developing a REM in *ETSETB Telecom BCN* facilities. In order to go ahead with this project, a radio environment measurer equipment is available. The equipment is composed by an omnidirectional antenna and a spectrum analyser.

Next figure extracted from [14] shows the study result. The real REM is constructed using a propagation model of path-loss exponent (α) equal to 3.5, path-loss correction of 38.4 dB and using a log-normal shadowing standard deviation of 8 dB:

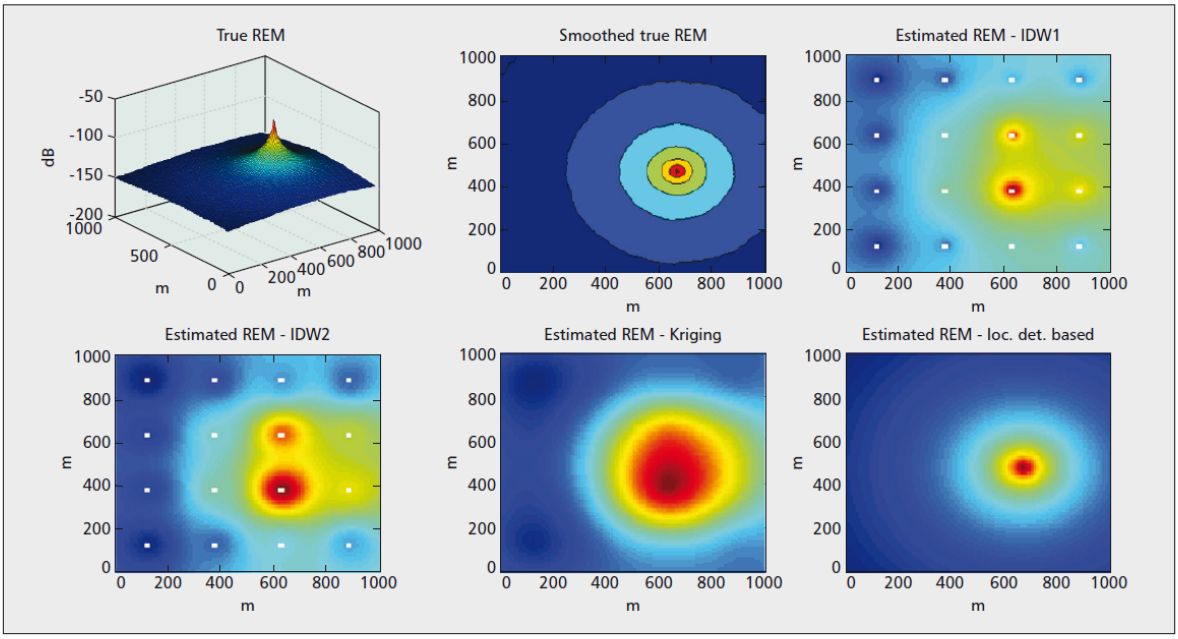


Figure 8: Check of REM quality using different estimation methods [14].

A real REM will be constructed following spatial statistics based method, measuring the mean received power of a TV channel at strategically nodal points. Global Positioning System (GPS) will be used to locate nodal points inside the REM, as coordinates x and y. Because civilian GPS precision is not too much large (especially inside buildings where we have a precision of about 10-15 meters), it sounds reasonably to define a circular limited area around each nodal point where nodal point information will be valid. The gaps between nodal point areas will be filled using Kriging method.

The next section will show all performed procedures to build a radio environment map for cognitive radio networks at *ETSETB Telecom BCN* facilities, valid for UHF TV band.

3. Methodology / project development

Section number 3 of this thesis is focused on explain all the employed methodology to go ahead with the REM construction. The development of these procedures and their justification are also placed here. Next section will include the final results of testing the REM in *ETSETB Telecom BCN* facilities.

3.1. Introduction

As explained in previous sections and summarized here, the UHF TV band radio environment map may include three parts:

- An informative part, which contains all information related on authorities regulation about this band. In Spain, the organism responsible of that regulation is *Comisión Nacional de los Mercados y la Competencia* (CNMC). Current regulation is published in the *Official State Gazette* (BOE), available on [7] and summarized in section 2.2. This scope will also contain information about TV broadcasters into REM environment limits, that is, the list of primary users who are licensed to emit into UHF TV band. The list must only contain TV broadcaster name, available multiplexers (each multiplexer occupies one 8 MHz TV channel), the channel number where the multiplexer is emitting and emission place (with coordinates).
- A technical part containing a coverage map inside REM geographical limits using the high equivalent isotropic radiated power (EIRP) that each channel could emit, which is the worst case in terms of looking for a TVWS. With this data and geographical terrain relieve information it is possible to elaborate a simulation graph of coverage. It would be interesting if simulations are done using most relevant propagation models (ITU Terrain, Okumura-Hata, etc). The aim of this scope is to have a simple overview of channels coverage in mean terms, in order to see if this received power is lower or higher referring to DTT receiver threshold.
- A values part, where all measured data of all channels in all nodal points is stored. This scope must also explain the way to search this information, even at not nodal points. In order to make this REM user-friendly, the server which stores the REM online must implement some fast ways to get the desired information for both human users and directly a cognitive radio network interface client. Is not the purpose of this thesis to design an interface for accessing the REM but instead of this, to be able to provide the desired information available from REM database.

The development and design of previous scopes is completely explained on corresponding 3.3, 3.4 and 3.5 subsections, respectively. On the other hand, the results of testing previous designs on *ETSETB Telecom BCN* facilities will be found at corresponding points of section 4 (see Table of Contents).

Before starting to design REM structure, it is important to spend some time analysing all measurement equipment. Its properly calibration will ensure best measurement results when it is time to test REM design. This equipment setup is found at next section.

3.2. Measuring equipment calibration and setup

The measuring equipment is composed by an omnidirectional antenna and a spectrum analyser. The spectrum analyser allows estimating the received power into a certain band, while the antenna helps capturing that power coming from electromagnetic field. The chosen antenna is model *DA753G Compact Discone Aerial* [16] and the chosen spectrum analyser is model *R&S FSL6* [17]. Both are from *AOR USA Ltd* and *Rohde and Schwarz* companies respectively.

The kind of antenna used here must have a uniform beam pattern, because the objective is to induce electromagnetic field coming from all spatial directions without any gain. This is not possible due to physical characteristics of the antennas; however, the omnidirectional beam pattern is the closest one to the objectives. It receives nothing at vertical direction but that is not a critical problem because Line of Sight (LoS) of a digital terrestrial TV channel comes from a transmitter placed at the surface of the Earth; it does not come vertically from the sky.

The following figure shows *DA753G Compact Discone Aerial* antenna and its basic specifications extracted from [16].

- Height: **0.87 m.**
- Weight: **0.690 kg.**

- Total band: **75 MHz – 3 GHz.**
- Transmitting range: **144, 430, 904 and 1200 MHz band.**
- Impedance: **50 Ω.**
- Gain (144 MHz band): **2.15 dBi.**
- Gain (rest of range): **3 dBi.**
- Voltage Standing Wave Ratio (VSWR): **< 1.5.**

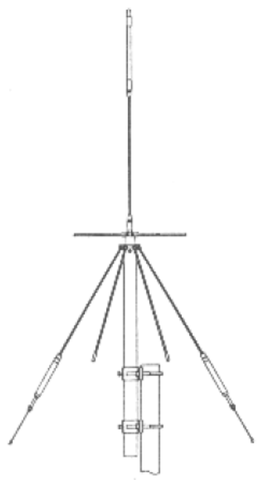


Figure 9: DA753G Compact Discone Aerial antenna.

Analysing the antenna specifications, it is seen that Spanish UHF TV band (470 - 790 MHz) falls perfectly into working total received range. Concretely, it is identified 430 MHz band specified at antenna datasheet as the working band. Here, the specified antenna gain is about 3 dBi, that is, it concentrates all induced electromagnetic field causing an equivalent effect of multiplying the amount of received electromagnetic field power in one direction of the horizontal plane by a factor of 2. This phenomenon is not under the interest of this thesis, because total received power of a TV channel in a certain location wants to be estimated as closer as possible to the value that will result of doing the same measure using an ideal isotropic antenna. Thus, subtracting 3 dBi from real measured result will be a good approximation to the real value.

Doing that subtraction will eliminate the amplification effect due to use an antenna with non-isotropic beam pattern, with the consent of inducing any electromagnetic field contribution coming from the vertical plane of the antenna. However, it is not the only correction that must be done in order to make our measurement system as much transparent as possible in terms of distortion.

DA753G antenna was designed to have an input impedance of 50 Ω over a wide band of about 2.925 GHz; starting at 75 MHz and ending at 3 GHz. First it sounds very unrealistic to have good matching impedance conditions over the full band. Commonly, when designing and antenna of any kind, the appropriate values to each antenna parameters is selected in order to have best matching conditions at the central frequency of the band where we want to operate, and try to maintain these matching conditions along the full operation band. Reflection coefficient (S_{11} parameter or return loss in other terms) shows those conditions as a function of the frequency. In linear units, to have a reflection coefficient of 0 implies perfect matching at the impedance where the coefficient is referred to; whereas having a value of 1 or -1 implies total mismatching conditions.

DA753G datasheet [16] provides the refection coefficient over the full operative band. The next figure shows the modulus of this coefficient in logarithmical units. In this case, having peaks of lower negative values implies matching impedance points.

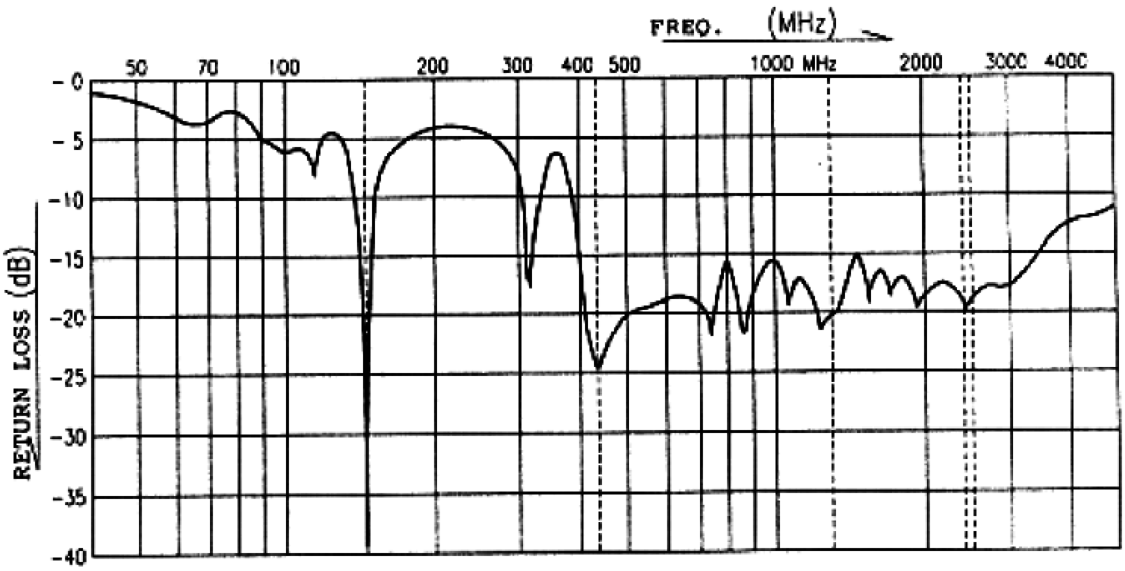


Figure 10: DA753G antenna reflection coefficient over full operative band [16].

The figure shows a very good matching point around 150 MHz and a good behaviour of matching conditions at frequencies greater than 400 MHz until 3 GHz, where reflection coefficient starts to increase again. Last figure is a theoretical graphic of all antennas of that model. We have measured the practical reflection coefficient of our physical antenna at UHF TV band using *HP 8753C Vector Network Analyser*. The next two figures plot the obtained results of reflection coefficient in terms of logarithmic modulus (as figure 10), phase and Smith Cart:

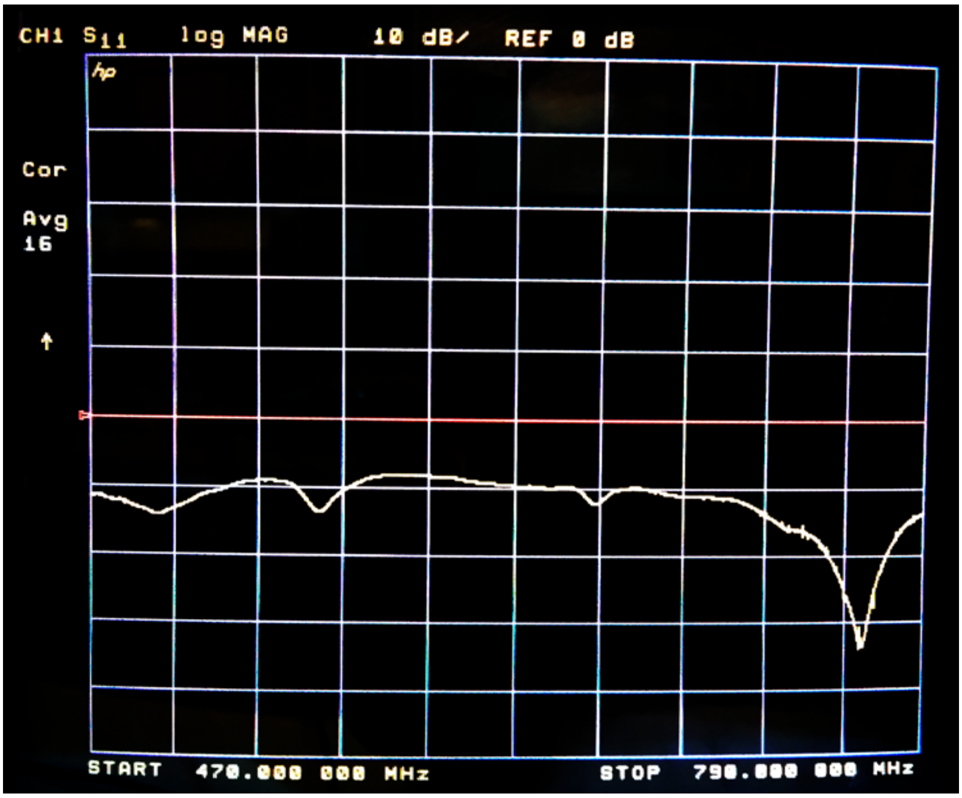


Figure 11: Measured modulus reflection coefficient over UHF TV band.

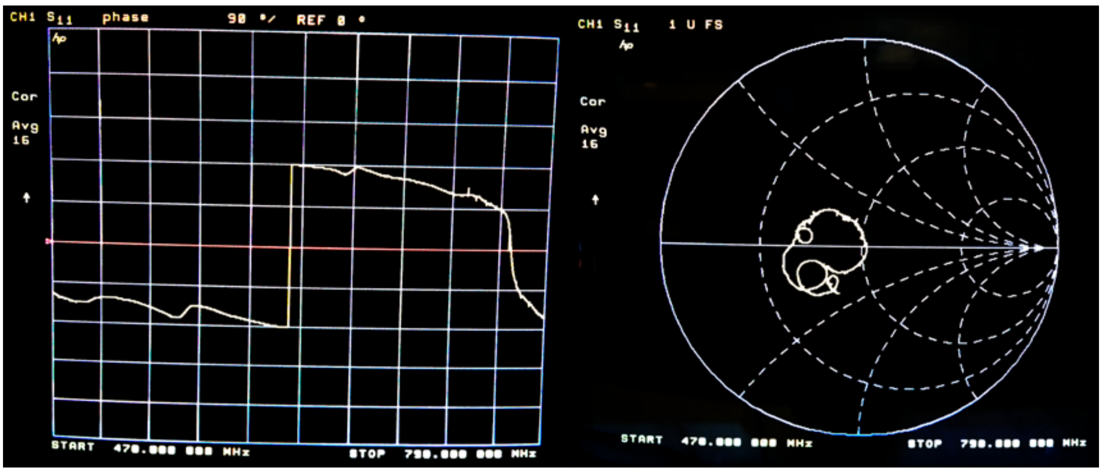


Figure 12: Measured reflection coefficient phase and Smith Cart (same band).

The measured values of reflection coefficient (modulus in logarithmic terms and phase) have been extracted at central frequencies of all TV channels along the band. The next table shows the obtained values:

Frequency [Ch] (MHz)	Amplitude (dB)	Phase (degrees)	Frequency [Ch] (MHz)	Amplitude (dB)	Phase (degrees)
474 [21]	**-11.4**	**-123.2**	634 [41]	**-9.4**	**177.3**
482 [22]	**-11.9**	**-130**	642 [42]	**-9.7**	**173.2**
490 [23]	**-12.9**	**-134.9**	650 [43]	**-9.7**	**168.9**
498 [24]	**-13.8**	**-124.8**	658 [44]	**-11.7**	**162.7**
506 [25]	**-12.2**	**-121.8**	666 [45]	**-10.6**	**176.1**
514 [26]	**-10.9**	**-124.8**	674 [46]	**-9.9**	**167.3**
522 [27]	**-10.1**	**-128.5**	682 [47]	**-10.2**	**158.6**
530 [28]	**-9.2**	**-136.7**	690 [48]	**-10.8**	**154.7**
538 [29]	**-9.1**	**-146.7**	698 [49]	**-11**	**151.7**
546 [30]	**-9.7**	**-156.9**	706 [50]	**-10.8**	**144.8**
554 [31]	**-12.9**	**-157.9**	714 [51]	**-11.5**	**137.6**
562 [32]	**-11.6**	**-133.5**	722 [52]	**-12.7**	**128.1**
570 [33]	**-9.5**	**-138.1**	730 [53]	**-14.7**	**123.2**
578 [34]	**-8.3**	**-147.1**	738 [54]	**-15.8**	**121.7**
586 [35]	**-8.1**	**-155.9**	746 [55]	**-16.9**	**109.1**
594 [36]	**-7.9**	**-162.4**	754 [56]	**-20.4**	**90.8**
602 [37]	**-8.3**	**-169.5**	762 [57]	**-27.8**	**64.9**
610 [38]	**-8.7**	**-175**	770 [58]	**-24.1**	**-72.5**
618 [39]	**-9.1**	**-178.1**	778 [59]	**-17.3**	**-144.5**
626 [40]	**-9.4**	**179.3**	786 [60]	**-14.3**	**-143.6**

Table 11: Measured reflection coefficient values at all central frequencies.

Analysing the obtained results, reflection coefficient modulus has a constant tendency around -10 dB until 700 MHz, where a matching peak is present around 770 MHz. Having better matching conditions will imply directly better frequency responses up from 700 MHz than lower frequencies. In order to ensure and quantify this effect, an experiment has been executed.

The objective of this experiment was to quantify the frequency response of the antenna in relative terms of power. *DA753G* antenna was put into one corner of an anechoic chamber with dimensions small enough so that does not introduce any important distortion due to reflections. In the other corner another antenna with different characteristics has been put. Actually, this antenna is completely mismatched in terms of matching impedance, but the reflection coefficient is absolutely flat along all TV band. The losses are enormously great (more than 70 dB) but the antenna does not introduce any distortion.

The emission antenna was connected to an *HP 8648C Signal Generator* and receiver antenna to an *HP 8593A Spectrum Analyser*. The signal generator was set to emit a constant power sine tone at each central frequency of all TV channels. The non-constant received power values at spectrum analyser are, thus, due to *DA753G* frequency response if distortion coming from the emission antenna and the anechoic chamber could be neglected. At this point, taking the most high received power value as a 0 dB reference, the rest of the TV channel received power values can be expressed as the distance in negative dB to the reference. Thanks to the following graph, it is able to equalize the received power values of each TV channel when it is time to build the radio environment map. Of course, it is not 100% sure that received power at TV channel where the reference was taken at equalization frequency curve is actually the real value; but at least, thanks to the equalization curve, the same little measurement error will be committed at the rest of TV channels.

Figure 13: Mounted antennas into the anechoic chamber.

The following figure shows the measured frequency response of *DA753G* antenna along TV band. The obtained results are relative values to the reference; that is, all dB values are negative in order to indicate that received power at certain channel is many dB below than the highest received power value.

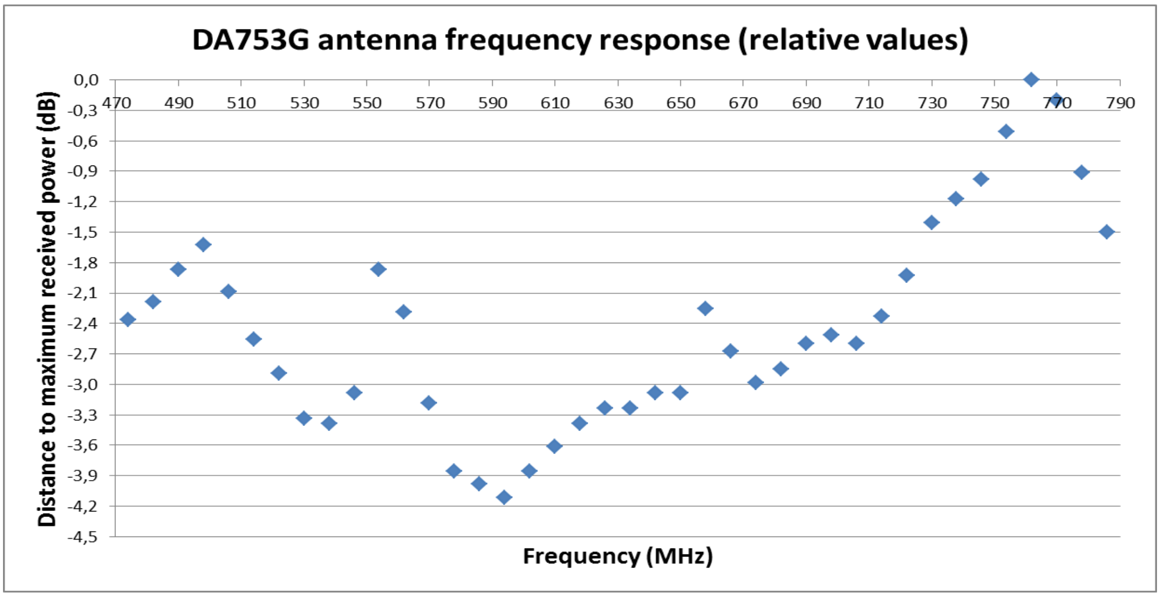


Figure 14: DA753G antenna frequency response (relative values).

It is difficult to see the direct relationship between measured antenna frequency response (figure 14) and measured antenna reflection coefficient (figure 11). The tendency of frequency response curve shows that *DA753G* antenna has fewer losses at higher frequencies of TV band; it can be compared with reflection coefficient tendency, which shows that higher frequencies have better matching impedance conditions.

Using the following table the frequency response curve can be equalized by adding the corresponding value in dB to the measured one. The following values are the opposite of the previous graph. The 3 dBi gain of the antenna must also be subtracted from next values in order to cancel the directivity effect that it introduces.

Frequency [Ch] (MHz)	Equalizing value (dB)	Frequency [Ch] (MHz)	Equalizing value (dB)	Frequency [Ch] (MHz)	Equalizing value (dB)
474 [21]	**2.3622**	578 [34]	**3.8555**	682 [47]	**2.8496**
482 [22]	**2.1851**	586 [35]	**3.9828**	690 [48]	**2.5941**
490 [23]	**1.8691**	594 [36]	**4.1151**	698 [49]	**2.5143**
498 [24]	**1.6224**	602 [37]	**3.8555**	706 [50]	**2.5941**
506 [25]	**2.0852**	610 [38]	**3.6145**	714 [51]	**2.3257**
514 [26]	**2.5539**	618 [39]	**3.3905**	722 [52]	**1.9286**
522 [27]	**2.8947**	626 [40]	**3.2327**	730 [53]	**1.4058**
530 [28]	**3.3370**	634 [41]	**3.2327**	738 [54]	**1.1757**
538 [29]	**3.3905**	642 [42]	**3.0828**	746 [55]	**0.9780**
546 [30]	**3.0828**	650 [43]	**3.0828**	754 [56]	**0.5106**
554 [31]	**1.8691**	658 [44]	**2.2543**	762 [57]	**0 (ref)**
562 [32]	**2.2897**	666 [45]	**2.6765**	770 [58]	**0.1981**
570 [33]	**3.1819**	674 [46]	**2.9872**	778 [59]	**0.9131**
				786 [60]	**1.4986**

Table 12: Channel equalization table in dB.

Finally, the complete used equipment to carry the experiment out can be seen in figure 15. In order from left to right, *HP 8753C Vector Network Analyser*, *HP 8648C Signal Generator* and *HP 8593A Spectrum Analyser* are shown:

Figure 15: HP 8753C, HP 8648C and HP 8593A equipment.

After analysing the antenna, at this point the induced electromagnetic field is able to be processed under certain conditions. To do this a spectrum analyser can be used. The spectrum analyser is an active device that allows us to select the piece of spectrum that wants to analyse and the way to plot the obtained information on the spectrum analyser screen. On sub section 3.5 the optimal values to set up on the spectrum analyser will be discussed in order to get best results. By now, the possible configurable parameters that the spectrum analyser manages will be shown.

The chosen spectrum analyser is *R&S FSL6* [17]. It has a very wideband frequency range and, at the same time, a very good frequency accuracy, making possible to analyse signals with thousands of kHz of bandwidth which has its central frequency up to several GHz. It has continuous RF frequency range from 9 kHz to 6 GHz, 28 MHz of demodulation bandwidth and low measurement uncertainly; a very interesting characteristic if the objective is to see with certain precision where a TV channel starts and ends. Moreover, it has comprehensive set of measurement functions and features more typical of high-end analysers.

Figure 16: R&S FSL6 equipment.

The following chart shows *R&S FSL6* spectrum analyser basic specifications [17]:

- Frequency range: **9 kHz to 6 GHz.**
- Frequency accuracy: **10^{-6}.**
- Resolution bandwidth (RBW): **300 Hz to 10 MHz in 1/3 sequence, zero span additionally 20 MHz.**
- Filter types: **Gaussian, EMI (6 dB), FFT, channel, RRC.**
- Video bandwidth (VBW): **10 Hz to 10 MHz.**
- Maximum number of points: **32001.**
- Signal analysis bandwidth: **28 MHz.**
- Phase noise (measured at 10 kHz from 1 GHz carrier): **-103 dBc.**
- Displayed average noise level (DANL): **-117 dBm typical value with 300 of RBW.**
- Third order intercept point (TOI): **+18 dBm typical value.**
- Kind of peak detectors: **positive negative peak, auto peak, RMS, quasi-peak, average, sample.**
- Level measurement uncertainty (from 30 kHz to 3 GHz): **<0.5 dB.**
- Level measurement uncertainty (from 3 GHz to 6 GHz): **<0.8 dB.**

R&S FSL6 overcomes expectations in terms of RBW, VBW and level measurement uncertainty. They contribute in exactitude and precision of measurements done. Moreover, low DANL will let to measure very low level occupied TV channels.

3.3. REM 1st section design

The first section of REM corresponds to the one that summarizes briefly the information related with regulation applied on TV band in Spain, actually the country where the REM will be built. Moreover, it also contains a list of authorized TV broadcasters that are nowadays emitting at least inside REM boundaries. DVB-T standard foresees the multiplexing of multiple TV and radio channels inside one classical TV channel, the one that is under regulation constrains. For this reason, in this list it is only necessary to entry TV broadcaster name, available multiplexers (each multiplexer occupies one TV channel), channel where the multiplexer is emitting and emission place (with coordinates).

The second part of REM 1st section, that it, the list of authorized TV channels, follows also a similar rule. In this case, the objective is to make a table containing the previous specified information; always extracting it from official sites, and finally put the accessed date and the official access link in order to verify current authorized TV channels situation.

In Barcelona, the Spanish city where *ETSETB Telecom BCN* facilities are placed, all the emissions come from Collserola Tower. Collserola Tower is a big architectonical building placed at top of Collserola mountain, a very good strategic place to provide full TV and radio coverage in Barcelona and other municipalities around the capital city. The building is only for telecommunications purposes and nowadays the operator who provides these TV and radio broadcasting services is *Abertis Telecom*.

In Barcelona (and the rest of Catalonia), the regulatory organism in charge of regulate which TV broadcasters are allowed to emit is the Government of Catalonia. In its official website it is possible to see the authorized TV broadcasters by regions [18] and the channel where they emit. Next chapter will show full REM 1st section design after following these requirements expressed in this subsection.

TV broadcaster	Multiplexers and their emission channel			
	Channel	Frequency	Channel	Frequency
Corporació Catalana de Mitjans Audiovisuals (CCMA) S.A.	44	658 MHz	61	794 MHz

Table 13: Example of authorized TV broadcasters information table.

The previous table will also contain those channels that are placed these days out of UHF TV band boundaries specified previously, according to new Spanish UHF TV band boundaries normative that will apply on 1st January 2015 [3]. These channels placed outside the band are relevant because after the law takes effect, they will be placed in TV channels that are nowadays empty, modifying downwards the number of available TVWSs for cognitive radio networks.

When building REM 3rd section it is expected to have occupied only those TV channels that are part of REM 1st section authorized TV broadcasters table. All these broadcasters will emit from Collserola Tower. However, it can be seen perhaps certain amount of power in other TV channels expected to be a TVWS. This residual radiation is coming from other TV broadcasting centres or is part of signalling systems used by TV broadcast service provider. Usually the received mean power is below the one needed for DTT receiver to decode properly the channel.

TV band regulation information can be found at CNMC or, indirectly, under *Official State Gazette* (BOE) releases [7]. Because all regulation information is perfectly tabulated under single tables, the first part of REM 1st section will be easy to prepare: It is a simply copying, mixing and pasting process of the regulation table and then to accompany that table with a short summary of current law. A part from this, it is important to put the accessed date in order to verify whether previous information could be outdated. If it is the case, an access link to regulators page must be provided to allow future REM consultants to check if regulation has changed or not.

3.4. REM 2nd section design

The 2nd section of the REM has the objective to provide a single simulation of the TV channels coverage over the full REM surface in a worst case. Thanks to this coverage map it is possible to predict the coverage values of any TV channel that are actually emitting. It is important to remark this because if TV channels are received in mean terms below DTT receiver threshold, then the same channel could be used by a cognitive radio network in a closest area; if the carrier to interference (C/I) is quite good and the total radiated power in the boundaries is still below DTT receiver minimum power threshold.

The goal of 2nd section, thus, is to build a bidimensional coverage map of a TV channel into UHF TV band, using several appropriate propagations models and also appropriate simulation software. It is also needed a terrain map of REM geographical place. In this thesis *Atoll* software will be used as the propagation simulator software. It was developed by *Forsk* Company. There is more available information about *Atoll* in the following link: http://www.forsk.com/web/EN/11-atoll-overview.php.

In order to go ahead with the simulation, it is needed to know the geographical position where the TV channels are going to be broadcast and its equivalent isotropic radiated power (EIRP). The EIRP value is, actually, a function of the carrier frequency, the kind of DVB-T services that TV channel is offering and the coverage range that TV channel has. The kind of DVB-T services is referred to services offered by the multiplexer. Depending on how many radio and TV channels are offered, the multiplexer EIRP value could change in accordance with its coverage, because high definition channels need more received power than standard definition ones to be decoded properly.

Collserola Tower is placed at 41.4172º north, 2.1143º east coordinates. A part from its geographical position, another important aspect to take into account is the antennas beam pattern. Because of Collserola Tower strategic position, at top of Collserola mountain range, it is expected to be as closer as an omnidirectional beam pattern. However, the population distribution around Collserola Tower is not uniform, basically because Mediterranean Sea is closest to Collserola mountain range looking at east direction; while there is more inhabited land on the opposite direction. This is one of the purposes of why the real beam pattern is not exactly omnidirectional. There is no sense to broadcast DVB-T signals over the sea but it is important to reach coverage distances as far as possible taking into account DVB-T standard.

Atoll software allows placing properly the information previously mentioned in a smart way. The main is to create a project and then add the desired information, following an order as explained in next single steps:

1. Import geographical data into *Atoll* project, such as DEM (digital elevation models) and vector data. DEM files show area relief; they are used to compute propagation diffraction on the ground. In contrast, vector data files have information of physical linear objects such as roads, railways, airports, etc. Moreover, a satellite image of REM limits can be included in order to visualize better the simulation area.
2. Delimitate the simulation area where *Atoll* will compute propagation simulations. All imported data will contain the simulation area and more locations around it; for this reason it is important to delimitate the simulation area.
3. Place the transmitter, Collserola Tower, into its coordinates and define antennas beam pattern, gain and other relevant parameters. It is important to define also the EIRP and the antennas elevation from the ground, because some propagation models need those data.
4. Proceed to compute propagation losses by choosing the appropriate propagation models and plot the results over the geographical data previously imported.

The result will be a map like next figure, showing in coloured scale the amount of received mean power in all REM locations. The study is done in worst case terms, using a transmitter with maximum authorized EIRP value to transmit TV signals.

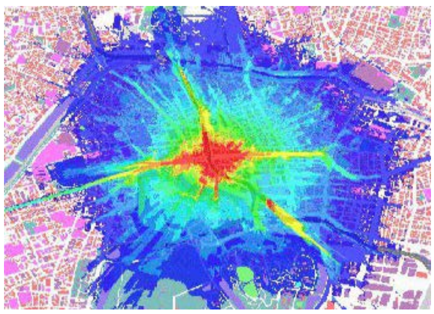


Figure 17: Example of bidimensional coverage maps using Atoll software.

The real values will be the ones obtained in REM 3rd section. The aim of REM 2nd section, as explained before, is to have a worst case overview of coverage of any occupied TV channel. We want to evaluate the probabilities of receive its power under DTT receiver minimum limit and, thus, be able to declare this channel in a certain location as a TVWS according to this criterion.

3.5. REM 3rd section design

The last section of the REM contains the values part, where all measured data of all channels in all measured points is stored. This part also explains the way to retrieve this information, even at not nodal points. Because of the great amount of data that the final REM contains, it is difficult to show the results in a document like this. As an exception, in order to show a resulting measured point, in section 4.3 a table containing obtained data is included.

REM data is obtained after processing measured data from spectrum analyser. In order to carry out data processing, a mathematics tool called *MATLAB* is used. *MATLAB* is proprietary software developed by *MathWorks* Company. It consists on a programmatic mathematical calculator, with a lot of pre-programmed routines and the capability of develop own functions and scripts.

In order to build our REM, what it is needed first is to obtain spectrum data from a certain location. Being that the main purpose of the REM is to tabulate the mean received power of all TV channels, it is needed to capture as many points as possible of each TV channel spectrum. Another aspect to take into account is the slow but existing variability of the instantaneous TV channel received power, making necessary to record more than one trace of each channel.

Reviewing *R&S FSL6* specifications, the appropriate configuration of the involved parameters to carry out the measurements at any location is:

- Central frequency: **8 MHz TV channel between 470 MHz and 790 MHz.**
- Span: **8 MHz (TV channel full bandwidth).**
- Resolution bandwidth (RBW): **300 Hz.**
- Filter type: **FFT (the most appropriate for stationary signals).**
- Video bandwidth (VBW): **Not available for FFT filters.**
- Number of points: **32001.**
- Number of traces: **50 per channel.**
- Preamplifier: **ON.**

Last configuration avoids a loss of information due to spectral channel digitalization, fulfilling expression (9):

$$SPAN \leq RBW * Number\ of\ points \quad \rightarrow \quad 8\ MHz \leq 300\ Hz * 32001 = 9.6003\ MHz \qquad (9)$$

Taking 50 independent snapshots of any channel ensures enough channel variability data, making possible to compute its standard deviation. The use of the preamplifier is necessary because allows to detect signals closer to spectrum analyser noise level.

After taking 50 snapshots of all TV channel in a certain location, *R&S FSL6* spectrum analyser provides as many *MATLAB* files (.mat) as TV channels are. Each file contains a single 32001x50 matrix; that is, the totally 50 traces of 32001 points each one. The values are all stored in dBm due to its precision. The entire group of *MATLAB* files will be used to obtain REM point data for that certain location.

REM data of each measured point is structured in a POINT file, defined previously using *classdef* structure. A POINT file contains the following data:

- pointType: Point identifier (NODAL or KRIGING). A NODAL point corresponds to a physical measured point, just one explained before. A KRIGING point corresponds to an estimated point, that is, its values comes from the result of evaluate the Kriging algorithm at a certain location.
- latitude: GPS latitude of the specific point.
- longitude: GPS longitude of the specific point.
- values: A matrix containing REM processed data for each TV channel, putting results in columns. The order of the results is: TV channel number (21-60), TV channel carrier frequency in MHz (474-786), mean received power of the channel (dBm), standard deviation of the previous value (dB), is TVWS Boolean result using DTT receiver sensitivity method (less restrictive) and is TVWS Boolean result using Probability of False Alarm (PFA) method (more restrictive).

Next table is an example of how to show the results of any POINT file:

Point type: **NODAL.** Latitude: **41.4172º.** Longitude: **2.1143º.**

Channel number	Frequency (MHz)	Mean received power (dBm)	Standard deviation (dB)	Is TVWS (DTT)?	Is TVWS (PFA)?
21	474	**-58**	**1.2**	**1 (Yes)**	**0 (No)**
…	…	…	…	…	…
60	786	**-70**	**0.8**	**1 (Yes)**	**1 (Yes)**

Table 14: Example of how to show NODAL or KRIGING points results.

In the case of being a nodal point, MATLAB processing algorithm follows next steps in order to obtain POINT file from *R&S FSL6* spectrum analyser captured data:

1. Read *R&S FSL6* data file (32001x50 matrix) of one of the channels. The channel number is present on filename so it is easy to implement the reading process in a recursive loop inside MATLAB processing script.
2. For one trace, take all discretized power values and summate all of them in linear units. It is possible to be done assuming that spectral power density of TV channel is flat into 300 Hz resolution bandwidth.
3. Scale the obtained result by expression (10).
4. Repeat 2nd and 3rd step for the rest of the traces and compute the mean and the standard deviation of the obtained value in 3rd step in logarithmic units.

5. Decide if this channel at this location could be a TVWS using two methods expressed in the previous list, and detailed as follows.
6. Repeat previous steps for the rest of TV channels.
7. Store the results in a POINT file of type nodal.

$$Power\ scaling\ factor = \frac{SPAN}{(Number\ of\ points - 1) * RBW} = \frac{5}{6} \tag{10}$$

When it is time to decide if a certain TV channel could be a TVWS at measured location, two methods are used. The first one has been discussed yet in this thesis; the one that consists on determine if the mean received power plus its standard deviation is below the DTT receiver sensitive established by [8]. The second method, called Probability of False Alarm (PFA), declares a channel as a TVWS if the power of more than 10% of traces is above spectrum analyser noise level; comparing channel by channel. As it can be seen, the second method is more restrictive than the first one because DTT receiver sensitive is many dB above spectrum analyser noise level.

When all measured data is processed and stored as nodal points, REM is able to provide the information to any WSD that requests data. However, it is practically impossible to find a WSD placed in the same location, according to GPS precision, as it was placed the spectrum analyser collecting REM data. At this point it is necessary to define two more additional capabilities to our REM in order to make it flexible.

Firstly, it is crucial to define a validity area around nodal point in order to neglect GPS low accuracy effect. For civilian applications, GPS accuracy is around 10-15 meters in normal coverage conditions, so defining a circular validity area of this radius will be enough. On the other hand, there are still not covered zones by any nodal point and its validity area. These places are fulfilled using Kriging algorithm method, explained in section 2.5 as complementary part of a REM generated using spatial statistics method. At this point, MATLAB processing algorithm is able to generate a POINT file of type in between where values are the result of computing Kriging algorithm.

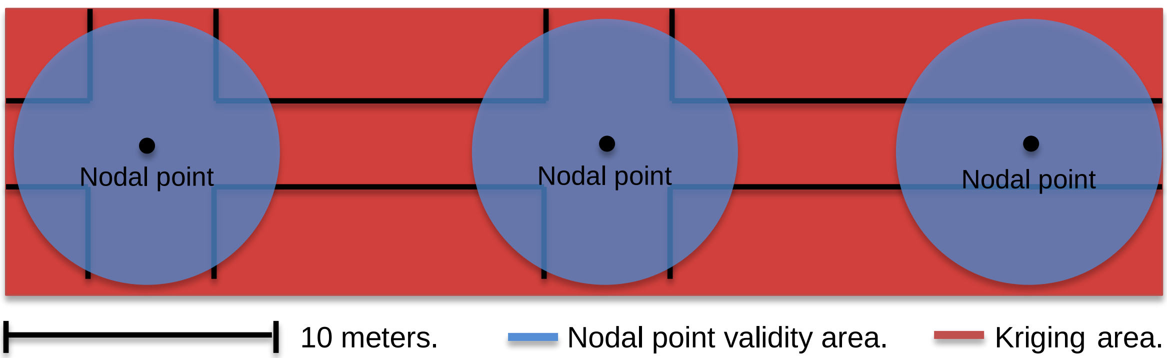


Figure 18: Understanding REM functionality and kind of data source.

3.6. Summary

Now, the REM is able to provide the necessary information to a WSD such a cognitive radio network or directly a human user. It is easy to see that REM 1st and 2nd section are optimized to human users and the 3rd one is the best to use with WSDs.

If a certain human user wants to know what the situation of DVB-T received multiplexers is; he can look up REM 1st section table to know the authorized TV channels to emit. If that list is longer than the list of available TVWSs, then the user will look forward to a second chance if, at least in the worst case, there is any probability of finding a null of coverage for a channel which is actually in emission, in a certain location inside REM limits. REM 2nd section provides this information thanks to bidimensional coverage maps.

Another case is found when a WSD wants to operate in a certain channel or an amount of them. Before decide which the most appropriate place is, the device can look up into REM database to see the real availability of TVWSs at a certain point. The WSD knows somehow which its current GPS location is; the only needed requirement to recover REM data. REM 3rd section allocates measured nodal point's data and also it contemplate the way to compute desired REM information in the remaining area, by using Kriging method.

4. Results

The results of designed REM are detailed here. The three REM sections can be found, following chapter 3 specifications. In some cases some punctual justifications of the obtained results are needed to understand better the obtained results.

4.1. REM 1st section results

This REM has been developed in Barcelona (Spain), concretely it covers full *ETSETB TelecomBCN* facilities area. Spanish regulation about DVB-T services, including transmission and reception units, can be summarized in the following table [7] [8]:

Parameter	**Description**
Application	Terrestrial broadcasting (DTT DVB-T)
Frequency band	470 MHz – 790 MHz 790 MHz – 862 MHz (no longer applicable since January 1st, 2015)
Channelization	8 MHz
Modulation	QAM/COFDM
Emission type	8M00X7FXF
Requires license	Yes
Transmitted power	Specified at license document
Frequency planning	According to National Technical Plans
DTT receiver sensitivity (dBµV/m)	$3 + 20\log(f)$ f in MHz

Table 15: DVB-T Spanish regulation summary.

http://www.minetur.gob.es/telecomunicaciones/es-ES/Servicios/Normalizacion/ provides updated information about the normative that must fulfil any licensed TV broadcaster. It includes both technical information and the information procedure according to technical regulations.

REM involved area receives UHF TV broadcast services coming from Collserola Tower, placed at latitude 41.4172º North and longitude 2.1143º East. The authorized TV broadcasters table is [18]:

TV broadcaster	**Multiplexers and their emission channel**			
	Channel	Frequency	Channel	Frequency
rtve *Corporación de Radio y Televisión Española (RTVE) S.A.*	31	554 MHz	64	818 MHz

Operator	Channel	Frequency	Channel	Frequency
Mediaset España Comunicación S.A. / Sociedad Gestora de Televisión (SGT) Net TV S.A. Grupo Vocento	27	522 MHz	68	850 MHz
Prisa TV S.A. Grupo Prisa	47	682 MHz	67	842 MHz
Atresmedia Corporación de Medios de Comunicación S.A. / Veo TV S.A.	34	578 MHz	69	858 MHz
Corporació Catalana de Mitjans Audiovisuals (CCMA) S.A.	44	658 MHz	61	794 MHz
Emissions Digitals de Catalunya (EDC) S.A.U. Grup Godó	33	570 MHz		
Barcelona TV / TV Badalona / Televisió Hospitalet	26	514 MHz		

El Punt-Avui TV / Gibson Time S.L.	Channel	Frequency
	48	690 MHz

Table 16: Authorized TV broadcasters table.

Reference [18] contains directly the list of authorized TV channels according to the Government of Catalonia webpage. The previous list has been elaborated the accessed day established in reference (see Bibliography).

4.2. REM 2nd section results

Theoretically all TV channels currently emitting over the REM geographical limits are coming from Collserola Tower, placed at coordinates 41.4172º north and 2.1143º east. This location is placed only 3 kilometres away from REM area, but these kilometres are not many in order to not receive TV channels properly. A part from this, Collserola Tower is placed on the top of Collserola mountains, providing good propagation conditions and large distance coverage.

These facts go against WSD expectations; because good reception of broadcasted TV channels decreases the probability of find TVWSs in those occupied channels in some certain locations. An example of this situation could be a place behind a building blocking signal Line of Sight (LoS) coming directly from Collserola. The decrease in power terms of mean received power could not be enough to set mean received power below DTT receiver minimum threshold, situation in which the channel will be declared as a TVWS using this criterion.

Every allowed TV channel is broadcasted from Collserola Tower with a different Equivalent Isotropic Radiated Power (EIRP) due to different propagation conditions and excepted coverage limits. That is, a local TV channel will be broadcasted with a less EIRP than a national TV channel because the territory to cover is also smaller. Broadcast national TV channels with a high value of EIRP will diminish the number of needed signal repeaters to cover full national territory. There is a maximum threshold of EIRP in order to avoid nearest DTT receivers to the broadcasting centre to get saturated.

The exactly value of TV broadcasted channels EIRP is not part from public information; so it could not be used in this thesis to elaborate REM 2nd section computations. However, it is known that the EIRP of broadcasted TV channels fluctuates between 1000 W (60 dBm) and 5000 W (67 dBm). The first value is for TV channels with local influence and the second one is for TV channels with national influence. In order to have a worst case model the highest value will be taken. Next figure shows the simulated received power in dBm units over full REM geographical area.

Propagation computations are done at the central frequency of TV band, using geometric mean as expression number (11). TV band goes from 470 MHz up to 790 MHz, so the central frequency is:

$$f_0 = \sqrt{470\ MHz * 790\ MHz} = 609.3439\ MHz \tag{11}$$

The deterministic propagation models used inside *Atoll* project to provide the simulated coverage map are two. They have been selected according to terrain conditions (non-flat environment) and location (urban place).

- ITU-526. This model predicts the path loss as a function of the height of path blockage and the First Fresnel zone for the transmission link.
- Okumura-Hata Urban. It takes into account the effects of diffraction, reflection and scattering caused by city structures.

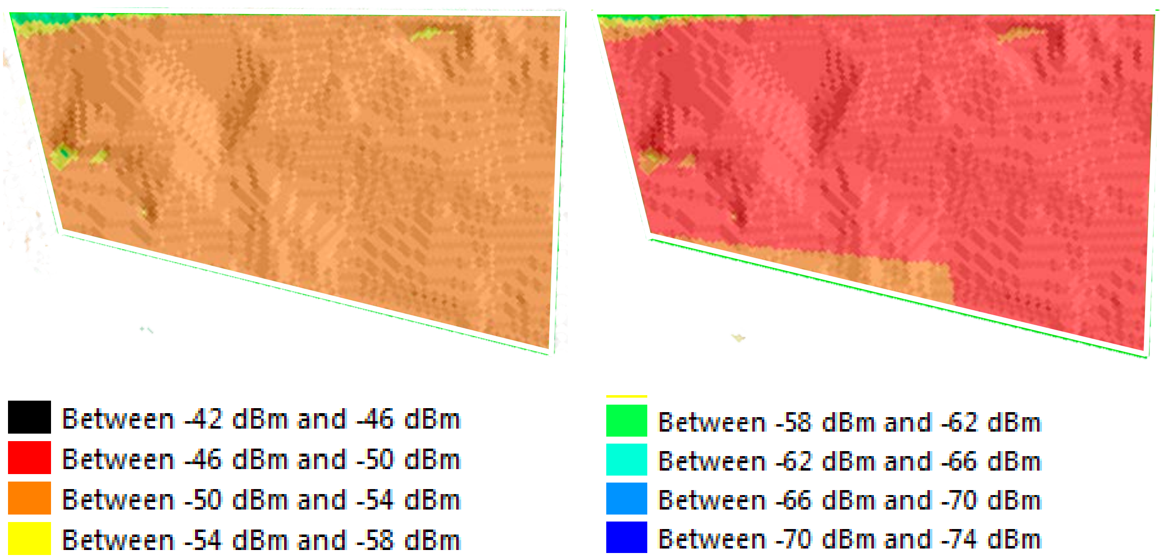


Figure 19: Simulation results using ITU-526 and Okumura Hata models.

4.3. REM 3rd section results

Radio Environment Map most relevant information can be found here. Due to its redundant and repetitive information, only one representative part of any kind of interesting data is found as results. As an example of previously mentioned, the results of only one chosen nodal point will be shown. The rest of nodal points have the same information varying their values. REM data is formed by 35 nodal points containing each one relevant data mentioned in section 3.5, for all TV channels.

Next figure shows REM geographical map with all measured nodal points marked using location pins. As it can be seen, the areas with more building density is covered using more nodal points, because fading effects due to shadowing, multipath and other phenomena appears rapidly with just moving few meters away from each nodal point. On the contrary, the areas with low building density (bottom and right area from *UPC Campus Nord* facilities) are enough covered using fewer nodal points.

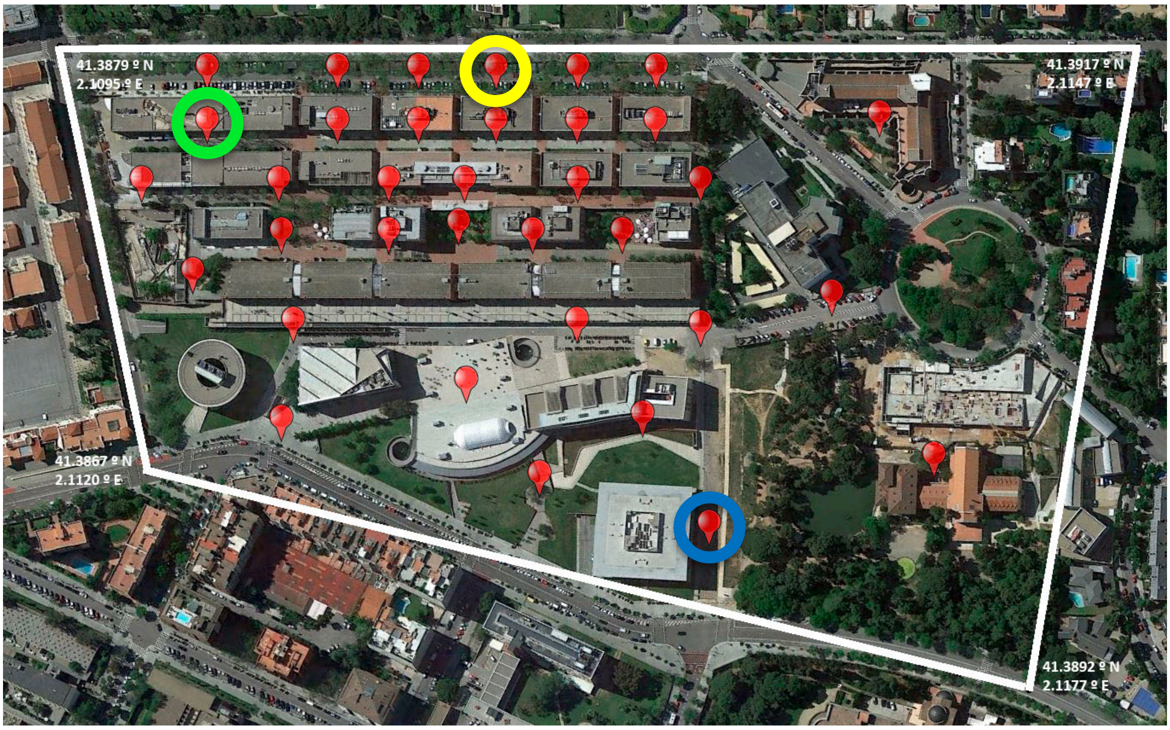


Figure 20: UPC Campus Nord facilities map with all measured nodal points.

Next figure shows for blue circled nodal point and Ch. 44 all measured traces superimposed with different colors, in order to see the minimal fluctuation that the channel suffers at each trace, Noise level with a value of -110 dBm is also marked.

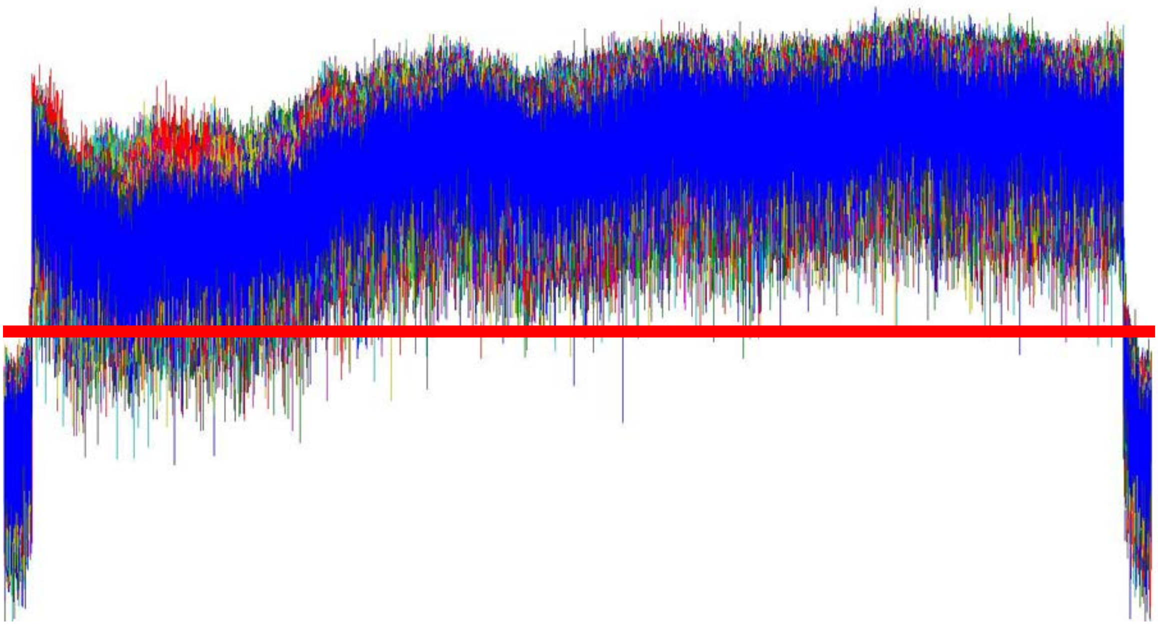


Figure 21: Blue circled nodal point Ch. 44 measured spectrum.

The fact of needing a great number of nodal points to cover full REM geographical area is justified by the same explanation used before to justify the need of more nodal points in the areas with high building density. Fading effects induces a variation of mean received power of the same TV channel throughout all nodal points. As an example, Ch. 44 (at frequency 658 MHz) is received with a maximum mean power of -43.6921 dBm (at nodal point circled by blue circumference) whereas its minimum mean power is -74.5826 dBm at nodal point circled by green circumference).

This channel, thus, suffers a maximum fluctuation of its mean received power of 30.8905 dB. The rest of TV channels suffer the same behavior. The observed shape of spectral power density also varies, causing a variation of the mean received power throughout all nodal points.

Finally next table shows the results after processing captured data at the nodal point circled by yellow circumference. The columns with Boolean values of ‘1’ and ‘0’ indicate, respectively, if each channel can be declared as a TVWS using DTT receiver (3rd column) or PFA (4th column) criteria. These channels can be used by any WSD, taking into account that perhaps the full bandwidth is not available due to other small transmissions.

Point type: **NODAL.** Latitude: **41.3893º.** Longitude: **2.1118º.**

Channel number	Frequency (MHz)	Mean received power (dBm)	Standard deviation (dB)	Is TVWS (DTT)?	Is TVWS (PFA)?
21	474	**-74,8976**	**0,03221**	**1 (Yes)**	**1 (Yes)**
22	482	**-39,8979**	**0,499551**	**0 (No)**	**0 (No)**
23	490	**-71,9327**	**0,155967**	**1 (Yes)**	**0 (No)**
24	498	**-75,4975**	**0,038878**	**1 (Yes)**	**1 (Yes)**
25	506	**-75,0988**	**0,025132**	**1 (Yes)**	**1 (Yes)**
26	514	**-46,925**	**0,279594**	**0 (No)**	**0 (No)**
27	522	**-51,4446**	**0,600126**	**0 (No)**	**0 (No)**
28	530	**-73,8794**	**0,026558**	**1 (Yes)**	**0 (No)**
29	538	**-72,1572**	**0,129188**	**1 (Yes)**	**0 (No)**
30	546	**-74,1808**	**0,027392**	**1 (Yes)**	**0 (No)**
31	554	**-55,06**	**0,491105**	**0 (No)**	**0 (No)**
32	562	**-74,9168**	**0,026435**	**1 (Yes)**	**1 (Yes)**
33	570	**-61,9469**	**1,479579**	**0 (No)**	**0 (No)**
34	578	**-51,6026**	**0,690966**	**0 (No)**	**0 (No)**
35	586	**-73,0099**	**0,040578**	**1 (Yes)**	**0 (No)**
36	594	**-47,7218**	**0,608004**	**0 (No)**	**0 (No)**
37	602	**-73,3723**	**0,096922**	**1 (Yes)**	**0 (No)**
38	610	**-73,6292**	**0,026626**	**1 (Yes)**	**0 (No)**
39	618	**-73,6214**	**0,036158**	**1 (Yes)**	**0 (No)**
40	626	**-73,6975**	**0,03328**	**1 (Yes)**	**0 (No)**
41	634	**-73,7268**	**0,030494**	**1 (Yes)**	**0 (No)**
42	642	**-74,0445**	**0,024792**	**1 (Yes)**	**0 (No)**
43	650	**-72,4182**	**0,138586**	**1 (Yes)**	**0 (No)**

44	658	-46,5406	1,043222	0 (No)	0 (No)
45	666	-74,3974	0,027459	1 (Yes)	1 (Yes)
46	674	-74,1568	0,023532	1 (Yes)	0 (No)
47	682	-54,0066	0,611756	0 (No)	0 (No)
48	690	-65,1375	0,280798	0 (No)	0 (No)
49	698	-74,715	0,026085	1 (Yes)	1 (Yes)
50	706	-74,6697	0,022912	1 (Yes)	1 (Yes)
51	714	-74,9497	0,025989	1 (Yes)	1 (Yes)
52	722	-75,3718	0,029679	1 (Yes)	1 (Yes)
53	730	-75,9142	0,026652	1 (Yes)	1 (Yes)
54	738	-76,1704	0,031103	1 (Yes)	1 (Yes)
55	746	-76,4169	0,02599	1 (Yes)	1 (Yes)
56	754	-76,9161	0,029891	1 (Yes)	1 (Yes)
57	762	-77,4402	0,027326	1 (Yes)	1 (Yes)
58	770	-77,3012	0,023181	1 (Yes)	1 (Yes)
59	778	-76,6448	0,02864	1 (Yes)	1 (Yes)
60	786	-76,1383	0,028683	1 (Yes)	1 (Yes)

Table 17: Yellow circled nodal point final results.

Possible points obtained using Kriging algorithm will also have the same structure, with standard deviation assumed as the minimum square error, the same for all channels. In order to see how Kriging algorithm has been implemented in a *MATLAB* script, next figure shows its flow chart.

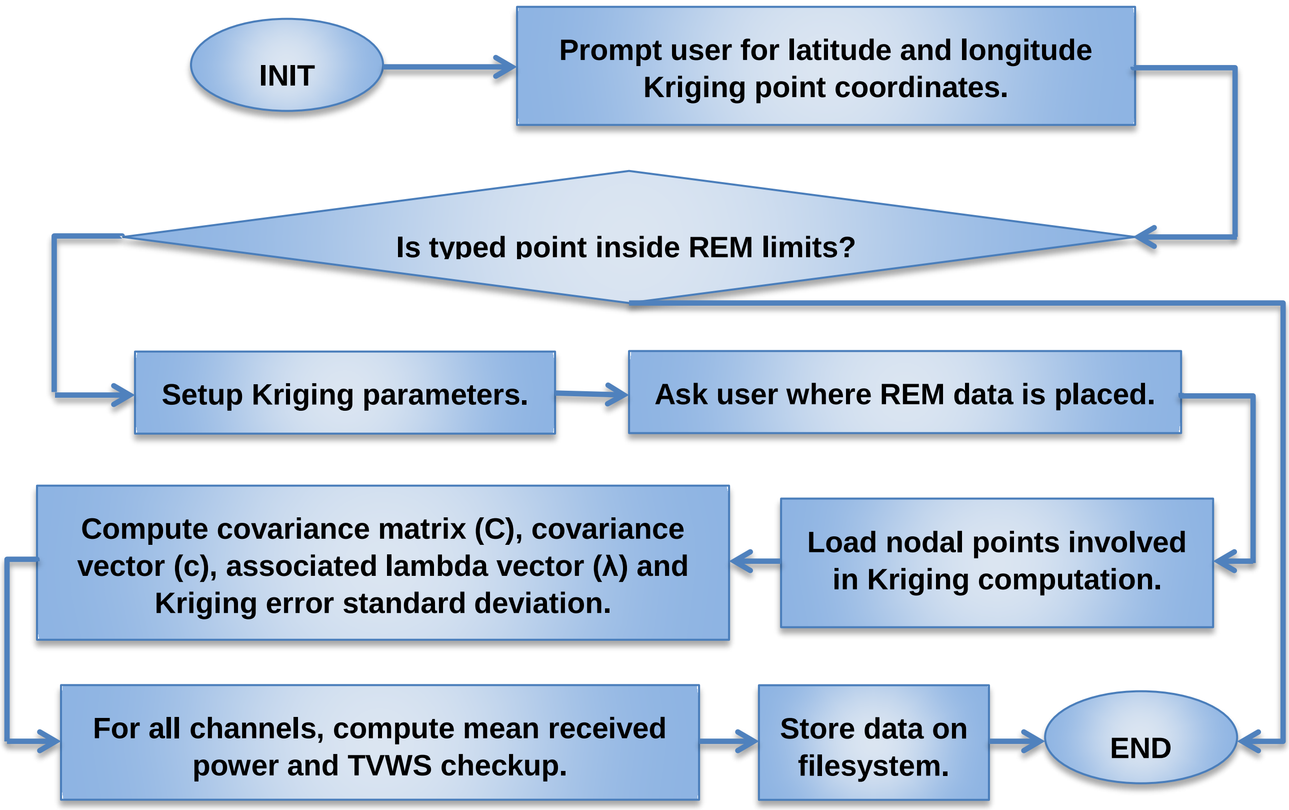


Figure 22: Implemented Kriging algorithm flow chart.

5. Budget

This thesis has been developed in accordance with *Mobile Communications Research Group* (GRCM) as a draftsman. The estimated cost of developing this thesis can be found summarized in this section, including labor and material costs.

Approximately, the total number of dedicated hours is about 600, destining most part of them with searching, studying, analyzing and discussing the theoretical scopes which form part of this thesis. The remaining hours have been dedicated to understand, calibrate and use the technical equipment to carry out REM measures.

Atoll acquired license is an educational one, which has a discount in its price which respect to the commercial license. On the other hand, *MATLAB* license is also an educational one but this kind of license is the only one available because *MATLAB* is a tool destined to research and educational purposes.

Next table summarizes the total estimated amount of costs:

Concept	**Cost (€)**
Labor costs: 600 hours rated at 12€ per hour.	7200
Equipment: *DA753G Compact Discone Aerial* antenna.	122
Equipment: *Rohde&Schwarz FSL6* spectrum analyzer.	12500
Software: *Mathworks MATLAB*.	2000
Software: *Forsk Atoll*	5000
TOTAL	**26822**

Table 18: Costs table.

6. Conclusions and future development

On the one hand the problematic of wireless networks growth, expansion and its bandwidth needs against current radio spectrum capacity is analysed on this thesis, contributing to this last topic using some information extracted directly from government official web sites. The main conclusion extracted here is the need of more radio spectrum bandwidth to support the wireless networks growth, beyond current assigned bands. On the other hand this radio spectrum migration could be done throughout UHF TV Band, because the current deployment of TV broadcasters, together with the regulation of these broadcasts and remarking the fact of finding a great number of empty channels makes this deployment possible. The condition of this usage is joined to the appearance of new TV broadcasters that could be deployed on these empty channels.

After seeing that a Radio Environment Map (REM) is a smart way to store and show information related with radio spectrum occupancy, in that case TV channel occupation, inside a delimited geographical area; and building one inside *ETSETB Telecom BCN Campus Nord* facilities, the main conclusions that can be extracted are:

- The percentage of occupied TV channels among the total number of them inside 470 MHz – 790 MHz band, according to the list of official occupied TV channels, is exactly a 20%. This value increases to 32.5% if the occupied TV channels placed at 790 MHz – 862 MHz are considered to be reallocated to any empty channels, a fact that will happen in Spain since January 1st, 2015. Moreover, looking at Table 16, 22th and 36th channels look to be occupied but there is not any official assignment to them. Thus, the final percentage of occupied TV channels will be about 37.5% by 2015; allowing a remaining 62.5% of empty spectrum ready to be operated by WSDs.
- The greatest number of absolute consecutive white channels is 12, between 49th and 60th channels. This corresponds to a total empty bandwidth of 96 MHz, making possible to deploy here any cognitive radio network with a bandwidth more than twice the bandwidth of any IEEE 802.11n wireless network (40 MHz).
- Looking at Figure 19, it looks that mean received power of any occupied TV channel in worst case has close values throughout all REM area. The simulation was done without placing any building inside REM area; thus, it does not take into account any fading effect produced by their presence. The obtained levels of mean received power are strong enough to consider, at first look, practically impossible to reuse any occupied TV channel to deploy cognitive radio networks. However, real obtained values at REM 3rd section show some little areas affected by fading where this is not true. So, in practical terms it is possible to find zones with more TVWSs available.
- The standard deviation of any measured TV channel, without taking into account if it is empty or not is about 1 dB or less in most cases. The same value at any point obtained by Kriging algorithm is about 2 dB, indicating that Kriging algorithm introduces some but not relevant errors. Assuming that the number of traces is 50, can be ensured that this value is correctly taken because TV broadcasting signals are enough stationary. The total capturing process lasts 26 seconds per channel, according to that each trace lasts 520 ms to be captured by *R&S FSL6* spectrum analyser with specified settings in section 3.5.

The objective of this thesis has been raised but this does not also mean that all the job is also done. There are some maintenance tasks that must be done periodically in order to maintain REM up-to-date and somehow building similar REMs to other interesting radio spectrum bands:

- Update REM data at least since January 1st, 2015 in order to capture new changes introduced in UHF TV band after channel reallocation. The REM data update must be done following the guide provided in Appendix section to maintain the same structure. The changes affecting list of authorized TV channels (REM 1st section) must be updated, too.
- Improve propagation simulation done in REM 2nd section but taking into account buildings distribution in order to obtain a more precise simulation. This fact could be important to help human users looking at REM for zones where received power of TV channels could be low; without having to look nodal point by nodal point information.
- Build additional REMs of other places or bands like VHF following the same criteria exposed in this thesis but modifying properly *R&S FSL6* spectrum analyser settings to obtain the same precision and *MATLAB* scripts. Moreover, the antenna used during REM building process must be measured in the same terms as done in section 3.1 in order to be able to compensate the obtained measured results.
- Optimize Kriging parameters to obtain more good results in accordance with *ETSETB TelecomBCN* facilities or other places.
- Develop an interface able to provide relevant REM data to any human user (REM 1st and 2nd sections exposed in chapter 3) and any WSD (REM 3rd section), taking into account nodal points location and its validity area as exposed in section 3.5. The interface must provide directly nodal points information starting from GPS latitude and longitude, provided by the WSD, if its coordinates are inside a nodal point validity area or use Kriging algorithm instead to compute point results. Moreover, the interface can provide REM data using other styles like showing a table joining the mean received power of a certain TV channel at all nodal points, or the availability of TVWSs over them.

Bibliography

[1] Dirección de Estudios, Estadísticas y Recursos Documentales. “2012 Informe Económico-Sectorial. Consejo 14 junio 2013”. *Comisión del Mercado de las Telecomunicaciones (CMT),* 2013. [Online] Available: http://www.cmt.es/c/document_library/get_file?uuid=c427b477-2ccc-4290-9135-5a3532e7f0c4&groupId=10138. [Accessed: 25 March 2014].

[2] "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2013–2018". Cisco report, Cisco Systems Inc, California, The United States, February 5, 2014.

[3] "Televisión terrestre en España". *Wikipedia, la enciclopedia libre*. 2014. [Online] Available: http://es.wikipedia.org/wiki/Televisi%C3%B3n_terrestre_en_Espa%C3%B1a#Reasignaci.C3.B3n_de_frecuencias_y_el_.22dividendo_digital.22. [Accessed: 27 March 2014].

[4] "UN-36.- Cuadro nacional de atribución de frecuencias (CNAF)". *Secretaría de Estado de Telecomunicaciones y para la Sociedad de la Información. Ministerio de Industria, Energía y Turismo. Gobierno de España*. 2013. [Online] Available: http://www.minetur.gob.es/telecomunicaciones/Espectro/CNAF/cuadroAtribuciones2013.pdf. [Accessed: 27 March 2014].

[5] "Frecuencias telefonía móvil". *BANDAANCHA.ST*. 2014. [Online] Available: http://wiki.bandaancha.st/Frecuencias_telefon%C3%ADa_m%C3%B3vil. [Accessed: 27 March 2014].

[6] "ISM Band". *Wikipedia, The Free Encyclopedia*. 2014. [Online] Available: http://en.wikipedia.org/wiki/ISM_band. [Accessed: 27 March 2014].

[7] "IR-71.- Transmisores de radiodifusión de televisión digital terrenal en UHF". *Secretaría de Estado de Telecomunicaciones y para la Sociedad de la Información. Ministerio de Industria, Energía y Turismo. Gobierno de España*. 2013. [Online] Available: http://www.minetur.gob.es/telecomunicaciones/es-ES/Servicios/Normalizacion/InterfacesRadioelectricas/Interfaces/Radiodifusión/IR%2071.pdf. [Accessed: 03 April 2014].

[8] "BOE-A-2011-5834. Real Decreto 346/2011, de 11 de marzo, por el que se aprueba el Reglamento regulador de las infraestructuras comunes de telecomunicaciones para el acceso a los servicios de telecomunicación en el interior de las edificaciones". *Agencia Estatal Boletín Oficial del Estado. Ministerio de la Presidencia. Gobierno de España*. 2011. [Online] Available: https://www.boe.es/boe/dias/2011/04/01/pdfs/BOE-A-2011-5834.pdf. [Accessed: 10 April 2014].

[9] Joseph W. Mwangoka, Paulo Marques, and Jonathan Rodriguez. "Exploiting TV White Spaces in Europe: The COGEU Approach". *IEEE International Symposium,* Instituto de Telecomunicaçôes, Campus Universitário de Santiago, Portugal, 2011.

[10] Jaap VAN DE BEEK, Janne RIIHIJÄRVI, Petri MÄHÖNEN. "Intrinsic challenges (and opportunities) to deploy LTE in Europe’s TV white spaces". *Future Network and*

MobileSummit Conference, IIMC International Information Management Corporation*, ISBN: 978-1-905824-30-42,* 2012.

[11] José María Hernando Rábanos (and others). "Introducción al estado de la situación de los "TV White Spaces" y "LSA" propiciados por la Radio Cognitiva". *Grupo del Espectro,* Colegio Oficial de Ingenieros de Telecomunicación, April 2013.

[12] *Technical and operational requirements for the operation of white space devices under geo-location approach*. ECC Report 186, January 2013.

[13] Berna Sayrac, Sana Ben Jemaa and Pascal Cordier. "Radio Environmental Maps (REMs): A Cognitive Tool for Environmental Awareness". *Orange Labs,* Colegio Oficial de Ingenieros de Telecomunicación, 2013.

[14] H. Birkan Yilmaz, Tuna Tugcu, Fatih Alagöz and Suzan Bayhan. "Radio Environment Map as Enabler for Practical Cognitive Radio Networks". *IEEE Communications Magazine,* Electrical and Electronics Engineers, December 2013.

[15] Geoff Bohling. "Kriging". *Kansas Geological Survey,* C&PE 940, October 2005.

[16] *DA753 Compact Discone Aerial Antenna Specifications*. AOR USA Ltd.

[17] *R&S FSL6 Spectrum Analyzer*. Rohde & Schwarz.

[18] "Oferta de canals de TDT per municipi". *Tot sobre la TDT. Mitjans de comunicació. Generalitat de Catalunya.* 2014. [Online] Available: http://mitjansdecomunicacio.gencat.cat/ca/temes/televisio/tot_sobre_la_tdt. [Accessed: 02 June 2014].

Appendix: How to update REM using provided MATLAB scripts

The Radio Environment Map has been designed to operate in any geographical environment, although the main objective is to make it operable at *ETSETB TelecomBCN* facilities. The first contribution of the REM was developed on 2014 first semester. Changes affecting UHF TV band spectrum could make change current REM data, that is, perhaps some TVWSs are not available or they have been shifted to other channels. Next short guide has the aim of solving the need of maintaining the REM up-to-date.

REM data and processing routines are stored in MATLAB files on the same folder, in order to guarantee its correct functionality. There are two kinds of files: REM data files, containing complete REM data and REM processing routines, which are MATLAB routines whose aim is to process spectrum captured data to versatile REM data. These REM data files are stored in *.mat* files, while MATLAB routines are stored in *.m* files. Next table summarizes all files, with their filename, their kind and a short description of their content.

Filename	Short description
DeleteFreqFiles.m	MATLAB script whose aim is to delete all *.mat* files containing ‘Frequencies’ word in filename. These files come from *Rohde&Schwarz FSL6* spectrum analyser and they contain a matrix with the frequency value in Hz of each discretized measuring point in columns. The number of columns depends on the number of requested traces for the measure. These files are for plotting purposes, but may cause confusion on MATLAB routines, so before starting processing task, frequency files must be deleted.
EqualizeMatrixScript.m	MATLAB script that generates *equalMatrix.mat* file, which contain the values in dB that must be subtracted for each channel in order to compensate antenna frequency response (see 3.1 section).
equalMatrix.mat	Equalizing matrix data file.
GUI.m / GUI.fig	MATLAB program developed by Oriol Ros Fornells, in accordance with *Mobile Communications Research Group* (GRCM) whose aim is to facilitate *FSL6* spectrum analyser parameters set operation.
kriging.m	MATLAB function that computes Kriging algorithm (see 2.5 section) for a certain coordinated location. This function must be used only inside *KrigingScript.m* script.
KRIGING_PARAMETERS.m	MATLAB structure containing all needed parameters to compute in Kriging algorithm. The values of this structure are set in *KrigingScript.m* script.
KrigingScript.m	MATLAB script that prompts user to introduce the latitude and the longitude of a certain point inside REM environment limits and then it calls *Kriging.m* function. The script stores the result as an in between point.

NoiseMatrixScript.m	MATLAB script that processes separately measured spectrum analyser noise data. Noise data has the same structure as captured data, channel by channel. This script generates *NoiseMatrix.mat* file, containing 50 realizations of estimated noise power value for all channels. These values are used by *TVWS_PFA.m* function in order to decide if a certain channel is declared as a TVWS according to PFA criterion.
NoiseMatrix.mat	Noise matrix generated by *NoiseMatrixScript.m* script.
POINT.m	MATLAB structure representing a nodal or an in between point. After processing data the results are stored in *.mat* files containing a variable of this kind. It contains the latitude and longitude of the point and the obtained results: mean received power of each channel in dBm, standard deviation in dB and two '1' and/or '0' values expressing whether the channel is or not a TVWS according to DTT sensibility and PFA criteria, in this order.
ProcessAllPoints.m	MATLAB script in charge of start processing data coming from spectrum analyser. The script contains a matrix with all coordinates pairs. The script calls recursively *processPoint.m* function point by point.
processPoint.m	MATLAB function which processes all captured data from a certain point. The results of processing point data are filled and stored in a nodal point file. For a certain point, this function looks up captured data from spectrum analyser and processes it, according to 3.5 section.
REMLimits.m	MATLAB script that generates *REMLimitsMatrix.mat*, the one containing four coordinate points that encloses polygonally REM limits. These points are used by *kriging.m* function in order to check if entered point is inside REM limits or not.
REMLimitsMatrix.mat	REM limits matrix generated by *REMLimits.m* script.
sphericalCov.m	MATLAB function used by *kriging.m* function to compute spherical covariance, the base of Kriging algorithm.
TVWS_DTTReceiver.m	MATLAB function used in *processPoint.m* function that decides if a certain TV channel of a certain point can be declared as a TVWS using DTT receiver sensitivity criterion, as explained in 3.5 section.
TVWS_PFA.m	MATLAB function used in *processPoint.m* function that decides if a certain TV channel of a certain point can be declared as a TVWS using PFA criterion, as explained in 3.5 section.
NODAL_x.xxxx_y.yyyy.mat	REM processed data is stored in this format. These files are the output of *processPoint.m* function. 'NODAL' word determines this point belonging to REM point's network. x and y are the point latitude and longitude, respectively.

Ch_x.xxxx_y.yyyy*.m	Captured data using the spectrum analyser must have this structure. Each file contains a matrix of all discretized points of the spectrum of one TV channel (its number is placed in place of 'Ch' word); and x and y are the latitude and longitude of the point, respectively. Asterisk at the end of filename indicates whatever text.
Ch_NOISE*.m	Spectrum analyser noise measured data. These files have the same structure as last one. They do not represent any nodal point but noise power of each TV channel, placing the number in 'Ch' word. These files are used by *NoiseMatrixScript.m* to compute *NoiseMatrix.mat.* Asterisk at the end of filename indicates whatever text.

Table 19. REM data and MATLAB processing routines.

Understanding REM files structure is crucial when it is time to update or make larger the REM. The possible actions that could be carrying out in the REM are the following:

- Increase or decrease REM dimensions by adding or eliminating nodal points.
- Update the captured information of any nodal point.

Both previous actions follow similar actions but with one difference. In case of adding or subtracting a certain number of nodal points, their coordinates must be added or subtracted in point's matrix inside *ProcessAllPoints.m* script. Moreover, *totalNodalPoints* value must be changed in accordance with new number of total nodal points to be processed. At this step, both actions follow common procedures that must be followed in order, according to next step-by-step guide:

1. Set up and calibrate the spectrum analyser to the appropriate configuration, according to section 3.5 of this thesis.
2. Capture data from the place to be a new nodal point or from the same place, taking the coordinates with a tolerance of 10 meters, where the nodal point to be updated is placed. It does not matter how many traces are captured and how many points does each trace have, p*rocessPoint.m* function adapts its behaviour.
3. Ensure that obtained data accomplishes processing requirements. Concretely, the obtained file must contain only one matrix with all captured traces in columns. Each column must contain the total amount of discretized values.
4. Repeat 2nd and 3rd steps for all TV channels. Remember to store the obtained following the structure previously mentioned, that is, putting first the TV channel number and then the latitude and longitude of the relevant nodal point.
5. Put obtained files into the same folder where all previous MATLAB scripts are present. Execute *DeleteFreqFiles.m* script to delete frequency files.
6. Include directory on *MATLAB* path. Right click on folder, then 'Add to Path'.
7. Execute *ProcessAllPoints.m* script. Nodal points will be computed automatically.

Glossary

The following list shows all the appeared acronyms in this thesis with their meaning:

A:

- **AP**: Access Point. Device that allows wireless devices to connect to a wired network.

B:

- **BOE**: Official State Gazette. Document containing applicable laws of a certain country. The acronym means *Boletín Oficial del Estado* in Spanish.

C:

- **Ch:** Channel. Piece of bandwidth dedicated to one full service of the band.
- **C/I:** Carrier over Interference. Figure of merit comparing the power of the carrier of the desired signal with the power of the interference carrier.
- **CMT:** Market Telecom Commission. Old regulator of radio electric spectrum in Spain. The acronym means *Comisión del Mercado de las Telecomunicaciones* in Spanish.
- **CNMC:** National Market and Competence Commission. Current regulator of radio electric spectrum in Spain, among other roles. The acronym means *Comisión Nacional de los Mercados y la Competencia* in Spanish.
- **COET:** Official School of Telecom Engineers. Organism of graduated Telecom Engineers in Catalonia. The acronym means *Col·legi Oficial d'Enginyers de Telecomunicació* in Catalan.
- **COFDM:** Coded Orthogonal Frequency Division Multiplexing. Modulation consisting on dividing available bandwidth with short-bandwidth frequency orthogonal independent sub-carriers.
- **COGEU:** COGnitive radio systems for efficient sharing of TV white spaces in. EUropean context. European project formed by a composite of technical, business, and regulatory/policy domains, with the objective of taking advantage of the analogue switch-off by developing cognitive radio systems.
- **CTI:** Common Telecommunications Infrastructures. Indoor telecom infrastructure which allows effective, free and quality access to any telecom service to the final user.

D:

- **dB:** Decibel. Ten times the logarithmical ratio between two power values.
- **dBc:** Decibel with respect to the carrier. Ten times the logarithmical value of the power of the carrier of the signal.

- **dBi:** Decibel with respect to the isotropic antenna gain. Ten times the logarithmical value of the gain of a non-isotropic antenna.
- **dBm:** Decibel with respect to the mW. Ten times the logarithmical value of a certain power expressed in miliwatts unit.
- **dBµV:** Decibel with respect to the µV. Twenty times the logarithmical value of a certain voltage expressed in Volts.
- **DANL:** Displayed Average Noise Level. The average of spectrum analyser noise level shown.
- **DEM:** Digital Elevation Model. 3D representation of a terrain's surface.
- **DSL:** Digital Subscriber Line. Family of technologies that provide Internet access by transmitting digital data over telephone wires.
- **DTT:** Digital Terrestrial Television. Television service modulated using digital modulations and only broadcast using terrestrial infrastructures.
- **DVB-T:** Digital Video Broadcasting Terrestrial. Standard used in Spain (and other countries) to broadcast DTT.

E:

- **EB:** Exabyte. Amount of information equivalent to ten to the eighteenth power bytes.
- **EHF:** Extremely High Frequency. Range of radio electric spectrum between 30 GHz and 300 GHz.
- **EIRP:** Equivalent Isotropic Radiated Power. Quantity of emitted power from an antenna taking into account the antenna gain and the feeder losses, in addition to emitter output power.
- **ETSETB:** Barcelona Telecom Engineers High Technical School. Official public school responsible of forming telecom engineers in Barcelona. The acronym means *Escola Tècnica Superior d'Enginyers de Telecomunicació de Barcelona* in Catalan.

F:

- **FCC:** Federal Communications Commission. Interstate and international regulatory organism of communications by radio, television, wire, satellite and cable in the US.
- **FFT:** Fast Fourier Transform. Mathematical operation done by the spectrum analyser filter to obtain measured spectrum of a certain range.

G:

- **GHz:** Gigahertz. Amount of frequency equivalent to ten to the ninth power hertz.
- **GPS:** Global Positioning System. American space-based satellite navigation system that provides location and time information in all weather conditions.
- **GRCM:** Mobile Communications Research Group. Association of students and professors responsible of UPC mobile communications research.

H:

- **HF:** High frequency. Range of radio electric spectrum between 3 MHz and 30 MHz.
- **HP:** Hewlett Packard. Company funded by William Redington Hewlett and Dave Packard, headquartered in Palo Alto, California, US. It provides hardware, software and services to consumers, small and medium-sized businesses and large enterprises
- **HSPA:** High Speed Packet Access. Amalgamation of two mobile telephony protocols, High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA), that extends and improves the performance of existing 3^{rd} generation mobile telecommunication networks.
- **Hz:** Hertz. Unit of frequency in the International System of Units. It is defined as one cycle per second.

I:

- **IEEE:** Institute of Electrical and Electronics Engineers. Professional association with its Corporate Office in New York City and its Operations Center in Piscataway, New Jersey
- **IP:** Internet Protocol. Most common protocol used to transmit and receive packets in any kind of network.
- **ISM:** Industrial Scientific and Medical band. Radio bands reserved internationally for the use of radio frequency for industrial, scientific and medical purposes other than telecommunications.
- **ITU:** International Telecommunications Union. Specialized agency of the United Nations that is responsible for issues that concern information and communication technologies.

K:

- **kHz:** Kilohertz. Amount of frequency equivalent to ten to the third power hertz.

L:

- **LF:** Low frequency. Range of radio electric spectrum between 30 kHz and 300 kHz.
- **LoS:** Line of Sight. In wireless propagation, electromagnetic beam coming directly from its source, without any kind of reflection.
- **LTE:** Long Term Evolution. 4^{th} generation standard for wireless communication of high-speed data for mobile phones and data terminals.

M:

- **MAC:** Medium Access Control. Sublayer providing addressing and channel access control mechanisms that make it possible for several terminals or network nodes to communicate within a multiple access network
- **MF:** Medium frequency. Range of radio electric spectrum between 300 kHz and 3 MHz.
- **MHz:** Megahertz. Amount of frequency equivalent to ten to the sixth power hertz.
- **mW:** miliwatt. Amount of power equivalent to ten to the minus third power Watt.

P:

- **PFA:** Probability of False Alarm. Method using to determine if a certain TV channel can be declared as a TVWS or not, comparing its mean power value of a certain amount of traces with the mean power of spectrum analyser noise level.

Q:

- **QAM:** Quadrature Amplitude Modulation. Digital modulation that conveys two digital bit streams, by changing the amplitudes of two carrier waves according to a quadrature constellation.
- **QoS:** Quality of Service. Empirical figure of merit that measures if the quality of a telecom received service is enough good or not.

R:

- **RBW:** Resolution bandwidth. Bandwidth of intermediate frequency (IF) filter used inside a spectrum analyser to filter incoming signals.
- **REM:** Radio Environment Map. Map containing mean received power of all channels of one or more radio spectrum bands in all geographical locations that map represents.
- **RMSE:** Root Mean Square Error. Figure of merit used in digital signal processing to measure if the used estimator to obtain a certain value is far from real value or not.
- **RRC:** Root Raised Cosine filter. Filter used by the spectrum analyser to filter incoming signals. Its frequency response is a root raised cosine with a certain roll off factor.
- **R&S:** Rohde & Schwarz. International electronics group, funded by Dr. Lothar Rohde & Dr. Hermann Schwarz, specialized in the fields of electronic test equipment, broadcasting, radiomonitoring and radiolocation, and radiocommunication

S:

- **SHF:** Super High frequency. Range of radio electric spectrum between 3 GHz and 30 GHz.

T:

- **TOI:** Third Order Interception Point. Measure for weakly nonlinear devices such as a spectrum analyser. It is based on the idea that the device nonlinearity can be modelled using a low-order polynomial. TOI value represents input power when third order output power contribution equals linear output power contribution.
- **TSC:** Signal and Communications Signal. UPC Cathedra where GRCM forms part of. The acronym means *Teoria del Senyal i Comunicacions* in Catalan.
- **TVWS:** TV White Spaces. TV channels that are not used to broadcast television.

U:

- **UHF:** Ultra High frequency. Range of radio electric spectrum between 300 MHz and 3 GHz.
- **UPC:** Polytechnic University of Catalonia. Largest engineering university in Catalonia. The acronym means *Universitat Politècnica de Catalunya* in Catalan.

V:

- **V:** Voltage. Unit of electric potential in the International System of Units. It is defined as electric potential difference between two points.
- **VBW:** Video bandwidth. Low-pass filter directly after the envelope detector used to filter measured signals before showing them on the spectrum analyser screen.
- **VHF:** Very High frequency. Range of radio electric spectrum between 30 MHz and 300 MHz.

W:

- **W:** Watt. Unit of power in the International System of Units. It is defined as the amount of energy per unit second.
- **Wi-Fi:** Wireless Fidelity. Local area wireless technology that allows an electronic device to exchange data or connect to the internet using 2.4 GHz UHF and 5 GHz SHF radio waves.
- **WiMAX:** Worldwide Interoperability for Microwave Access. Wireless communications standard designed to provide 30 to 40 Mbps data rates in rural wide area environments.
- **WSD:** White Space Device. Wireless device able to find and take advantage of an empty channel like a TVWS to operate.