Instituto Politécnico de Castelo Branco
Escola Superior de Tecnologia

IMPLEMENTATION OF A RADIO TRANSCEIVER FOR OPPORTUNISTIC MOBILE COMUNICATIONS IN TV BANDS

(IMPLEMENTAÇÃO DE UM TRANSCEIVER PARA COMUNICAÇÕES MÓVEIS OPORTUNISTAS NA BANDA DE TV)

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2012

Dedico esta dissertação ao meu filho João e á minha esposa Fátima.

O júri

Presidente

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Prof. Doutor José Carlos Meireles Monteiro Metrôlho

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Keywords

Cognitive Radio, Transceiver, Wireless Microphone, TV White Space, PMSE, USRP, LabVIEW

IMPLEMENTATION OF A RADIO TRANSCEIVER FOR OPPORTUNISTIC MOBILE COMUNICATIONS IN TV BANDS

Abstract

This document describes the work developed to implement a prototype able to operate in TVWS.Gives an overview about the digital switchover roadmap in Europe and surveys the trends in the TVWS market for different European countries. Describe the prototype specifications, also an overview about the TVWS prototype state of art.
Describes the sensing techniques for PMSE detecting used in the prototype and the thresholds calculations.The metrics to evaluate the algorithms selected are presents.
Also, describes the SDR systems, the chosen hardware, USRP and the features and limits, daughterboard selected. A resume about the software platform is present and the features that make this platform, Labview, the choice for integrating in the prototype
Describes the development and implementation of the prototype and also include the test scenario conditions and results.

Palavraschave

Cognitive Radio, Transceiver, Wireless Microphone, TV White Space, PMSE, USRP, LabVIEW

IMPLEMENTAÇÃO DE UM TRANSCEIVER PARA COMUNICAÇÕES MÓVEIS OPORTUNISTAS NA BANDA DE TV

Resumo

Este documento descreve o trabalho efetuado para a implementação de um protótipo capaz de operar nos TVWS. Apresenta uma visão geral da transição para a TV digital no contexto europeu e estudos sobre as tendências para o mercado de TVWS nos países europeus. Apresenta as especificações do protótipo e também uma visão geral sobre o estado da arte dos protótipos para TVWS.

É feita uma descrição geral sobre os algoritmos de sensing utilizados no protótipo e também é apresentado o cálculo de thresholds. São apresentadas as métricas utilizadas para a verificação e validação dos algoritmos.

É feita uma descrição dos sistemas SDR e do hardware escolhido, USRP, características e limitações. É apresentado resumidamente a plataforma de desenvolvimento de software, LabVIEW e as razões da sua escolha para a integração do protótipo.

É feita uma descrição do desenvolvimento e implementação do protótipo e são também apresentados os cenários de teste e os resultados

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List of abbreviations

ADC	Analogue To Digital (Convertor)
ASIC	Application Specific Integrated Circuit
ATSC	Advanced Television Systems Committee
BPSK	Binary Phase Shift Keying
3GPP	Third-generation
CDMA	Code Division Multiple Access
CellBE	Cell Broadband Engine Architecture
COMREG	Commission For Communication Regulation (Ireland)
CR	Cognitive Radio
DAC	Digital To Analogue (Convertor)
DSA	Dynamic Spectrum Access
DSP	Digital Signal Processing
DTT	Digital Terrestrial Television
DTV	Digital Television
DVB-H	Digital Video Broadcasting - Handheld
FCC	Federal Communications Commission

FFT	Fast Fourier Transform
FPGA	Field-Programmable Gate Array
GPP	General Purpose Processor
GPS	Global Positioning System
HDTV	High-Definition Television
IDE	Integrated Development Environment
IEEE	The Institute of Electrical and Electronics Engineers
ISM	Industrial Scientific and Medical (band)
LNB	Low Noise Block (Convertor)
LTE	Long Term Evolution
MAC	Medium Access Control
OFDM	Orthogonal Frequency Division Multiplexing
OOB	Out Of Band (Emissions)
PAPR	Peak-to-Average Power Ratio
PMSE	Programme Making and Special Events
PN	Process Network
QPSK	Quadrature Phase-Shift Keying

RAT	Radio Access Technology
RF	Radio Frequency
SDF	Synchronous Data Flow
SDR	Software Defined Radio
TVWS	Television White Space
UMTS	Universal Mobile Telecommunications System
USRP	Universal Software Radio Peripheral
USRPUHD	USRP Universal Hardware Driver
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
XML	eXtensibleMarkup Language

Chapter 1

1 Introduction

1.1 Motivation

The spectral bands VHF (174-230 MHz) and UHF (470-872 MHz) are currently occupied by analogue television. From 2012, all analogue radio broadcast European cease. Part of this spectrum will be used by DVB-T (Digital Terrestrial Television) and a significant part will be released for new applications (Digital Dividend). This spectrum section offers attractive features like high building penetration, wide coverage, and moreover, the wavelength of UHF bands signals is sufficiently short such that resonant antennas with sufficiently small footprint can be used which are acceptable for many portable use cases and handheld devices. In this context, there are opportunities to use spectrum for secondary use by mobile communication systems. For this it is necessary to ensure non-interference with the primary users of these bands, or DVB-T systems and PMSE (wireless microphones).Additionally, digital television technology geographically interleaves spectrum bands, or TV White Spaces (TVWS), to avoid interference between neighbouring stations, leaving a space for deploying new wireless services.

Information and Communication Technologies (ICTs) have drastically changed the world in which we live. With increased interconnections in economic activities, knowledge sharing, entertainment, socializing etc., billions of people around the world today are utilizing ICTs to function in real-time across the world without delay and with blurred distinction between physical and digital experiences. These experiences are further magnified by access to mobile broadband networks where the limitations of wire-line access are overcome by giving people the ability to communicate anytime and anywhere. From the European Union's (EU) perspective, the Lisbon Treaty envisions providing significant improvements in mobile broadband, multimedia and Internet access to European citizens. To this end, the European Commission is putting forth efforts to make a pan-European mobile broadband network become a reality through harmonizing the spectrum usage of the 27 EU Member States, especially by creating an innovation space in the digital dividend, after the re-allocation of broadcast spectrum.

The broadcast spectrum is a low frequency spectrum in the VHF and UHF portion of the radio spectrum; a portion that has traditionally been used exclusively by television broadcasters for analogue transmission. The spectrum section offers attractive features like high building penetration, wide coverage, and moreover, the wavelength of UHF bands signals is sufficiently short such that resonant antennas with sufficiently small footprint can be used which are acceptable for many portable use cases and handheld devices. However, regulatory rules don't allow the use of unlicensed devices in the TV bands, with the exception of remote control, medical telemetry devices and wireless microphones. Currently, there is a global move to convert TV stations from analogue to digital transmission. This is called the digital switch-over (DSO) or in some cases the analogue switch-off (ASO) referring to the time when digital transmission effectively starts, or when analogue transmission effectively stops operation respectively.

Although the DSO process is underway in EU countries, the ASO process will differ from country to country depending on the market configuration. It is predictable that the European Commission's call for the completion of the ASO process by 2012 will be difficult to achieve for some Member-States. On the other hand, however, it is expected that the experiences of countries that have completed the ASO process or undertaken extensive planning will provide useful lessons for countries only beginning the planning process.

Due to the spectrum efficiency of DTV, some of the spectrum bands used for analogue TV will be cleared and made available for other usage. Moreover, DTV spectrum allocation is such that there are a number of TV frequency bands which are left unused within a given geographical location so as to avoid causing interference to co-channel or adjacent channel DTV transmitters; that is to say, the spectrum bands are geographically interleaved. The cleared bands and the unused geographical interleaved spectrum bands provide an opportunity for deploying new wireless services. These opportunities create what is called the “Digital Dividend”. For the European Commission, the Digital Dividend (cleared spectrum and geographical interleaved spectrum) constitutes a great opportunity to achieve important goals of the EU Lisbon strategy, especially in the area of providing mobile broadband Internet access.

Market analysis indicates that the digital dividend in Europe is a unique opportunity to realise economic/social benefits across Europe. This is a key to maintaining Europe's competitiveness – especially given digital dividend advances in other regions. Secondary markets initiatives in Europe generally lag the rest of the developed world – there has been very little progress in the development of comprehensive frameworks for secondary trading at European level.

The digital dividend could be valuably employed by cognitive devices. The Cognitive Radio (CR) technology is a key enabler for both real-time spectrum markets and dynamic sharing of licensed spectrum with unlicensed devices. It performs spectrum acquisition, either through purchasing (in cleared spectrum) or sensing (in vacant bands e.g., geographic interleaved spectrum), over a range of frequency bands, dynamically acquires unused spectrum, and then operates in this spectrum at times and/or locations when/where it is able to transmit in a non-interfering basis while achieving its service's QoS. Currently Cognitive radio is being intensively researched for proper access to the TV White Spaces (TVWS) which become available on a geographical basis after the digital switchover.

In December 2009, the RSPG published the final draft of their report on 'Cognitive Technologies', which makes explicit comments on the possibility of supporting trading mechanisms for CR technologies. This report describes the vertical and the horizontal models for the licensed sharing of spectrum. The vertical model, which is most likely of more relevance, envisages the licensed user, i.e. the DTT broadcaster, allowing secondary usage of its spectrum at locations and times that it is not used. The horizontal model, on the other hand, is of less relevance to horizontal sharing because it pools all the spectrum held by a group of licenses such they can then access that spectrum according to their given demand profiles.

1.2 The proposal

The objective of this work is design, develop and test a radio for mobile communications able to make use of TV channels as an opportunistic way. The device should make use of cognitive capacities. It must integrate communication with a geo-location database, making use of geo-location function.

The project follows the objectives of COGEU project. So that it is integrated in COGEU. An overview of COGEU project is presented in next subsection.

1.2.1 COGEU Overview

COGEU, COGnitive radio systems for efficient sharing of TV white spaces in EUropean context is a FP7 - Seventh Research Framework Programme project from ICT - Information and Communication Technologies.

COGEU is a composite of technical, business, and regulatory/policy domains, with the objective of taking advantage of the TV digital switch-over (or analogue switch-off) by developing cognitive radio systems that leverage the favourable propagation characteristics of the TVWS through the introduction and promotion of real-time secondary spectrum trading and the creation of new spectrum commons regime. COGEU will also define new methodologies for TVWS equipment certification and compliance addressing coexistence with the DVB-T/H European standard.

The innovation brought by COGEU is in the combination of cognitive access to TV white spaces with secondary spectrum trading mechanisms in a real demonstrator.

At the **technical level** the mail goals are to:

- Design, implement and demonstrate enabling technologies based on cognitive radio to support mobile applications over TVWS for spectrum sharing business models.
- Quantify the impact of TVWS devices on DVB-T receivers and define methodologies for TVWS equipment certifications and compliance in the European regulatory context.

At the **business models leve**l the mail goal is to:

- Investigate business models enabling innovative wireless services which increase spectrum utilization through the exploitation of TVWS based on spectrum commons and secondary market regimes.

At the **regulatory/policy level** the mail goals are to:

- Define spectrum policies and etiquette rules to promote fairness and avoid the tragedy of the commons in case of unlicensed spectrum usage, and monopolization in case of the secondary spectrum market usage.
- Analyse the dynamics of bandwidth sharing and pricing in a spectrum market environment of TVWS under QoS and regulatory constraints.

1.2.2 COGEU proposal

At a technical level, the main objective of COGEU is to design, implement and demonstrate technologies that will enable cognitive radios to exploit the TV white spaces (TVWS) that will be created when the switchover to DTV is complete.

However, primary users of the spectrum, such as DVB-T systems, must be protected from interference, and one consensual method to protect them is based ongeo-location databases, combined with spectrum sensing.There are several advantages for the use of geo-location to support the detection of incumbent systems. The most important is that the database stores the required information to compute the TVWS spectrum pool available in a specific location. Information such as DVB-T protected areas; specifications of DVB-T transmitters, advanced propagation models, protection rules, can be used to compute the maximum transmit power. With a database, part of the complexity associated with sensing and maximum power computation is transferred to the core network, decreasing complexity and power demand of TVWS devices. This approach only protects the register users and in Europe and in many countries, Public Making and Special Events (PMSE) devices operate mostly in unlicensed basis, without any record. Even so, PMSEs are incumbent users of the spectrum and as such, they must be protected from secondary user's interference. The only way to protect these unregistered PMSEs is through sensing. The combined sensing and geo-location approach has the advantage of reducing the risk of interference with PMSE compared to sensing only. Combining the two approaches relaxes the sensitivity required for sensing devices, which is a major limitation of TVWS developments. Also, since local sensing is only performed in a limited number of TV channels indicated by the database, a hybrid approachwill speed up the sensing process: Autonomous sensing and geo-location database approaches are combined to detect the presence of primary users in a specific location, based on a "double affirmative", as depicted in Figure 1.1

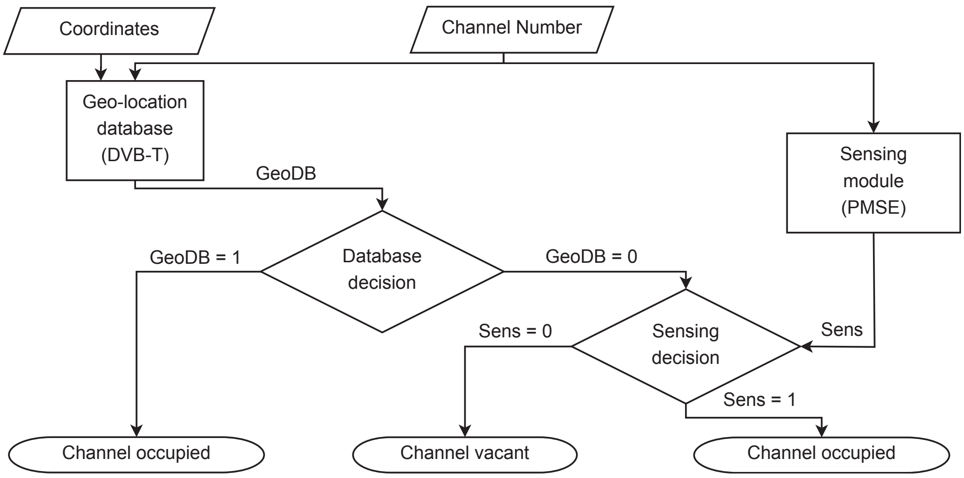


Figure 1.1: Flow chart of the decision-making process for combination of geo-location data with local sensing.

The purpose of the COGEU TVWS radio transceiver is primarily to facilitate the development, evaluation and demonstration of a range of novel algorithms and techniques that will enable cognitive radio devices to efficiently exploit geographically interleaved TV spectrum. As such, the COGEU TVWS is a prototyping platform, not a production platform. Its primary aim is to provide a basis for the ready development of novel techniques and novel systems. It will serve to prove the viability of a number of key concepts whose feasibility is critical to the potential deployment of cognitive radios in the European TVWS.

The COGEU TVWS transceiver will be based upon a software defined radio (SDR)-based architecture as this approach enables the rapid development and evaluation of novel techniques at low cost. The system is mainly develop using LabVIEW develop software platform and the Universal Software Radio Peripheral (USRP) a RF front-end that fulfils the requirements of an experimental, prototyping platform.

The work described here will focus only the sensing module, the transmitter/receiver module is responsibility of other COGEU team, but both sensing module and transmitter/receiver module have to beintegrating as one device.

The rest of document is laid out as follows. Chapter 2 gives a global perspective of the TVWS, chapter 3 presents the transceiver specifications including a state of art revision, chapter 4 refer to prototype implementation, on chapter 5 is described a test scenario and the obtained results, in chapter 6 are presented the conclusions and the on-going work and the list of publications related with the project.

Chapter 2

2 Global perspective of the TVWS

This chapter is dedicated to describe the important resource that the COGEU project is going to exploit, that is, TVWS[34]. First, the current situation of the digital switchover around the globe is overviewed. Second, a conceptual definition of the digital dividend is given and the TVWS is elicited. Third, a general overview of incumbent systems in TVWS is given. These incumbents are important since COGEU systems have to consider coexistence with them. Forth,the availability of TVWS in Europe.

2.1 Current situation of the digital switchover

The digital switchover process is underway. Around the world, countries have launched their Digital Terrestrial Television (DTT) services and begun planning to switch off their analogue networks. But analogue switch-off is not easy. Ending the transmission of analogue services can have terrible consequences if viewers were not adequately prepared. Governments will not want the risk of viewers without television and will want to ensure that proper safeguards are taken. But doing so will require careful planning and the involvement of the entire broadcast industry.

The process of analogue switch-off will differ in countries depending upon the market configuration. Countries with many households relying on the terrestrial platform will need to take different measures than countries with few terrestrially dependent households. The experiences of countries that have completed analogue switch-off or undertaken extensive planning can provide useful lessons for countries only beginning the planning process. Understanding which approaches work best, as well as pitfalls that should be avoided, can help ensure a successful process. The transition to digital television at present is largely a preoccupation of the advanced economies of the world and the major markets are the USA, Japan and Europe.

2.1.1 Outside Europe

The DTT transition in the United States was the switchover from analogue to exclusively digital broadcasting of free over-the-air television programming. For full-power TV stations, the transition went into effect on June 12, 2009, with stations ending regular programming on their analogue signals no later than 11:59 p.m. local time that day. The transition was originally scheduled for February 17, 2009. However, since around two million families were not prepared for the transition, the switch-off of analogue was postponed.

In Japan, the switch to digital is scheduled to happen on July 24, 2011. In Canada, it was scheduled to happen on August 31, 2011. China is scheduled to switch-off in 2015. Brazil switched to digital on December 2nd of 2007 in major cities and it is estimated it will take seven years for complete signal expansion over all of the Brazilian territory.

Figure 2.1shows the status of analogue to digital transitions worldwide.

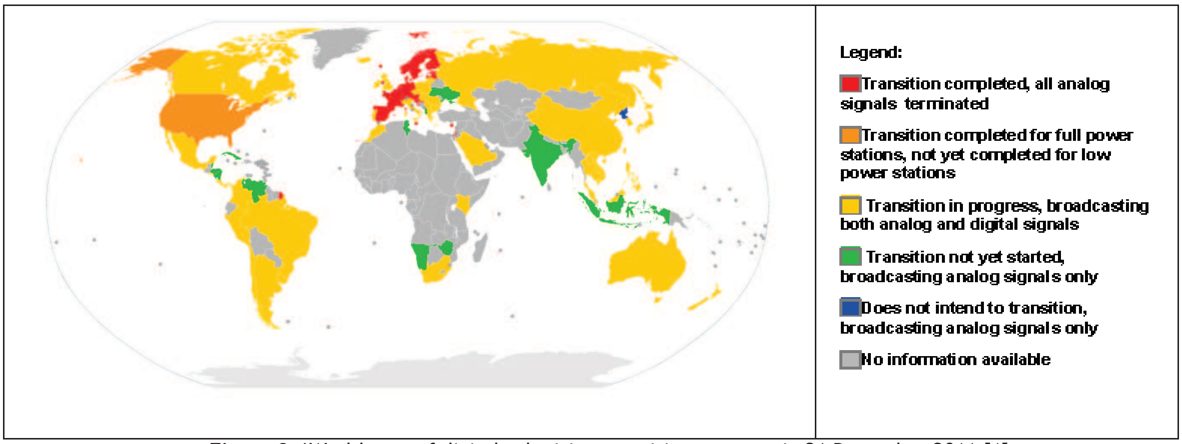


Figure 2.1 World map of digital television transition progress in 21 December 2011 [1]

2.1.2 Within Europe

The switchover from analogue to digital terrestrial TV in Europe will free up highly valuable radio frequencies due do the greater efficiency of digital broadcasting transmission. This "digital dividend" has great potential for the provision of a wide range of services, as the radio signals in this range travel far and equipment can be easily used indoors. It represents a unique opportunity for Europe to meet the growing demand for radio spectrum, particularly to provide wireless broadband to rural areas, thereby bridging the digital divide, and to stimulate the take-up of new wireless services such as the next generation of mobile broadband, as well as to support the development of terrestrial broadcasting. It can therefore contribute significantly to the Lisbon Agenda goals of competitiveness and economic growth and satisfy some of the important social, cultural and economic needs of European citizens.

The digital dividend spectrum will become available throughout Europe within a relatively short space of time, as all Member States should complete the switch-off of analogue TV by 2012 at the latest. It is essential that this window of opportunity is used to ensure an appropriate level of coordination in the European Union to reap the full social and economic benefits possible from access to this spectrum, and to provide a clear EU roadmap for Member States moving ahead at different speeds as a result of differing national circumstances.

The opening of the digital dividend spectrum for different services creates an opportunity particularly for wireless broadband network operators to gain valuable radio spectrum. This would allow for more effective competition in the provision of broadband services.

As of late 2009, 10 countries had completed the process of turning off analogue terrestrial broadcasting. Many other countries had plans to do so or were in the process of a staged conversion. The first country to make a wholesale switch to digital over-the-air (terrestrial) broadcasting was Luxembourg, in 2006, followed by the Netherlands later in 2006, Finland, Andorra, Sweden and Switzerland in 2007, Belgium and Germany in 2008, and the Denmark and Norway in 2009. In Table 2.1we can see the digital television launch date (and the termination of analogue TV).

Table 2.1: Situation the switchover [Source: DigiTAG]

Country	Launch date	Compression format	Completion of ASO (Analog Switch Off)
UK	1998	MPEG-2	2012
Sweden	1999	MPEG-2	Completed
Spain	2000/ 2005	MPEG-2	2010
Finland	2001	MPEG-2	Completed
Switzerland	2001	MPEG-2	Completed
Germany	2002	MPEG-2	Completed
Belgium (Flemish)	2002	MPEG-2	Completed
NL	2003	MPEG-2	Completed
Italy	2004	MPEG-2	2012
France	2005	MPEG-2/MPEG-4 AVC	2011
Czech Republic	2005	MPEG-2	2011
Denmark	2006	MPEG-2/MPEG-4 AVC	Completed
Estonia	2006	MPEG-4 AVC	2010
Austria	2006	MPEG-2	2010
Slovenia	2006	MPEG-4 AVC (TBC)	2011
Norway	2007	MPEG-4 AVC	Completed
Lithuania	2008	MPEG-4 AVC	2012
Hungary	2008	MPEG-4 AVC	2011
Ukraine	2008	MPEG-4 AVC	2014
Latvia	2009	MPEG-4 AVC	2010

Portugal	2009	MPEG-4 AVC	2012
Croatia	2009	MPEG-2	2011
Poland	2009	MPEG-4 AVC	2013
Slovakia	2009	MPEG-2	2012
Ireland	2010	MPEG-4 AVC	2012
Russia	to be confirmed	MPEG-4 AVC	2015

The Member States that launched DTT early mainly broadcast using MPEG-2 compression technology, while Member States that have recently launched, or are yet to launch (such as Ireland, Latvia, Lithuania, Romania, and Slovenia) plan to use MPEG-4 compression technology from the outset. Austria, Denmark, Finland, Germany, Italy, Luxembourg, Portugal, Sweden and the UK all consider future migration to the MPEG-4 standard to be highly likely. In particular, Sweden and Denmark intend to simulcast using both the MPEG-2 and MPEG-4 standards in the foreseeable future.

Market evidence shows that the MPEG-4 AVC compression technology is increasingly being integrated in to DTT receivers. Markets that have launched DTT services since 2008 have overwhelmingly adopted MPEG-4 AVC while markets that presently use MPEG-2 will likely transition to MPEG-4 AVC. In France, and as from 2010 in Spain, all HD receivers must include an MPEG-4 AVC chipset. As a result, MPEG-4 AVC is expected to become the de-facto compression technology used in almost all DTT receivers.

The average simulcast period for analogue and digital terrestrial TV in Member States is about 5.5 years. Smaller Member States with extensive cable infrastructure/take-up, such as the Netherlands and Luxembourg, switched off their analogue TV signals nationally overnight. Germany, as a larger nation with extensive cable infrastructure, adopted a regional digital switchover plan and had a simulcast period of almost six years. In contrast, in the UK, where terrestrial TV is one of the main TV platforms, simulcast is expected to occur for a total of 14 years prior to ASO.

As we have seen, Member States have varying approaches to their Digital Switch-Over (DSO) plans. The pace at which they are being executed appears to depend on geography, the television platform landscape, policy objectives and political will, as well as the level of technological advancement. In general, Western European Member States have started, and are likely to complete, their DSO before Eastern European Member States. Indeed, five (Finland, Germany, Luxembourg, the Netherlands and Sweden) have already switched off their analogue transmissions.

The European Commission's call for the completion of analogue switch-off by 2012 may be difficult to achieve for some Member-States. Based on currently available evidence, it can be generally assumed that the digital switchover process will take between 14 years (as in the United Kingdom) and 3 years (as in the Netherlands) from the time of the first launch of DTT services to the switch-off of the last analogue services. Factors that will influence the process include the number of viewers relying on the terrestrial television platform, spectrum availability, and the penetration of DTT services.

Countries that have already launched DTT services and begun to switch-off their analogue terrestrial platform will likely complete digital switchover by 2012. However, countries that have not yet launched their DTT platforms risk being unable to complete analogue switch-off by 2012.

At this stage, all Member-States, apart from Poland, appear to have confirmed their intention to complete analogue switch-off by 2012. Already, the process have been completed by 5 Member-States (Finland, Germany, Luxembourg, the Netherlands, Sweden) while a further 8 Member-States (Austria, Belgium, Czech Republic, Estonia, France, Italy, Spain, the United Kingdom) have begun switching off analogue services in one or more areas. It is expected that these countries will be able to complete analogue switch-off by 2012, if not earlier. Member States that have not yet launched DTT services will have more difficulty in reaching a sufficiently high level of penetration to allow for analogue switch-off by 2012[2].

2.2 What is the TVWS ?

2.2.1 The Digital switch-over

Broadcast television services operate in licensed channels in the VHF and UHF portion of the radio spectrum. The spectrum section offers attractive features like high building penetration, wide coverage, and moreover, the wavelength of UHF bands signals is sufficiently short such that resonant antennas with sufficiently small footprint can be used which are acceptable for many portable use cases and handheld devices. However, regulatory rules don’t allow the use of unlicensed devices in the TV bands, with the exception of remote control, medical telemetry devices and wireless microphones. Currently, there is a global move to convert TV stations from analogue to digital transmission. This is called the digital switch-over (DSO) or in some cases the analogue switch-off (ASO) referring to the time when digital transmission effectively starts, or when analogue transmission effectively stops operation respectively [3].

2.2.2 The Digital Dividend

Due to the spectrum efficiency of DTT, some of the spectrum bands used for analogue TV will be cleared and made available for other usage. Moreover, DTV spectrum allocation is such that there are a number of TV frequency bands which are left unused within a given geographical location so as to avoid causing interference to co-channel or adjacent channel DTV transmitters;

that is to say, the spectrum bands are geographically interleaved. The cleared bands and the unused geographical interleaved spectrum bands provide an opportunity for deploying new wireless services. These opportunities create what is called the “Digital Dividend” in theliterature [3][4][5][6][7][8][9].In other words, the digital dividend refers to the “leftover” frequencies resulting from the change of TV broadcasting from analogue to digital.

The UK regulator, Ofcom, has led Europe in creating a digital dividend. As illustrated in Table 2.2, the UK’s digital dividend comprises [8]:

- Cleared spectrum –128 MHz that will become available for new uses primarily as a result of digital switchover;
- Geographical interleaved spectrum (or Television White Spaces - TVWS) – the capacity available within the spectrum that will be retained for digital terrestrial TV after switchover. **This is known as interleaved spectrum because not all this spectrum in any particular location will be used for digital terrestrial TV and so is available for other services on a shared (or interleaved) basis.** Since the COGEU project is based on TVWS, more details will be given in the next section.

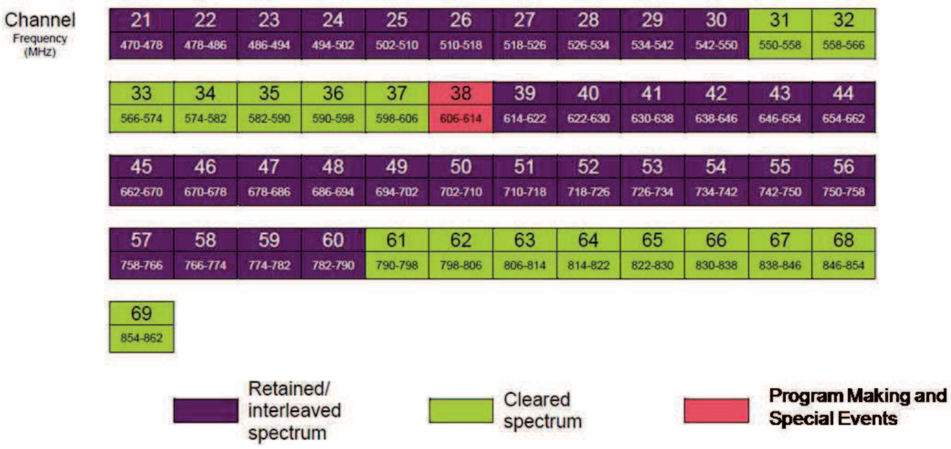


Figure 2.2: Spectrum allocation after the Digital switchover in the UK

Following the UK’s leadership, it is now clear that a growing number of other European countries will release a digital dividend, but within a slightly wider block of spectrum than the UK’s, at 790-862 MHz (the so-called 800 MHz band). For example:

- In Sweden, a governmental decision taken in 2007 came into force on January 1, 2009;
- In Finland, the Government allocated the band 790-862 MHz to digital broadband mobile networks; the decision came into force on July 1, 2008;
- In France, the government announced the allocation of the 790-862MHz band to digital broadband mobile networks; with auctions/beauty contest announced for 2009.

As Finland, France and Sweden have already decided to release this wider block of spectrum of 72 MHz, a number of other countries are expected to do likewise. On the other hand, the European Commission is under consultation on how to harmonize the realization of the digital dividend over the whole of Europe so as to avoid fragmentation in terms of policies among member states [3][5][6][7][9].As we have seen above, the Ofcom on its part is already aligning its digital dividend to the 72 MHz wider block so that devices can operate all over member states.

For the European Commission, the Digital Dividend (Cleared spectrum and geographical interleaved spectrum) constitutes a great opportunity to realize significant elements of the EU Lisbon strategy, e.g. providing significant improvements in mobile broadband, multimedia and Internet access. **The COGEU project aims the efficient exploitation of the geographical interleaved spectrum (also called TVWS).**

2.2.3 TVWS or geographical interleaved spectrum

2.2.3.1 CEPT definition

The European Conference of Postal and Telecommunications Administrations (CEPT) identifies white space as a part of the spectrum, which is available for a radio-communication application (service, system) at a given time in a given geographical area on a **non-interfering non-protected basis** with regard to primary services and other services with a higher priority on a national basis [9].

The interleaved spectrum or TVWS arises because in a multiple frequency network any television channel is carried on a number of different frequency channels around the service area. On any given frequency channel there will be a geographical zone where use for high-power broadcasting is not possible because of the interference it would cause, but use for low\moderate power applications is possible, provided these are carefully designed so as to be compatible with the primary users DTV and other secondary users such as PMSE (Programme Making and Special Events).

As shown inFigure 2.3, the coverage area between broadcast services defines the white spaces that could be exploited by a cognitive radio network. According to the Geneva 2006 frequency plan (GE06), the majority of the European countries within CEPT obtained seven nationwide coverage for DVB-T in Bands IV/V and one DVB-T coverage in Band III. Figure 2.4 gives illustration of the availability of TVWS across Europe by showing the map of envisage DVB-T plan in UHF channel 21 (GE06), the white spaces are the areas without coverage and potential beneficiaries of the COGEU project results.

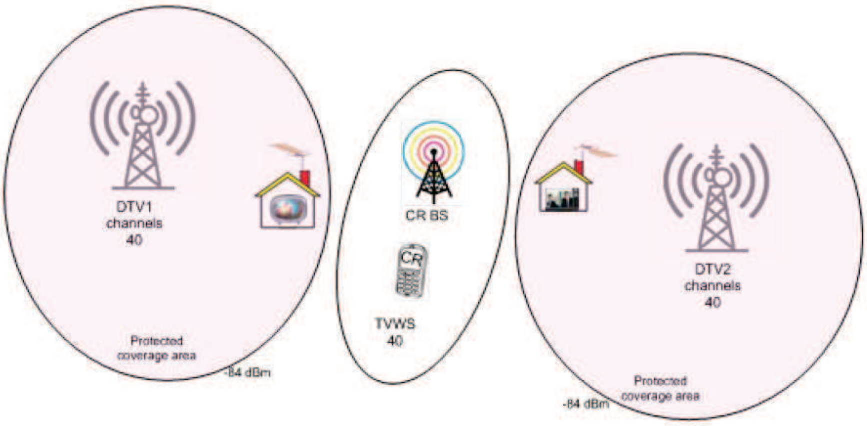


Figure 2.3: A Cognitive Radio network operating in a Television White Space (channel 40)

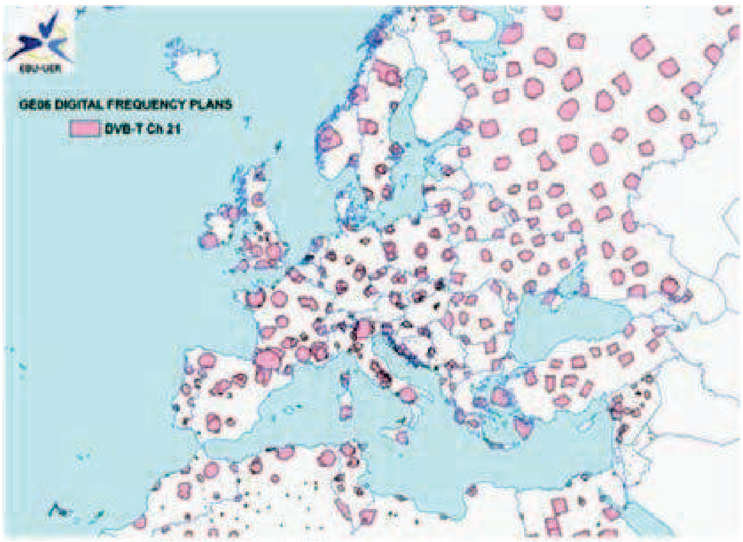


Figure 2.4: Map of DVB-T plan entries in UHF channel 21 in Europe and neighbouring countries [10]

2.3 General overview of incumbent systems in TV bands

The Band 470 – 790 MHz where potential TVWS may exist is currently used by several applications:

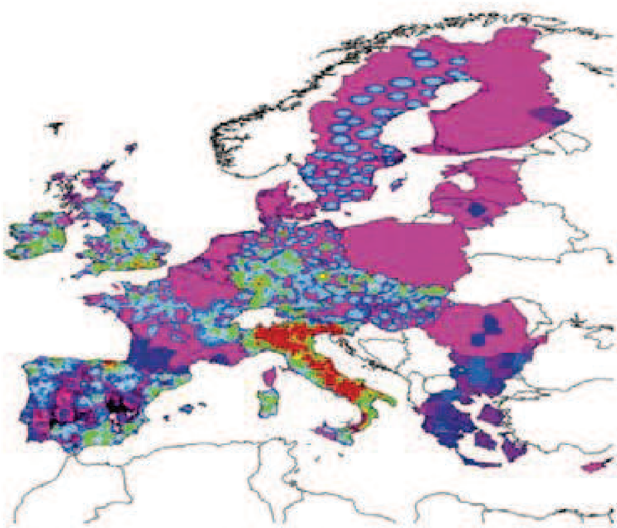
- Broadcast services
- PMSE Application

2.3.1 Broadcast services

The main usage is of course Digital terrestrial television based on DVB-T standard. In general, the transition to the digital terrestrial is well advanced and is completed in several countries. Three categories of countries can be defined:

- Countries which have already switched off analogue television;
- Countries which have started to switch off analogue television;
- Countries which will soon start to switch off their analogue transmissions.

In conjunction with this switch over process, there is the transition process towards the target GE06 plan. During the RRC-06 which established the GE06 plan the countries obtained 7 – 8 DVB-T so called layers. A layer is a network of frequency channels in order to obtain a nationwide coverage. From the GE06 plan one can easily estimate that an average frequency reuse factor of less than 7 characterizes the DVB-T usage scheme for MFN (Multiple Frequency Networks). In this configuration adjacent transmitters use different channels for broadcast the same content. In MFN frequency reuse is restricted by large safety distances to avoid interference between the transmitters using the same frequencies. Most of European countries use MSF as their standard which, for the case of analogue transmission is the only way to build a broadcast network. Figure 2.5gives an idea on the number of multiplexes after the GE06 plan:



Red indicates the maximum number of multiplexes in a given area and progressing through orange, yellow, green, blue, violet and black as the number of multiplexes reduces

Figure 2.5: Number of multiplexes obtained at the RRC06. (Source: EBU)

For digital transmission, MFN is not the only way as the characteristics of transmission system (guard bands which help to compensate different propagation times) also allows building up SFN (Single Frequency Networks). Within a SFN it is possible to cover larger areas (even a whole country) with the same channel for one multiplex. SFN also require less transmit power because possible signal fading can be compensated by an adjacent transmitter in the SFN. One limiting factor for the size of a SFN is the requirement for regional or even local TV programs. As programs are not transmitted separately but instead put together into multiplexes, SFN are limited in size by the coverage of the regional and local TV programs. Some European countries, e.g. Germany and Italy operate Single Frequency Networks. As an indicator, Table 2.2 gives some typical parameters of DVB-T operation:

Table 2.2: Typical parameters of DVB-T operation

16 QAM 2/3, fixed reception, ITU-R P 1546-3 (different antenna heights)	*Typical power*	*Coverage radius*
Full power transmitter (digital TV)	~100 kW	~80 km
Low power transmitter	~1 kW	~25 km
DVB-T repeater station	5-20 W	~7 km
Single Frequency Network	-	Up to countrywide
Full power transmitter (portable indoor)	~100 kW	~20 km

In parallel to the digital switchover, there are re-planning activities for the release of the 790 – 862 MHz spectrum which will intensify the usage of the band 470 – 790 MHz. Some countries will give up (parts of) layers while others will (try) to reconstruct the losses in the layers.

Moreover, there is an on-going process in some countries to negotiate additional resources for DTT enhancements like HDTV, or additional services. Additionally, it is expected that additional resources will be needed for the DVB-T2 simulcast. Another usage is the mobile television based on DVB-H. Although mobile television based in broadcast technology has not shown the expected success yet, there have been re-planning activities in order to reserve resources for mobile TV. In some countries the service has started whilst in other countries, there are still several open issues pending prior to a launch of service.

2.3.2 PMSE Applications

The band 470 – 790 MHz is further used for PMSE services on a secondary basis (non-interference to and non-protection against broadcast services). The PMSE services are Programmer Making and Special Events. It includes transmission of speech, music and/or pictures in the environment of news reports, productions and technical services. The transmission can be between a mobile transmitter and fixed receiver, a mobile transmitter and a mobile receiver or a fixed transmitter and a fixed receiver. More precisely, in the band 470 – 790 MHz the following applications are in use:

- In-ear monitors;
- PWMS;
- Professional cordless camera/Mobile airborne video links;
- Engineering link/Telecommand;
- Remote control;

- Temporary point to point audio link;
- Temporary point to point video link;
- Mobile audio link;
- Mobile vehicular video link;
- Talkback.

The usage scheme and the licensing regime vary importantly across Europe. This is among others due to the following:

- Countries with the PAL B, G, H, D, K, system used a 7 MHz in an 8 MHz channelization band plan, so that the 1 MHz gap became a candidate for additional PMSE usage. In these countries the usage of the TV Band developed more than in other countries with 8 MHz analogue TV standards;
- In some countries the higher frequencies were reserved for military applications (Germany e.g.), so that coexistence between Professional Wireless Microphone Systems (PWMS) and military applications became possible and the band was opened for PWMS as a general authorization. Following SE43 definition, PMSE equipment in the UHF band covers professional wireless microphone systems (PWMS), talk back systems and audio links. As Table 2.3shows, in the higher bands of UHF, above 790 MHz, only PWMS is allowed. As a consequence, the band 790 – 862 MHz became intensively used by PWMS. For example, in Germany the number of PWMS operating in the band 790 – 862 MHz is estimated around 600 000;
- The licensing regime was different and the devices aren't widely tuneable.

Table 2.3summarizes the usage scheme for Germany.

Table 2.3: Overview on the spectrum usage scheme for SAP/SAB applications in the band 470-862 MHz for Germany

Application	Frequency range	TV-channel	Max. ERP (Watt)	Max. RF-Band-width (kHz)
Temporary point to point audio link	470 - 606 MHz	21 – 37 (only 1 MHz-Gap)	250	300
Temporary point to point audio link	614 - 790 MHz	39 – 60 (only 1 MHz-Gap)	250	300
Talkback	470 - 526 MHz	21 – 27 (only 1 MHz-Gap)	30	20
Talkback	470 - 510 MHz	21 – 25 (only 1 MHz-Gap)	5	50
Talkback	510 - 790 MHz	26 – 60 (only 1 MHz-Gap)	5	50
Professional Wireless	470 - 606 MHz	21 – 37	50 x 10-3	200

Microphones				
Professional Wireless Microphones	614 - 790 MHz	39 – 60	50 x 10-3	200
Professional Wireless Microphones	790 - 814 MHz	61 – 63	50 x 10-3	200
Professional Wireless Microphones	838 - 862 MHz	67 – 69	50 x 10-3	200

In Germany, professional wireless microphones in the band 790 – 862 MHz have a general authorization. Below 790 MHz there is always a need for a license award, so that the possible interference to DVB-T is fully controlled and limited.

In Eastern Europe (e.g. Russia, Belarus), there is an additional primary allocation for aeronautical radio navigation services (ARNS) in the band 645 – 862 MHz. During the RRC-06 negotiations, the protection of these services led to some constraints regarding DVB-T transmissions. With the introduction of mobile services in the band 790 – 862 MHz there are still negotiations and constraints in order to protect the aeronautical navigation service. Finally, the radio astronomy on channel 38 (608 – 614 MHz) is in use in several countries or part of the countries, it has to be protected.

From the description of the frequency usage in the band 470 – 790 MHz, it can be concluded that the spectrum usage is dynamically evolving and that a regular update of the channel usage is necessary. The available resource for white space usage is unknown and may differ strongly from country to country as well as locally.

2.4 Overview of TVWS availability in Europe

For the COGEU project to be successful, the ability to quantify the availability of TV white spaces is important in both developing white space devices and also protecting incumbent systems. The guiding parameters in quantifying the number of available white spaces in a given location are the interference limitation thresholds set to protect incumbent system and the transmission power of cognitive radio devises. Moreover, the geographical pattern for the availability of TVWS is affected by factors like wireless signals propagation properties like shadowing, fading; as well as station/device design factors such as antenna pattern, maximum transmission power, etc.

The result of quantifying the available TVWS is information to help a secondary-market or commons spectrum user to operate without causing interference to incumbent systems. Specifically, in case where channels are available in a given geographical location, the results help the TVWS system to determine how much transmit power to use, and also what kind of modulation to use depending on the closeness or sparseness of available channels, i.e., whether contiguous or non-contiguous respectively.

2.5 Summary

This subsection resumes the main results of the estimation of TVWS availability.Countries where the use of a single frequency terrestrial network (SFN) is planned, white spaces can be found outside the boundaries of the SFN. Also, the different content requirements of regions and counties means that such networks need to be partitioned and suitable gaps left between those using the same frequency.

Typically the TVWS are more abundant in rural areas, with larger contiguous blocks of unused channels available, as broadcast network planning priorities are linked to population density. In areas with high population density the TVWS are more fragmented. Also, database coordination of white spaces combined with spectrum sensing is a most promising technique, as compared with spectrum sensing alone.

Even with the introduction of new services by broadcasters, TVWS will not disappear. This persistence is due to the DTV planning around relatively inflexible “high power- high tower” distribution networks. Whilst roll-out and operating costs may be lower with such sparse networks, they impose a cost in terms of spectrum efficiency that can be used as an opportunity for TVWS devices.

Chapter 3

3 COGEU transceiver platform specification

This chapter is dedicated to describe the prototype specifications. Here is present a review of the state of the art related to TVWS prototyping presenting some samples. It is present a description of the architecture of the prototype the hardware and software.

3.1 State of the art

TVWS is an important and current topic that has motivated research worldwide. Prototyping is part of this demand, since it is important to demonstrate the concepts and algorithms that result. .In the following sub-sections are present some cognitive radio prototypes for TVWS.

3.1.1 KNOWS prototype

The KNOWS project [11]is a collaborative industry effort (including Microsoft) toward building a prototype CR device for TVWS application in the USA. The device itself has three components: a host computer, a spectrum scanner, and a frequency translator between the 2.4 GHz industrial, scientific, and medical (ISM) and 512–698 MHz UHF bands. The host maintains the control plane, and contains the implementations of the MAC and higher layer protocols. It is equipped with a standard WiFi card, and the translator down converts the output signal to the UHF band and vice versa for the incoming signals. As each channel is defined as 6 MHz wide, the channel bandwidth of the output signal is limited to 5 MHz so that they can be contained within the standard UHF TV channels 21–51. However, these individual channels can be aggregated to form 5, 10, 15, and 20 MHz channels when contiguous channel vacancies are detected in the UHF band. The spectrum scanner is implemented in a USRP board [12]having a 50–8600 MHz TVRX receiver-only daughter-board. The scanning is set to intervals of 30 seconds, as the TV transmissions are unlikely to exhibit sudden fluctuations. Apart from these main components, the KNOWs platform also has a GPS module in the event that a database of the locations of TV stations and transmission towers is available. The platform also includes an x86 embedded processor that controls the radios, obtains MAC layer control packets from the host, and parses them into instructions for configuring the RF hardware, and conversely, aggregates the raw received signals into packets that can beoperated on by the host [13].

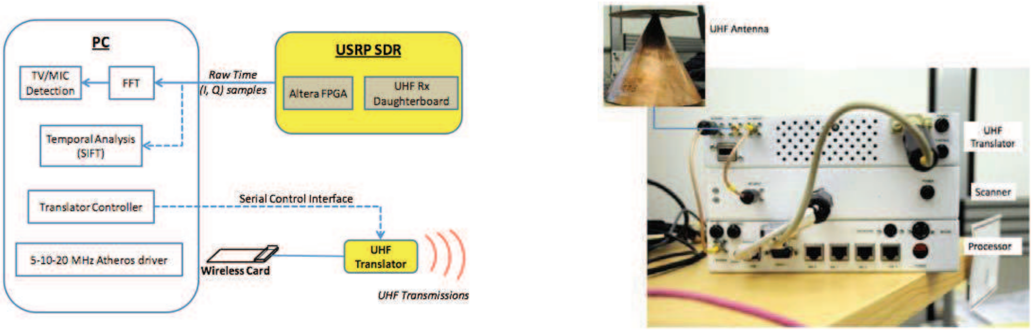


Figure 3.1: Functional block diagram of the KNOWS platform and hardware prototype [11].

3.1.2 ETRI prototype

South Korea Electronics and Telecommunications Research Institute – ETRI [14] developed a UHF band CR platform based on ECMA-392 international standard. ECMA-392 standard defines the MAC and PHY for operation in TVWS for communication between portable devices. Although the complete functionalities of the ECMA-392 standard are not implemented, experimental demonstration shows that the testbed system operates in lines with the FCC rules. A demonstrator with two CR devices was tested to transmit data in the presence of primary user signals, like ATSC (US DTV standard) and wireless microphones.

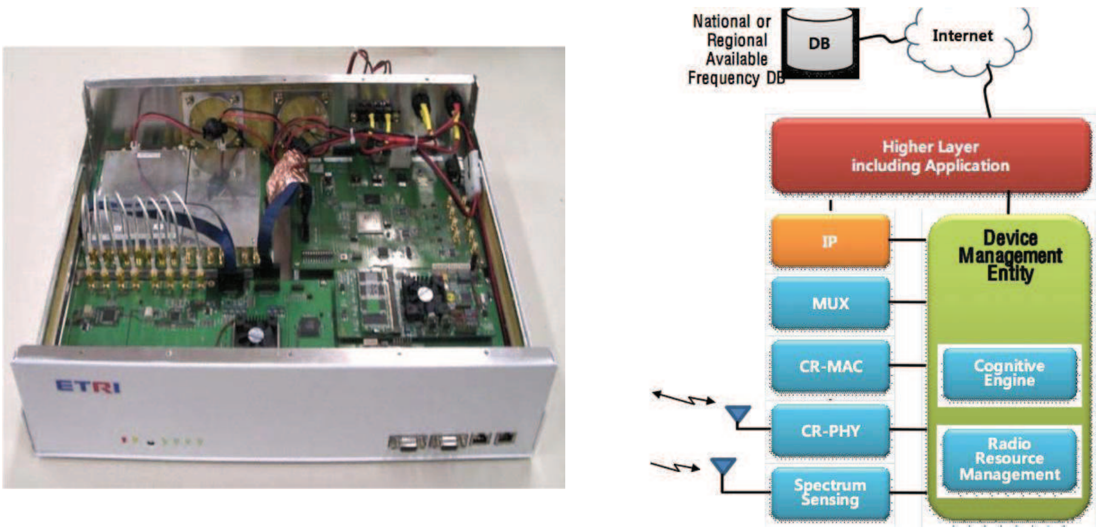


Figure 3.2: Hardware prototype and protocol architecture of the ETRI CR system [14].

3.1.3 MOTOROLA prototype

Motorola tested a prototype of a Cognitive Radio System using IEEE 802.11a MAC over UHF TVWS [15]. The Cognitive Radio Network consists of a Cognitive Access Point (that performs in-band and out of band sensing) and Cognitive Mobile Stations. The Cognitive Engine is designed to be agnostic of the underlying MAC and PHY. A Geo-location based approach for detecting incumbents like DTV, assisted by spectrum sensing, is also implemented. The system includes a Cognitive Engine Protocol for channel resource control between the Cognitive Access Point and Cognitive Stations. A GUI is present on the Cognitive Access Point, to portray the actions occurring in the Cognitive Engine (CE) with respect to spectrum sensing and channel status detection during each scan period in terms of numerous events.

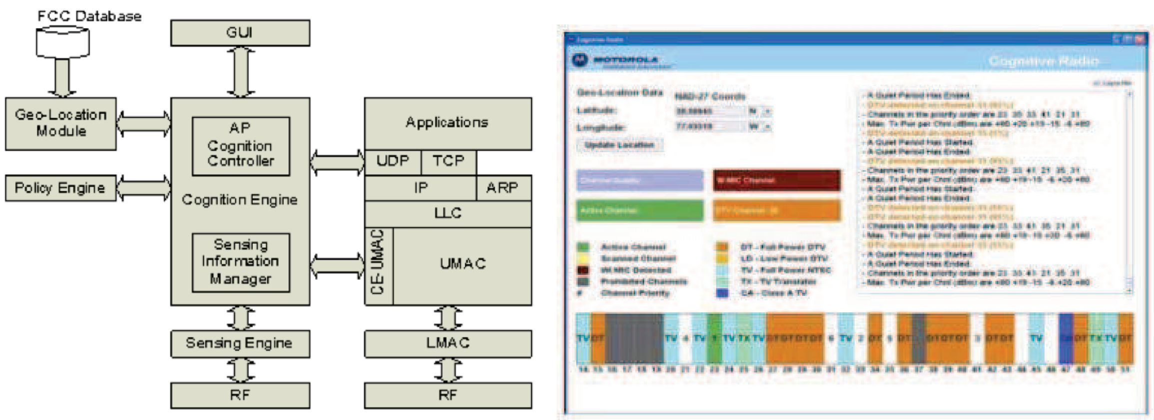


Figure 3.3: Cognitive access point architecture and cognitive radio GUI [15].

3.1.4 I2R prototype

Institute for InfocommResearch - I2R [16] as developed a TVWS device that has received approval for further development by USA's Federal Communications Commission (FCC).Figure 3.4 shows the main a block diagram of the device. I2R's device displayed a consistent ability in sensing digital TV (ATSC format) signals' occupancy and un-occupancy using spectrum sensing technique in actual field tests. For wireless microphone field tests, I2R's device was able to detect the wireless microphone transmissions during the live performance / game test while correctly identifying some unoccupied channels. Some of the main characteristics are of the CR prototype are:

- Signal detection sensitivities: -114dBm ~ -125dBm
- Supported frequency range: 48MHz ~1000MHz
- Channel raster: 25kHz
- Supported signal type: DTV (ATSC-8VSB), Wireless microphone

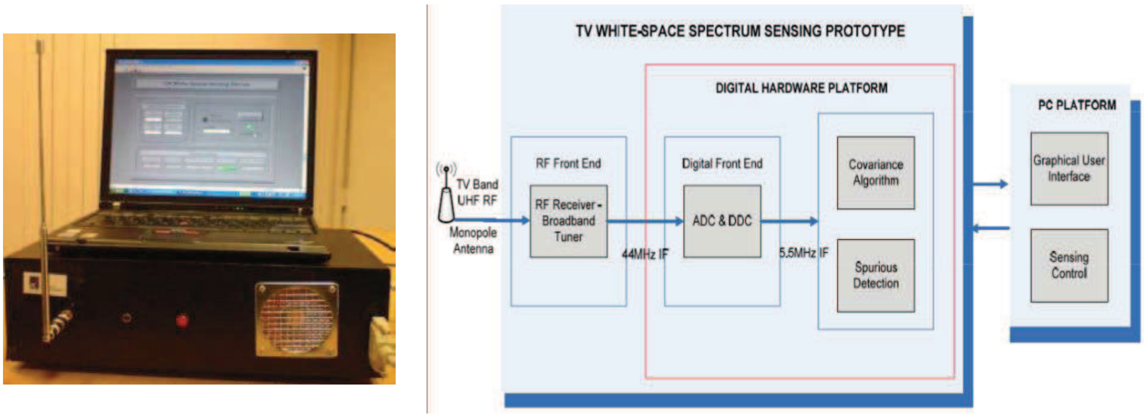


Figure 3.4: Prototype of I2R TVWS and architecture [16]

3.1.5 SAMSUNG prototype

The purpose of the CR platform proposed by SAMSUNG [17] is to evaluate the feasibility of the unlicensed wireless service in the UHF TV band. The platform consists of RF, baseband modem and MAC, including spectrum-sensing function. The performance of the spectrum sensing function combined with wideband RF IC that is designed for mobile broadcasting service in multiple bands is presented.

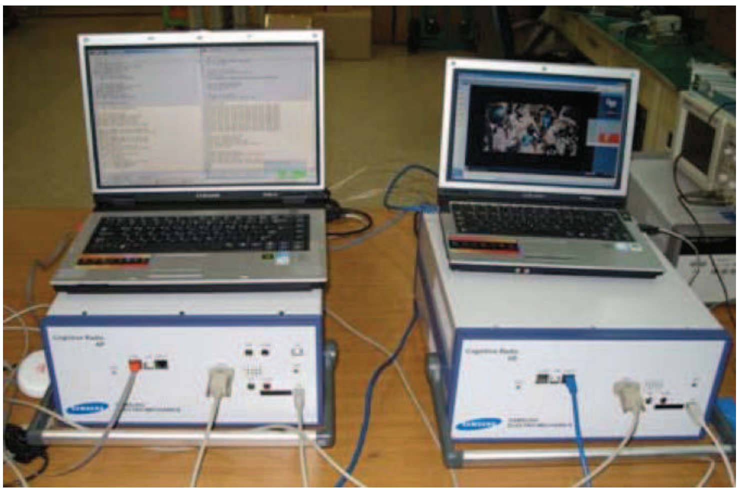


Figure 3.5: Cognitive radio platform under test [17].

3.2 COGEU TVWS Transceiver Platform Architecture

The purpose of the COGEU TVWS radio transceiver is primarily to facilitate the development, evaluation and demonstration of a range of novel algorithms and techniques that will enable cognitive radio devices to efficiently exploit geographically interleaved TV spectrum. As such, the COGEU TVWS is a prototyping platform, not a production platform. Its primary aim is to provide a basis for the ready development of novel techniques and novel systems.

It will serve to prove the viability of a number of key concepts whose feasibility is critical to the potential deployment of cognitive radios in the European TVWS. The COGEU TVWS transceiver will be based upon a software defined radio (SDR)-based architecture as this approach enables the rapid development and evaluation of novel techniques at low cost. The next subsection discusses the merits of reconfigurable component-based SDR architectures, paying particular attention to the manner in which they facilitate the creation of highly reconfigurable radios which can be used for cognitive radio experimentation. An overview of the COGEU TVWS transceiver is presented in the following subsection.

3.2.1 Reconfigurable Component-based SDR Architectures

One of the key motivations for the use of a software radio-based architecture is the flexibility which is afforded by the use of general purpose processor (GPP) platforms, and indeed other programmable processing fabrics such as field-programmable gate arrays (FPGAs). Elements of a radio that are implemented in software can be readily reconfigured, at varying levels of granularity, in a dynamic manner. When the software radio is enhanced with software-implemented controlling mechanisms, the inherent reconfigurability of the software radio can be harnessed to enable the exploration of concepts such as dynamic spectrum access and cognitive radio networks.

3.2.1.1 Software Defined Radio SDR

A Software Defined Radio (SDR)is a communication device whose operation is controlled by software. One most significant implication at the physical layer is the hardware in a robust SDR design requires extensive flexibility and high performance over a wide range of operating parameters in order to answer the demands of the software.More and more RF devices are being designed for software control, which changes the design requirements and introduces the need for new testing methodologies. In addition to network control of the operating frequency, more advanced SDRs allow dynamic control of modulation scheme, frequency hopping patterns, power levels, filtering, coding schemes and data rates. This added complexity presents not only RF design challenges, but also changes the nature of RF testing. Software now defines analogue/RF performance testing and continued analogue/RF test must be considered for software regression testing in addition to physical layer testing performance. Traditional transmitter tests, for example, measure power, modulation, spectrum occupancy, and interference steady state quantities. RF testing must be an integral part of SDR testing.

Compared to tradition RF transceivers technologies, SDR is advantageous because it offers increased flexibility. SDR provides the ability to reconfigure key system performance and functions on the fly.

The typical SDR architecture can be broken into two main conceptual components; the baseband processor and the RF-frontend. In simple terms, the baseband processor is responsible for the generation of waveforms to be transmitted and the analysis of waveforms which have been received, downconverted and digitized by the RF front-end, Figure 3.6.

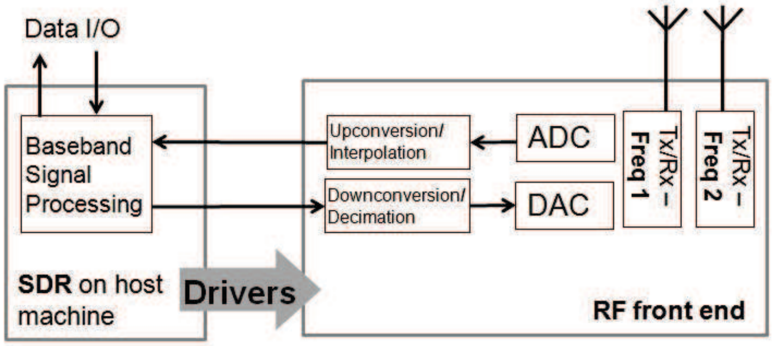


Figure 3.6: Basic SDR architecture[35].

SDR architectures offer a number for benefits when it comes to prototyping novel radio systems. All of these benefits revolve around the fact that by removing as much of the hardware of the radio as possible, i.e. moving the software element as close to the antenna as possible, one can easily manipulate radio waveforms using sophisticated mathematical techniques, many of which could not be easily or readily implemented in hardware. But at its core, a SDR enables three key design objectives, component-based design, reconfiguration and cognitive control:

- **Component-based design:** When a system, regardless of its application, is implemented in software rather than hardware it is immediately clear that it can be manipulated far easier than a hardware-based system could be. Software reduces a system to byte and bit-based structures which can be easily manipulated, created and destroyed. As long as elements of the system in question, i.e. a radio, can be modelled and represented in software then the power of software engineering can be unleashed on the system's design. A radio system, when described using a block diagram schematic can already be seen as comprised of a series of discrete components, i.e. filters, modulators, mixers, etc. Each component is linked together in a directed graph, each component being of vertex of such a graph. Such a system readily lends itself to being modelled in software. Each discrete component, which processes an incoming signal and passes it on, can be implemented as an individual software element or, as is commonly said, a component.
  Such a component-based, modular approach to the development of a radio has a number of advantages. Components can be developed by separate developers, can be reused and can be unit-tested. The benefits of object-oriented programming can be applied to a component-based architecture.

- **Reconfiguration**: While radio components are the basic building blocks of a SDR radio, the correct sequence of components must be connected in software for a radio to operate. In simple terms, a basic radio can be assembled by combining radio components to form two chains; a radio receiver chain and a radio transmitter chain. However, the power of the SDR approach to radio design is that these chains of components can be manipulated by software, i.e. components can be replaced, and modified or new components can be inserted. A SDR that can reconfigure the way in which its basic radio components are linked together meets the basic requirements of a radio suited to a dynamic spectrum access environment in which the challenges faced by the radio or the radio applications required may change over time. That said, the exact manner in which a radio can be reconfigured depends on design choices made by the architects of the SDR systems. As radios are systems that generally operate on a continuous basis, providing uninterrupted communication links for their users, the SDR architecture must carefully manage the transition from one radio instantiation to another.
- **Cognitive control**: A reconfigurable radio is one of the basic building blocks of a cognitive system. Cognitive radios are designed to observe their environment, decide on a course of action which optimises their use of spectrum (or some other objective), and act on that decision by changing some parameter of the radio to meet the objective. Reconfigurable radios offer a controlling cognitive entity, wherever it may be located, within the radio or in a centralised base-station, a range of options and parameters which it can optimise. Cognition is not possible in the absence of a reconfigurable system.

SDR systems can be used to verify theory-based research and have been demonstrated at a number of key international conferences on cognitive radio and reconfigurable radio systems. Modern radio communication standards and protocols feature increasing flexibility and reconfigurability as designers strive to use the resources available in the most efficient manner possible. From the self-organization and coexistence capabilities required by 3GPP LTE femtocells to the dynamic spectrum access of emerging cognitive radio standards such as IEEE 802.22, the ability of network nodes to examine the operating environment and reconfigure accordingly is becoming more and more important. The fact the bulk of the waveform processing happens in software makes SDR systems ideal for experimentation and prototyping; once a novel theory or concept has been demonstrated on a SDR it may be more economically sound to commit the concept to hardware.

One of the key enablers of the SDR is the processor fabric on which the baseband waveform processing software is executed. The range of baseband processing platforms ranges from application-specific integrated circuits (ASICs), through field programmable gate arrays (FPGAs) to digital signal processors (DSPs) and general purpose processors (GPPs). However, the key criteria for choosing one suitable for adoption as the baseband processor of an OFDM-based SDR platform is the speed and flexibility with which the novel transceiver systems can be prototyped and tested.

It is not a clear cut choice as to which should be chosen; rather there are a number of variables to be accounted for. Factors such as experience with the use of certain processors, the learning curve associated with each and the development tools available for those platforms should be considered. Furthermore, the performance of the SDR will depend on the processing power of the platform; dictating the bandwidth of signals that may be successfully generated and analysed in real-time. Also, in additionto being able to perform experiments on live signals, in real-time, the ability to store and process signals of interest offline may also be of interest. Lastly, the ease or difficulty with which the baseband processor can be integrated with the RF front-end must be considered.

The COGEU SDR transceiver is focussed on cognitive functionality, i.e. it is a platform which will enable the development of a radio system that can intelligently avoid the incumbent users of DTV spectrum. Cognitive systems, in addition to being defined in terms of their *smart* capabilities, i.e. being able to observe, decide and act, are also defined as radio systems which are feature-rich, i.e. the radio should have access to a suite of components so that it can make choices about what techniques to use and when to use them. A cognitive radio should be able to reconfigure its system components and the parameters of those components. SDRs are often cited as ideal platforms for cognitive radios as, if the right platform, i.e. baseband processor, is chosen, it is relatively easy to manipulate and reconfigure a complex radio system in software [18]. The flexibility afforded by GPP platforms allows for a level of adaptability and reconfiguration which cannot easily be achieved using the other systems; since all of the baseband processing is done in software it is easy to adapt the cognitive radio system on-the-fly, i.e. at run-time [19][20].

So, the speed and flexibility of prototyping are identified as key requirements for the choice of a prototyping platform. The available processing power and the ease with which the baseband processor can be integrated with the RF front-end are also important considerations. From the perspective of speed and flexibility, GPP-based systems provide significant advantages over alternative platforms as they may be programmed using a variety of high-level languages for which there are a wide range of development tools available. Platforms based on ASICs, DSPs or FPGAs, generally require much more specific knowledge of the low-level operation of the fabrics and, when compared to GPPs, there are far fewer tools available for the development of software applications that can run on them. Economies of scale tend to mean that there are more choices and more competition when it comes to selecting tools to develop programs targeted to GPPs. Oftentimes, high-level coding tools, of good quality, are freely available. This is seldom the case with fabrics such as FPGAs which do not use common high-level programming tools.

The use of integrated development environments (IDEs) provides key capabilities such as code debugging and performance profiling which help a radio developer to implement, test and optimise key radio algorithms. Critically, for the radio developers trying to get up to speed with the necessary skills to implement a radio transceiver, high-level programming languages reduce the steepness of the learning curve.

One limitation of using GPP-based baseband processor is that real-time operation is not absolutely guaranteed. The time taken to complete certain instructions, i.e. process a given data set, may vary over a number of iterations as the GPP system architecture involves the use of native thread schedulers, memory controllers and other functions which operate outside the control of the SDR running on the GPP. These processor-native functions may switch the allocation of processing resources amongst competing algorithms operating on the processor. Such a variation in execution time would not typically occur on a FPGA or DSP-based platform as the resources are dedicated to specific algorithms. Consequently, at design time it is necessary to factor in sufficient extra resources, i.e. processing time, so that such variations do not compromise the real-time operation of the SDR. Another limitation of the GPP-based processor is that of power consumption; typically the power required on a GPP is much higher than that on a FPGA or DSP-based implementation of the same radio system. As such GPP-based platforms may not be suitable for power-critical applications. However, as a rapid prototyping platform for novel cognitive radio system concepts power consumption should not be a consideration.

That said an advantage of the GPP-based approach is that there is an ever increasing range of such platforms available. Increasingly, the trend in GPP platforms is away for high processing-power single cores towards multi-core systems. Radio developers can leverage the power of parallelisation in their radio applications, thereby increasing the baseband processing power of their implementations. Also, the advent of advanced processor architectures designed for high speed vector processing greatly increases the possibility for the design of high data rate baseband processors running algorithms implemented using high-level programming languages. An example of such architecture is the Cell Broadband Engine.

3.2.2 COGEU TVWS Transceiver Architecture

This section presents an overview of the architecture which will be used to develop the COGEU TVWS radio transceiver platform. The basic form of the COGEU TVWS radio transceiver platform consists of 3 elements[35]: a software-based cognitive radio which will use the IRIS, GNU or other software Radio systems, a RF-frontend which will allow for access to the TV frequencies of interest and interfaces that will enable the radio to communicate with external controlling entities.

The cognitive SDR will enable COGEU to demonstrate novel PHY-layer techniques including sensing algorithms, spectrum shaping algorithms and advanced rendezvous techniques. These key elements of the COGEU project will serve to demonstrate that TVWS radio devices can be developed which can *safely* and *efficiently* access the interleaved DTV spectrum. The interfaces to external entities, such as the spectrum broker, will enable the integration of the COGEU transceiver with the broader COGEU reference architectures.

However, the COGEU TVWS transceiver mainly is a tool for development and demonstration, can also be seen as a prototype for future TVWS-capable reconfigurable radio. As such, the COGEU transceiver may be viewed as a potential addition to the suite of existing radio access technologies (RATs) that are commercially available today.

There are many forms in which the cognitive radio functionality developed by the COGEU project may ultimately manifest itself in future TVWS devices. Figure 3.7 depicts a simple TVWS-capable transceiver. This transceiver incorporates a SDR-based implementation of a cognitive radio can access TVWS spectrum coupled with a standard ASIC-based WLAN chip. The SDR-based RAT on this transceiver may implement an OFDM-based standard that has been shown to be compatible for use in TVWS when combined with COGEU-developed algorithms.

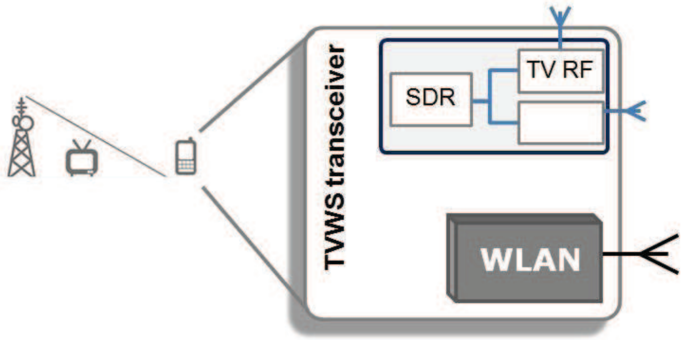


Figure 3.7:TVWS transceiver: SDR and ASIC-based WLAN[35].

Figure 3.8depicts a more feature-rich TVWS-capable transceiver. As with the transceiver in Figure 3.7, this transceiver combines the TVWS-accessing capabilities together with multiple ASIC-based implementations of standards which access other frequencies specifically allocated for those services. On the other hand, the transceiver depicted in Figure 3.9 represents a move towards a full SDR-based transceiver implementation. This reconfigurable transceiver would employ a variety of processing fabrics or differing capabilities, e.g. Cell BE, GPP, FPGA, to facilitate the software-based execution of multiple radio standards, such as those provided for in Figure 3.8using dedicated ASICs, or novel non-standardised radios which could only be developed on reconfigurable cognitive SDRs.

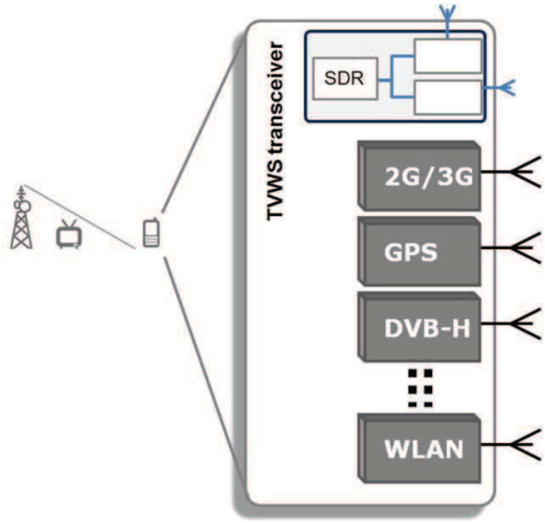


Figure 3.8: TVWS transceiver: SDR and multiple ASIC-implemented standards[35].

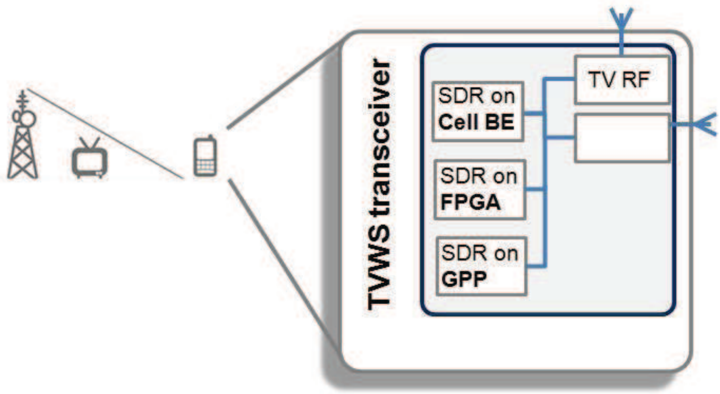


Figure 3.9:TVWS transceiver: All SDR-based implementations of radios[35].

3.3 Software development platform

The sensing module is built in LabVIEW development platform. LabVIEW isdevelopedby National Instruments andcombines a graphical programming language with the capability to create user-friendly user interfaces and the new universal drivers developed by National Instruments make it a preferred choice compared with other software solutions. It offers unrivalled integration with thousands of hardware devices and provides hundreds of built-in libraries for advanced analysis and data visualization – all for creating virtual instrumentation. The LabVIEW platform is scalable across multiple targets and OSs, and, since its introduction in 1986, it has become an industry leader [21]. In next subsections it is present an overview of LabVIEW platform.

3.3.1 Graphical, Dataflow Programming

LabVIEW is different from most other general-purpose programming languages in two major ways. First, Graphical programming (G) is performed by wiring together graphical icons on a diagram, which is then compiled directly to machine code so the computer processors can execute it. While represented graphically instead of with text, G contains the same programming concepts found in most traditional languages. For example, G includes all the standard constructs, such as data types, loops, event handling, variables, recursion, and object-oriented programming.Figure 3.10shows how is represented a while loop, the functions inside are executed until a stop condition is met.

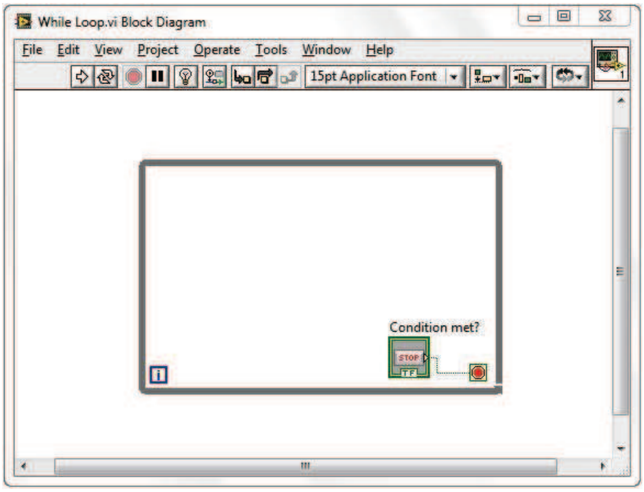


Figure 3.10:A While Loop in G is intuitively represented by a graphical loop, which executes until a stop condition is met[21].

The second main differentiator is that G code developed with LabVIEW executes according to the rules of data flow instead of the more traditional procedural approach (in other words, a sequential series of commands to be carried out) found in most text-based programming languages like C and C++. Dataflow languages like G (as well as Agilent VEE, Microsoft Visual Programming Language, and Apple Quartz Composer) promote data as the main concept behind any program. Dataflow execution is data-driven, or data-dependent. The flow of data between nodes in the program, not sequential lines of text, determines the execution order as despite in Figure 3.11, a node that receives data from another node can execute only after the other node completes execution.

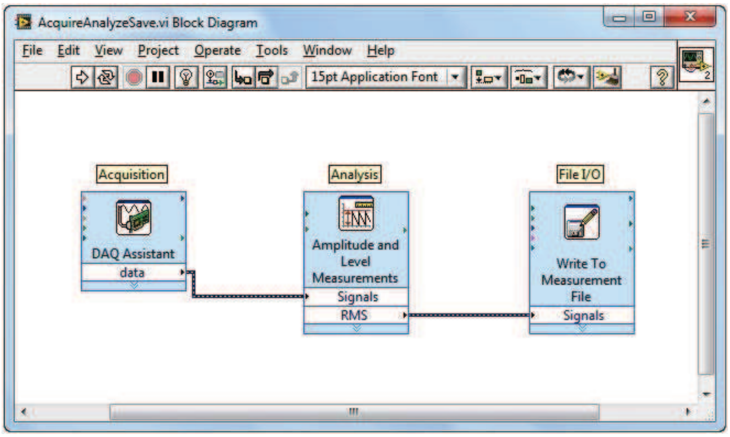


Figure 3.11: Data originates in the acquisition function and then flows intuitively to the analysis and storage functions through wires[21].

3.3.2 Interactive Debugging Tools

Graphical programming with G provides a more intuitive experience.Because LabVIEW graphical G code is easy to comprehend, common programming tasks, like debugging, become more intuitive as well. For example, LabVIEW provides unique debugging tools that you can use to watch as data interactively moves through the wires of a LabVIEW program and see the data values as they pass from one function to another along the wires (known within LabVIEW as execution highlighting, Figure 3.12.

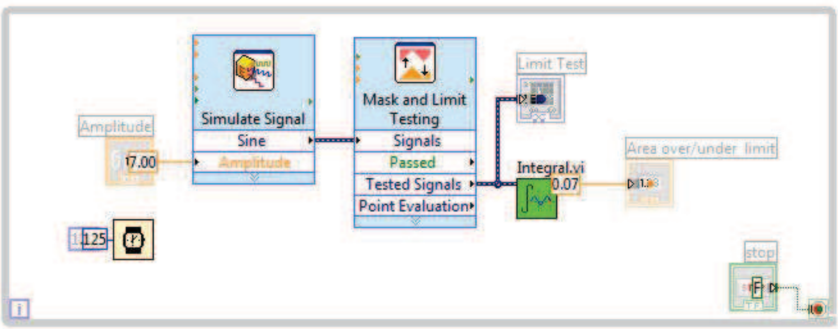


Figure 3.12: Highlight execution provides an intuitive way to understand the execution order of G code[21].

LabVIEW also offers debugging features for G comparable to those found in traditional programming tools. These features, accessible as part of the toolbar for a diagram, include probes, breakpoints, and step over/into/out of, Figure 3.13.

Figure 3.13: The block diagram toolbar offers access to standard debugging tools like stepping[21].

With the G debugging tools, you can probe data on many parts of the program simultaneously, pause execution, and step into a subroutine without complex programming. While this is possible in other programming languages, it is easier to visualize the state of the program and the relationships between parallel parts of the code (which are common in G because of its graphical nature).

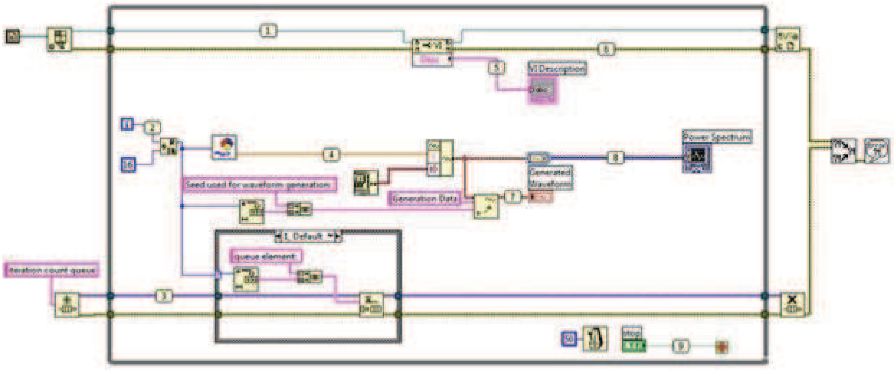


Figure 3.14: Probes are effective ways in LabVIEW to see values traveling on wires throughout the application, even for parallel sections of code[21].

One of the most common debugging features used in LabVIEW is the always-on compiler. While you are developing a program, the compiler continuously checks for errors and provides semantic and syntactic feedback on the application. If an error exists, the program cannot run and appears only a broken Run button in the toolbar, as showed in Figure 3.15.

Figure 3.15: The broken Run arrow provides immediate feedback indicating syntactical errors in the G code[21].

Pressing the broken Run button opens a list of problems that must be address, Figure 3.16. Once addressed these issues the LabVIEW compiler can compile the program to machine code.

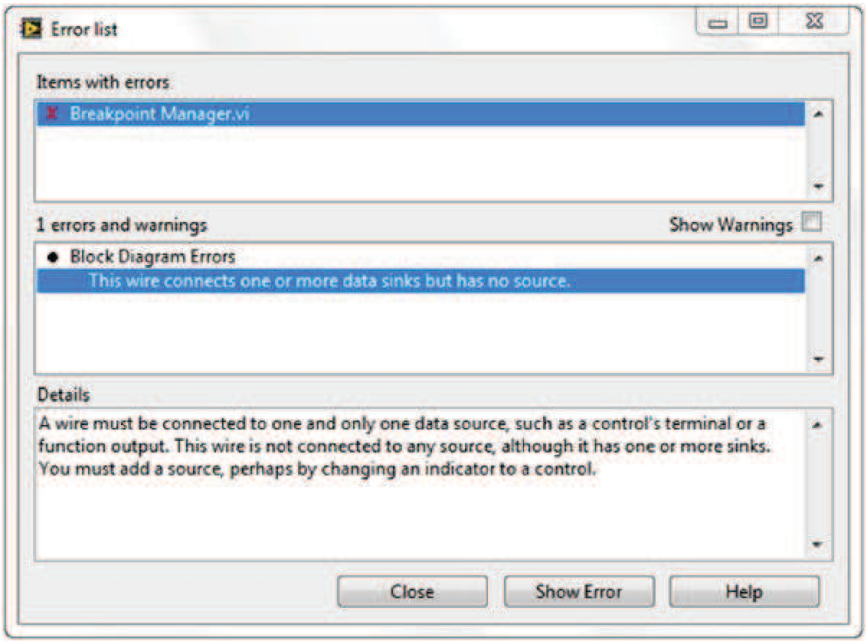


Figure 3.16: The error list displays a detailed explanation of each syntax error in the entire code hierarchy[21].

3.3.3 Automatic Parallelism and Performance

Dataflow languages like LabVIEW allow for automatic parallelization. In contrast to sequential languages like C and C++, graphical programs inherently contain information about which parts of the code should execute in parallel. For example, a common G design pattern is the Producer/Consumer Design Pattern, in which two separate While Loops execute independently: the first loop is responsible for producing data and the second loop processes data. Despite executing in parallel (possibly at different rates), data is passed between the two loops using queues, which are standard data structures in general-purpose programming languages.

Parallelism is important in computer programs because it can unlock performance gains relative to purely sequential programs due to recent changes in computer processor designs. For more than 40 years, computer chip manufacturers increased processor clock speed to increase chip performance. Today, however, increasing clock speeds for performance gains is no longer viable because of power consumption and heat dissipation constraints. As a result, chip vendors have instead moved to new chip architectures with multiple processor cores on a single chip.

To take advantage of the performance available in multicore processors, it is necessary be able to use multithreading within applications (in other words, break up applications into discrete sections that can be executed independently). In traditional text-based languages, it is necessary explicitly create and manage threads to implement parallelism.

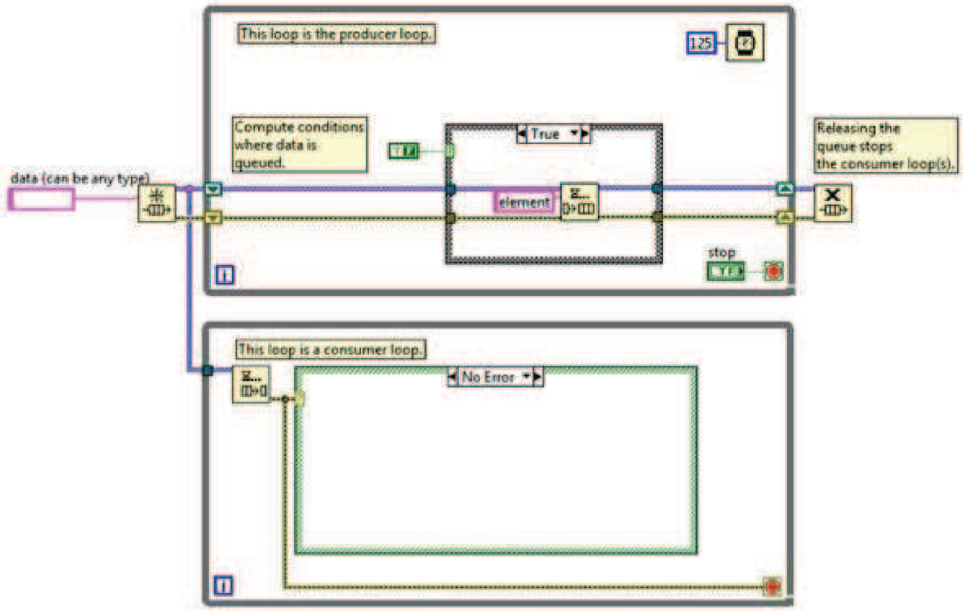


Figure 3.17: The LabVIEW Producer/Consumer design pattern is often used to increase the performance of applications that require parallel tasks[21].

In contrast, the parallel nature of G code makes multitasking and multithreading simple to implement. The built-in compiler continually works in the background to identify parallel sections of code. Whenever G code has a branch in a wire, or a parallel sequence of nodes on the diagram, the compiler tries to execute the code in parallel within a set of threads that LabVIEW manages automatically. In computer science terms, this is called "implicit parallelism" because it is not necessary to specifically write code with the purpose of running it in parallel; the G language takes care of parallelism on its own.

Beyond multithreading on a multicore system, G can provide even greater parallel execution by extending graphical programming to field-programmable gate arrays (FPGAs). FPGAs are reprogrammable silicon chips that are massively parallel – with each independent processing task assigned to a dedicated section of the chip – but they are not limited by the number of processing cores available. As a result, the performance of one part of the application is not adversely affected when more processing is added.

Historically, FPGA programming was the province of only a specially trained expert with a deep understanding of digital hardware design languages. Increasingly, engineers without FPGA expertise want to use FPGA-based custom hardware for unique timing and triggering routines, ultrahigh-speed control, interfacing to digital protocols, digital signal processing (DSP), RF and communications, and many other applications requiring high-speed hardware reliability, customization, and tight determinism. G is particularly suited for FPGA programming because it clearly represents parallelism and data flow and is quickly growing in popularity as a tool of choice for developers seeking parallel processing and deterministic execution.

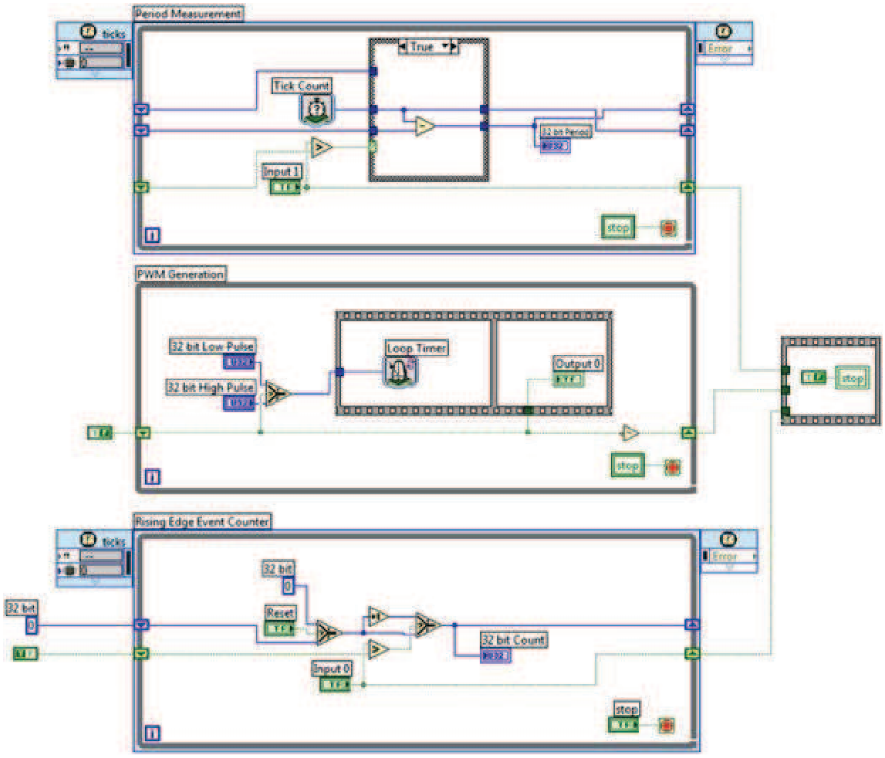


Figure 3.18: LabVIEW FPGA code with parallelism becomes truly independent pathways on the FPGA silicon[21].

3.3.4 Combining G with Other Languages

While G code provides an excellent representation for parallelism and removes the requirement on developers to understand and manage computer memory, it is not necessarily ideal for every task. In particular, mathematical formulas and equations can often be more succinctly represented with text. For that reason, it is possibleuse LabVIEW to combine graphical programming with several forms of text-based programming. For example, LabVIEW contains the concept of the Formula Node, which evaluates textual mathematical formulas and expressions similar to C on the block diagram. These mathematical formulas can execute side by side and integrate with graphical LabVIEW code.

Similarly, the MathScript Node adds math-oriented, textual programming to LabVIEW that is generally compatible with the commonly used .m file syntax, as showed in Figure 3.20.

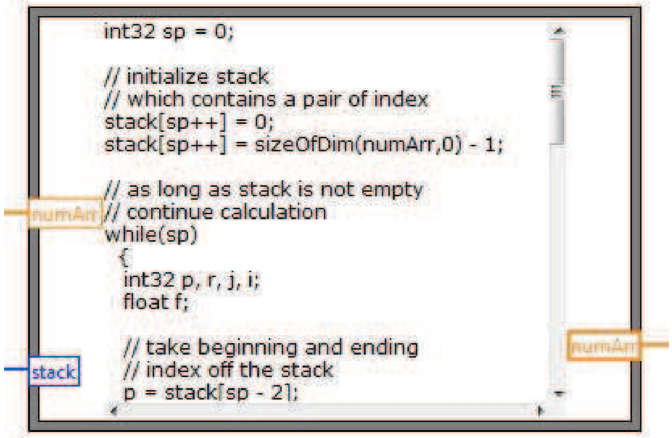


Figure 3.19: The Formula Node uses syntax similar to C to represent mathematical expressions in a succinct, text-based format[21].

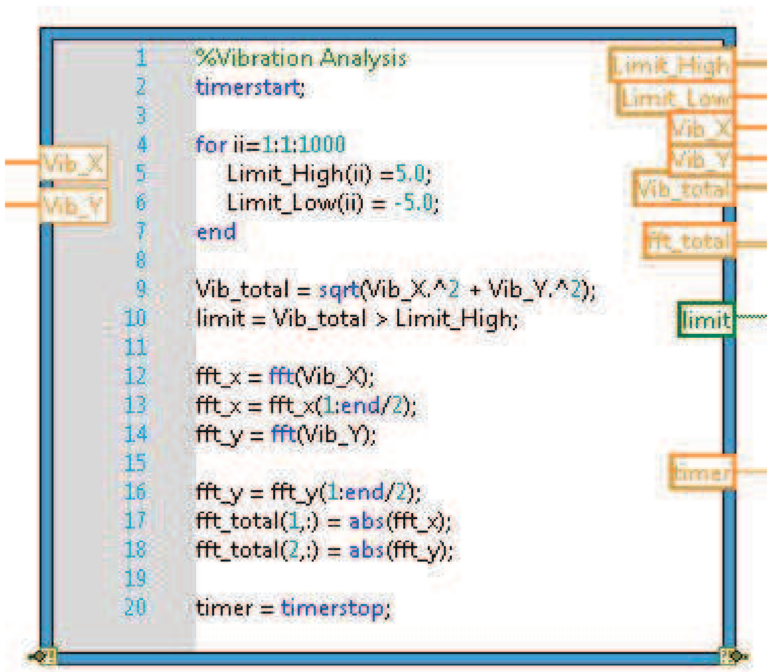


Figure 3.20: With the MathScript Node[21]

3.3.5 NI LabVIEW Data Visualization and User Interface Design

NI LabVIEW contains a comprehensive collection of drag-and-drop controls and indicators so you can quickly and easily create user interfaces for your application and effectively visualize results without integrating third-party components or building views from scratch.The quick drag-and-drop approach does not come at the expense of flexibility. Power users can customize the built-in controls via the Control Editor and programmatically control user interface (UI) elements to create highly customized user experiences.

Every LabVIEW virtual instrument (VI) has a front panel where you, as the developer, can choose to display data or expose controls to your users. If you create a VI with just the appropriate controls and displays for your specific need, you end up getting more accurate results while spending less time setting up measurements and interpreting the measured data.

3.3.5.1 Create Custom User Interfaces

LabVIEWpermit full control over what is to make visible to user on the front panel, and which parts of the application are keep to the block diagram source code. Right-click a control to edit properties such as input range, coercion, and tooltips that make the application easier to use and understand.

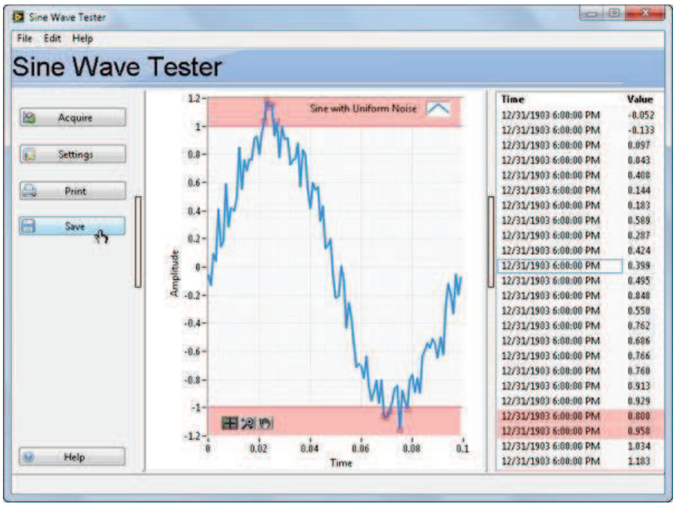


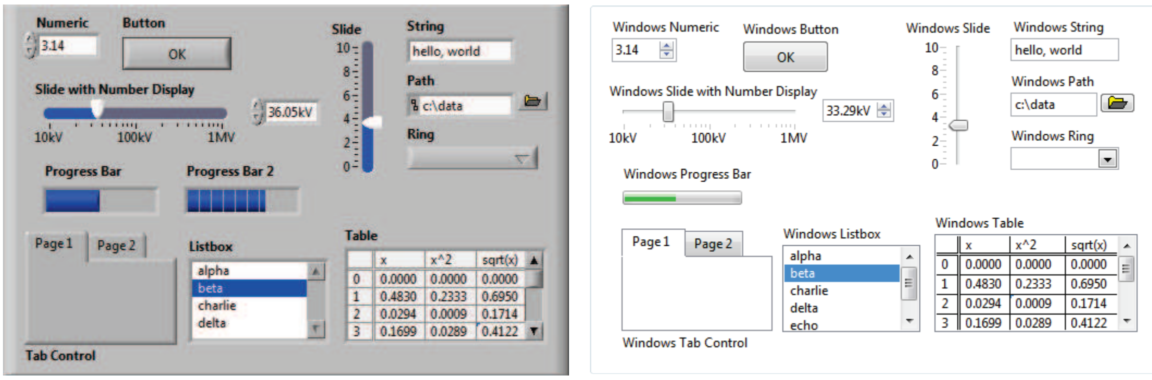
Figure 3.21:A Customized LabVIEW Front Panel[21].

Front-panel customizability is not limited to the type of controls or indicators to use. LabVIEW comes with three different customizable control themes. Using the defaults for the fastest development, make LabVIEW look like any other Windows application, or customize own controls and colour scheme to suit personal preferences.

3.3.5.2 Visualization and UI Features

- **Common OS Controls and Indicators**

  LabVIEW contains all of the standard OS-defined controls such as number and string displays, buttons, slides, progress bars, and tabs. Programmers have the option of using LabVIEW-styled controls, OS-styled controls, or modifying the style of the controls to meet own needs.



a) b)

Figure 3.22: Standard Controls and Indicators a) LabVIEW b) Windows [21].

- **Engineering-Specific Controls and Indicators**

  In addition to the standard controls programmer find in most full-featured programming environments, LabVIEW contains many more controls and indicators common in scientific and engineering applications.

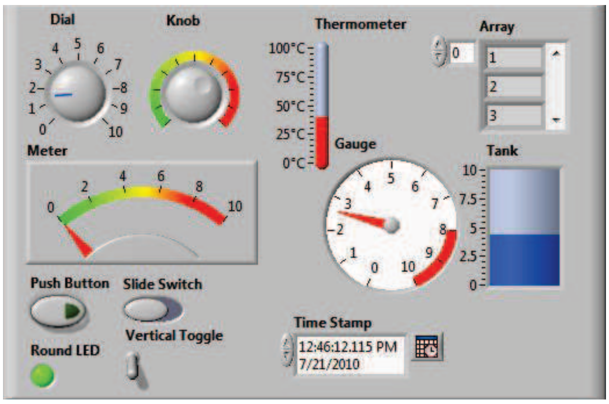


Figure 3.23: Engineering Controls and Indicators[21].

- **Analogue and Digital Waveform Graphs**

  After acquire or generate data, or if data is readily available in a file or database, it is possible use a graph or chart to graphically display data.Graphs and charts differ in the way they display and update data. Graphs display a set of data which is overwritten every time new values are sent to the graph. The waveform graph, which displays one or more plots of evenly sampled measurements, plots single-valued functions, as in y = f(x), with points evenly distributed along the x-axis, such as acquired time-varying waveforms. Cursors and annotations can be added both interactively and programmatically to highlight important data points.

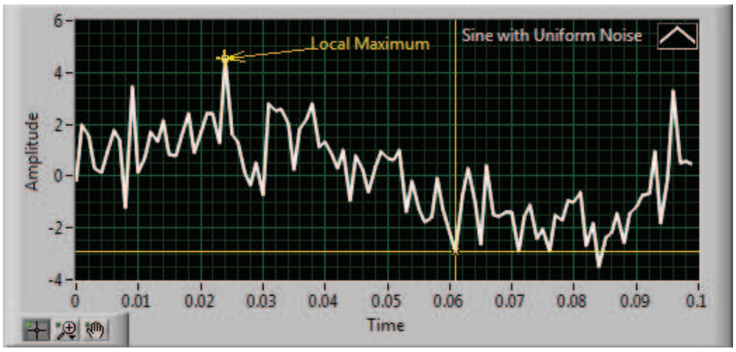


Figure 3.24: Waveform Graph with Annotation and Cursor[21].

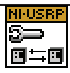
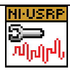
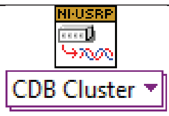
3.3.6 USRP drivers and components

National Instruments has recently acquired the EttusCompanywhichis the USRP developer. So that National Instruments is developing new drivers and components to integrate in LabVIEW development platform.

3.3.6.1 Received components

Table 3.1 resumes a list of components used for received mode.

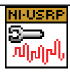
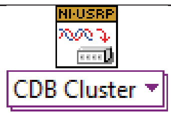
Table 3.1: Received components

	**niUSRP Open Rx Session VI**- Opens an Rx session to the device(s) you specify in the device names parameter and returns session handle out that you use to identify this instrument session in all subsequent niUSRPVIs.
	**niUSRP Configure Number of Samples VI**- Specifies whether the device operation is finite or continuous and the number of samples to acquire.
	**niUSRP Configure Signal VI**- Configures properties of the Tx or Rx signal.
	**niUSRP Initiate VI**- Starts the Rx acquisition. The niUSRP Initiate VI starts the waveform acquisition in a Rx session.
	**niUSRP Fetch Rx Data (poly) VI**- Fetches data from the specified channel list. Use the pull-down menu to select an instance of this VI.
	**niUSRP Abort VI**- Stops an acquisition previously started. For finite acquisitions, calling this VI is optional unless you want to stop the acquisition before it is complete. If the acquisition aborts successfully, the driver transitions to the Done state.
	**niUSRP Close Session VI** - Closes the session handle to the device.

3.3.6.2 Transmitting components

Table 3.2 resumes list of components used to create a transmission.

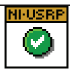
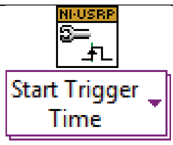
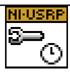
Table 3.2: Transmitting components

	**niUSRP Open Tx Session VI** - Opens a Tx session to the device(s) you specify in the **device names** parameter and returns **session handle out** that you use to identify this instrument session in all subsequent niUSRPVIs.
	**niUSRP Configure Signal VI** - Configures properties of the Tx or Rx signal.
	**niUSRP Write Tx Data (poly) VI** - Writes data to the specified channel list. Use the pull-down menu to select an instance of this VI.
	niUSRP Close Session VI - Closes the session handle to the device.

3.3.6.3 Utility components

In Table 3.3 it is listed the utility components.

Table 3.3: Utility components

	**niUSRP Commit VI** - Validates any changed properties and commits the settings to the device.
	**niUSRP Reset VI** - Resets the device to a known initialization state. This VI aborts any existing acquisitions or generations and restores the device properties to their default states.
	**niUSRPSelf-Test VI**- Performs a self-test of the device.
	**niUSRP Get Error VI** - Returns the error code and description for the last error that occurred.
	**niUSRP Clear Error VI** - Clears the last error code.
	**niUSRP Configure Trigger VI** - Configures the trigger generated by the onboard device timer. The trigger specifies the time to acquire or generate the first sample. Use the pull-down menu to select an instance of this VI.
	**niUSRP Set Time VI** - Sets the time value of the onboard device timer.
	**niUSRP Disable Start Trigger VI** - Disables the start trigger. When the start trigger is disabled, acquisitions and generations begin immediately when data is available.

3.4 RF Front-End Hardware

3.4.1 RF Front-End Requirements

The COGEU project aims to explore the efficient exploitation of the geographical interleaved spectrum. Consequently, the frequencies over which the TVWS transceiver may be expected to operate lie in those channels which will be retained for DTV use after the digital switchover. As described previously, the interleaved channels will range from Channel 21 (470 MHz – 478MHz) to Channel 60 (782MHz -790MHz).The target frequencies of COGEU are the upper band of the interleaved spectrum, in particular from channel 40 to channel 60, since COGEU addresses mobile and nomadic applications where compact antennas are required. However, we are unlikely to have access to spectrum in this frequency range for the duration of the project, or indeed for the early stage development and evaluation of the transceiver.

3.4.2 USRP

The Universal Software Radio Peripheral (USRP) was initially developed to address the hardware requirements of the GNU radio project which was initiated by Eric Blossom. Matt Ettus secured funding from the United States National Science Foundation (NSF), through the University of Utah, to design what would become the USRP. One of the core objectives for the design of the resulting radio hardware, the USRP, was that it would be cheap enough to be affordable for radio community developers and academics. Matt Ettus then founded Ettus Research LLC in 2004 to further the development of the USRP family and to make the hardware available on a commercial basis. In 2010 Ettus Research LLC was acquired by National Instruments Corporation and is now a wholly owned subsidiary of that company.

The aim of the USRP product family is to allow the creation of a software radio using any computer with a USB2 or Gigabit Ethernet port. The various plug-on daughterboards allow the USRP and USRP2 to be used on different radio frequency bands. Daughterboards are available from DC to 5.9 GHz, as listed in subsection3.4.3.The entire design of the USRP family is open source. The USRP and USRP 2 work with GNU Radio, IRIS and LabVIEW.

Figure 3.25:USRP 2.0

The National Instruments developed and is updating a new Universal Hardware Driver (UHD) which encapsulates everything needed to control all of the USRP hardware in a single driver. This enable software developers to use USRP hardware without having to worry about the low level details of daughterboard control, kernel drivers or other factors. The UHD will be cross-platform; allowing use on Linux, Windows, and Mac OS X. Currently, UHD is available for LabVIEW platform under windows, developers wishing to use the USRP in GNU or IRIS based platforms must write their own drivers to control the USRP hardware.

The USRP RF front-end serves to up-convert and transmits signals generated by the baseband processor and to down-convert and digitizes received signals prior to baseband processing. The USRP RF front-end is designed specifically for use with GPP-based software radio systems. The motherboard itself features four 64 MS/s 12-bit analogue to digital convertors (ADCs) and four 128 MS/s 14-bit digital to analogue convertors (DACs), allowing the use of 4 input and output channels (or 2 input and output in-phase – quadrature (I-Q) pairs). The board also includes an FPGA implementing four digital down convertors (DDCs) with programmable decimation rates and two digital up convertors (DUCs) with programmable interpolation rates. The use of the FPGA allows for high sample-rate processing to be performed on the board, allowing lower sample-rate processing to be performed on the host PC. This enables baseband signal data to be transferred over the Gigabit Ethernet link at 25MHz using 16-bit I-Q samples, for USRP2.

Nonetheless, a key advantage of the USRP lies in the flexibility provided in carrier frequencies, samples bandwidths and signal powers. Currently, each operating parameter of the system is controlled using register values which are read and written over the USB 2.0 interface. The development of the UHD should provide a cleaner mechanism for control of the USRP. The usable range of parameter values is dependent on the transceiver daughterboard in use; the available daughterboard are specified in subsection 3.4.3.Given this access to the specifications, a complete understanding of the system is possible and adaptations which are required by specific applications are facilitated.

Table 3.4 present the main USRP 2.0technical specifications:

Table 3.4:USRP Technical Specifications

Feature/Specification	**USRP 2.0**
Spurious Free Dynamic Range	*88 dB*
DAC	*2 x 400MS/s 16-bit*
ADC	*2 x 100MS/s 14-bit*
Digital Down convertor	*with programmable decimation rates*
Digital Up convertor	*with programmable interpolation rates*
USRP – Host Interface	*Gigabit Ethernet*

Signal processing capability	*Signals <= 100MHz wide*
MIMO capable	*MIMO*

3.4.3 RF daughterboard of interest:

There are tree USRP RF daughterboard that are of interest to the COGEU TVWS project; their specifications are listed in Table 3.5, below.

Table 3.5:USRP Daughterboard Specifications

Daughterboard	Frequency Range	Tx Power	Notes
WBX	50MHz to2.2GHz	100mW (20dBm)	
RFX400	400 to 500MHz	100mW (20dBm)	
TVRX	50 to 860 MHz		receive only – no tx

The WBX daughterboard fulfill the requirements for a TVWS transceiver accessing the interleaved spectrum (470 MHz - 790 MHz). The TVRX daughterboard also provides receive-only functionality specifically designed for the entire DTV frequency range.

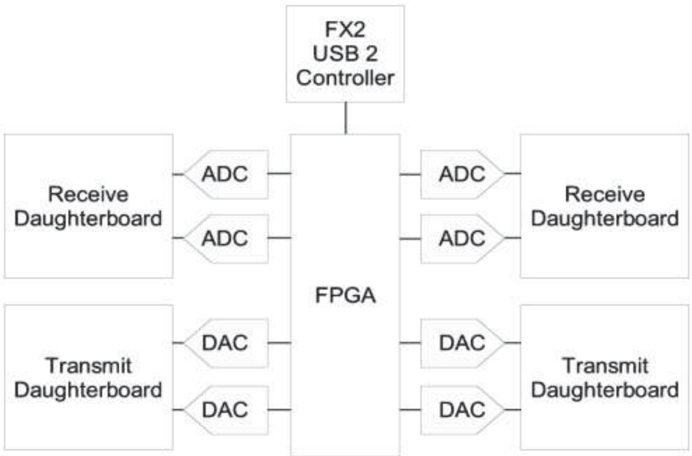


Figure 3.26: USRP + daughterboard block diagram

3.4.4 Limits of the RF frontends and impact on function as COGEU TVWS transceiver

There are a number of limits which must be considered when using the USRP in conjunction with an SDR-based radio. Limits occur on the USRP in a number of places:

- USRP to PC interface is a limiter as it places an upper bound on the rate at which samples can be transferred from the motherboard to the host platform, as noted in subsection 3.4.2.
- USRP hardware, e.g. decimators, DACs, etc, also constrain the operation of a transceiver application.

- USRP bandpass filter limits. The USRP 2.0 has a nominal bandwidth of 25MHz.

Furthermore, processing bottlenecks can occur on the software radio baseband processing platform if the rate of data coming from the USRP motherboard exceeds that which can be processed on the host platform; data buffer overruns can occur which may result in loss of communication.

However, the USRP has been used in numerous demonstrations. Experiments are generally bandwidth-scaled and transmit-power-scaled to account for both the limits of the USRP RF frontend, the limits of the current processor capabilities and the regulations governing the allowable transmit power. An example of this kind of demonstration was given in IEEE DySPAN2010 in Singapore [22]. The demonstration system involved a dynamic spectrum access network using reconfigurable OFDM-based waveforms to control out-of-band emissions in the presence of a primary user.

3.5 Summary

The COGEU transceiver platform will be based on a SDR-based architecture. Component based SDRs offer the flexibility required of a rapid, prototyping platform. More significantly, they enable reconfiguration, thus supporting the development of cognitive radios. SDR architectures combine two essential elements; the SDR which is hosted on computing device, performing the baseband processing, and a RF front-end which carries out the radio functions which it is not feasible or possible to execute in software. Currently, the most flexible and readily accessible baseband processing platforms are GPP-based.

Labview combines a graphical programming language with the capability to create user-friendly user interfaces and interact with the USRP, makes it a preferred choice compared with other software solutions. The possibility of multi-language usage, gives the possibility of multi solutions.

The combining of the hardware and the software will able to produce the prototype.

Chapter 4

4 Integration of Spectrum Sensing

4.1 Spectrum sensing module

An extensive study and simulation of several sensing algorithms, reported in [23], have shown that blind methods, in particular Covariance Absolute Value (CAV) and Blindly Combined Energy Detection (BCED),presented a superior performance compared to other algorithms, for PMSE detection. Their performances was measured against the Energy Detection (ED) algorithm, and confirmed that the higher complexity of CAV and BCED algorithms results in significant sensing gains compared to ED alone.Metrics used to evaluate each algorithm are the probability of false alarm (P_{FA}), the probability of detection (P_D) and the Receiver Operating Characteristic (ROC).

4.2 Overview of sensing algorithms

Sensing algorithms can be classified into three main categories, based on the amount of information used for sensing purpose:

1. Requires information on noise power only (noise dependent detection).
   These detection algorithms do not make any assumption on wireless microphones signal characteristics. Basically these techniques are detecting random signal in noise. They do not need prior information on the signal but on the other hand, very accurate information on noise statistics is necessary in order to obtain reliable detection performance.
2. Requires both source signal and noise power to be known (**feature detection**).
   These algorithms employ knowledge of structural and statistical properties of primary user signals in the decision-making.
3. . Requires no information on source signal or noise power (**blind detection**).

These detection algorithms rely on a statistical analysis, using covariance or eigenvalue matrix to identify the properties of a signal. These methods are independent of the noise power.

In [23]is presented an overview of the algorithms in each category, which can be used to sense Wireless Microphones (WM). In the following subsections, is present an overview of the algorithms implemented in the demonstrator

4.2.1 Hypothesis test

The sensing problem can be generally formulated as a binary hypothesis testing problem,

$$\begin{gathered} H_0 : x[n] = u[n] \\ H_1 : [n] = s[n] + u[n], n = 1,2, \ldots, Ns \end{gathered} \tag{4-1}$$

whereH_0 and H_1 are the hypotheses expressing the absence and presence of the wireless microphone (WM), respectively, and N_s is the number of samples. The terms $[n]$ and $[n]$ are sampled versions of the WM signal $s(t)$ and the noise $u(t)$ present in the system, respectively.

There are two ways to design hypothesis tests: Bayesian and frequentist (or classical). In the Bayesian setup, the prior probability of each hypothesis occurring is assumed known. However, it is not reasonable to assign an *a priori* probability in this particular application, since we don't know the probability of a PMSE signals being present in a particular place or time. In such cases we need a decision rule that does not depend on making assumptions about the *a priori* probability of each hypothesis. Here the Neyman-Pearson criterion offers an alternative to the Bayesian framework. The Neyman-Pearson criterion is stated in terms of certain probabilities associated with a particular hypothesis test, such as the probability of false alarm (P_{fa}) and the probability of detection (P_d) [33].

The WM signal is detected by comparing the output d of the sensing algorithm, with a decision level (threshold level - TH).Figure 4.1 illustrates the decision process.

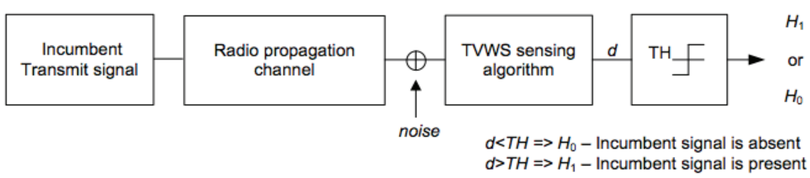


Figure 4.1: Sensing model diagram

Depending on the sensing technique, d is given by a test statistic that will be described for each algorithm implemented. Moreover, a detection threshold TH is determined based on the given probability of false alarm (P_{fa}) and is also dependent on the sensing algorithm. Depending on the test statistics, the threshold can be formulated from the formulations for probability of detection (P_d) or probability of false-alarm (P_{fa}) as follows,

$$P_{fa} = P(TH > d|H_0) = \int_d^\infty f_0(t)dt \tag{4-2}$$

$$P_d = P(TH > d|H_1) = \int_d^\infty f_1(t)dt \tag{4-3}$$

where $f_0(t)$ and $f_1(t)$ are the probability density functions (PDF) under the hypotheses H_0 and H_1, respectively. Thus, P_{fa} and P_d represent the two degrees of freedom in a binary hypothesis test, and do not involve a priori probabilities of the hypotheses. Depending on the detection algorithm, *TH* is computed analytically or by using heuristic methods. More details on the computation of *TH* are given in section. 4.2.5.

4.2.2 Energy Detection

The energy detector (ED) is one of the simplest kinds of detectors and estimates the signal power in the channel and compares that estimate to a threshold [24]. A signal is assumed to be present if the test statistic is above the threshold and vice versa. The test statistic is computed as,

$$\mathrm{d} = \max\left(\frac{1}{\mathrm{N_S}}\sum_{\mathrm{N}=0}^{\mathrm{N_S}-1} \mathrm{x[n]}.\mathrm{x^*[n]}\right) = \max\left(\frac{1}{\mathrm{N_S}}\sum_{\mathrm{N}=0}^{\mathrm{N_S}-1} |\mathrm{x[n]}|^2\right) \tag{4-4}$$

Moreover, wireless microphone signals manifest as a group of tones that can span 200 kHz range in frequency domain. By sufficiently averaging over time, the wireless microphone signals can stand out even at low signal levels. Due to this property, spectrum sensing can be also performed in the frequency domain, detecting the maximum peak of the estimated power spectral density (PSD) of the received signal [24][28][29][30].

$$d = \max\left(\frac{1}{N_S}\sum_{n=0}^{N_S-1} |FFT(x)|^2\right) \tag{4-5}$$

Instead of the FFT in equation (4-5), other well-known spectrum estimation method, such as the Welch periodogram, can also be used [29].

4.2.3 Covariance-based detection

The statistical covariance matrices of signal and noise are generally different. Thus this difference is used in the proposed methods to differentiate the signal component from background noise, i.e. this technique is based on measuring the whiteness or correlation level of the covariance matrix. In practice, there are only a limited number of received signal samples. Hence, the detection methods are based on the sample covariance matrix,

$$R_x[N_s] = \begin{bmatrix} \lambda[0] & \cdots & \lambda[L-1] \\ \vdots & \ddots & \vdots \\ \lambda[L-1] & \cdots & \lambda[0] \end{bmatrix}, \qquad (4\text{-}6)$$

where

$$\lambda[l] = \frac{1}{N_s} \sum_{m=0}^{N_s-1} x[m]x[m-l], l = 0,1, \dots L-1, \qquad (4\text{-}7)$$

are the sample autocorrelations of the received signal $x[n]$ and L is the smoothing factor. Test statistics are constructed directly from the entries of the sample covariance matrix and generally are given as

$$d = {F_1(r_{mn})}\Big/{F_2(r_{mm})} \qquad (4\text{-}8)$$

whereF_1 and F_2 are two functions and r_{mn} are the elements of the sample covariance matrix R_x. There are many ways to choose the two functions. The CAV test statistic is,

$$d_{CAV} = \sum_{n=1}^{L} \sum_{m=1}^{L} |r_{nm}| \Big/ \sum_{m=1}^{L} |r_{mm}| \qquad (4\text{-}9)$$

the presence of signal is decided by compared the ratio d_{CAV} with a threshold.

4.2.4 Eigenvalue-based detection

The eigenvalue- based detection algorithms compute the eigenvalues from the covariance matrix (4-6)$\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_L$. The maximum Eigenvalue to trace Detection also called Blindly Combined Energy Detection (MET_BCED. The MET_BCED test statistical is:

$$d_{MET\_BCED} = \lambda_1 \Big/ \sum_{m=1}^{L} \lambda_m \qquad (4\text{-}10)$$

Signal is present if d_{MET_BCED}> threshold

4.2.5 Threshold computation

Energy detector algorithm:

When noise $[n]$ is AWGN with variance σu2, the threshold TH can be derived analytically:

$$TH = \sigma_u^2 \left(1 + \frac{\sqrt{2}Q^{-1}(P_{fa})}{\sqrt{N_S}}\right) \qquad (4\text{-}11)$$

where Q-1 is the inverse Q function.

If $[n]$ includes also interference from other signals, the statistic of the interference is unknown, and the threshold can be determined by a heuristic method. This was accomplished using the following methodology:

- Compute the peak PSD value of the sensed channel, when no primary signal is present (noise only)
- Repeat the measurement N times and create a histogram of the results.
- Compute the complementary cumulative density function (CCDF).
- Search in the CCDF, for the threshold value associated with the desired probability of false alarm.

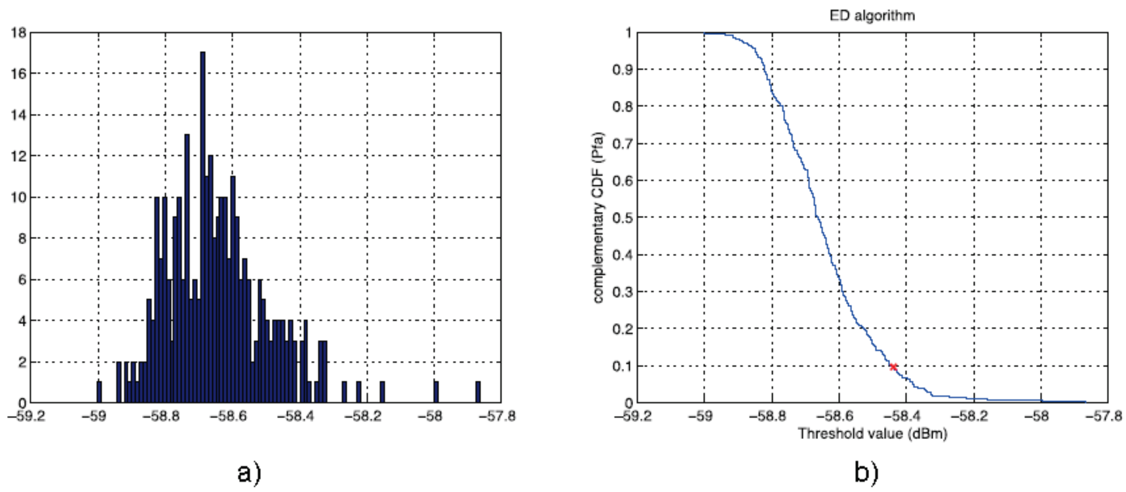


Figure 4.2:ED algorithm: a) Histogram and b) CCDF of the test statistic d in the presence of noise only. The red dot in b) represents the threshold for a Pfa of 10%[23].

As an example, the histogram for 1000 simulations of an AWGN noise signal, and associated CCDF, are given in Figure 4.2a) and b), respectively.

The estimation of the noise PSD is crucial for the performance of ED algorithms as the determination of the threshold is strictly dependent on the variance of the noise, as expressed in (4-11). In certain situations, the exact value of this variance is difficult to obtain and thus the influence of the noise uncertainty on the ED of signals can significantly deteriorate the performance of the sensing algorithm [24].

Blind detection algorithms

The Threshold for CAV and MET-BCED can be calculated by theoretical using the following equations [25]:

$$TH_{CAV} = \frac{1 + (L-1)\sqrt{\frac{2}{N_s \pi}}}{1 - Q^{-1}(P_{fa})\sqrt{\frac{2}{N_s}}} \tag{4-12}$$

forCAV and for MET_BCED is [26]:

$$TH_{MET\_BCED} = \frac{\left(\sqrt{N_s} + \sqrt{L}\right)^2}{N_s}\left(1 + \frac{\left(\sqrt{N_s} + \sqrt{L}\right)^{\frac{2}{3}}}{(N_s L)^{\frac{1}{6}}} F_2^{-1}\left(1 - P_{fa}\right)\right) \tag{4-13}$$

As for ED, the TH can be computed using the heuristic method as described next:

- Compute the ratio value of the sensed channel, with no primary user signal, (only noise)
- Repeat N times the measurement and create a histogram.
- Compute the complementary cumulative density function (CCDF).
- Search in the CCDF, for the threshold value associated with the desired probability of false alarm (P_{FA}).

Due to the experimental results mentioned in [23],the implemented method is the heuristic method, since performed better results than the theoretical one.

4.3 Metrics to evaluate sensing algorithms

Several sensing schemes were introduced for PMSE detection in previous sections. Each scheme may have a different performance in a different scenario. It is present here important performance evaluation metrics used in the algorithms selection[23].

4.3.1 SNR regime

A minimum detection threshold of -126 dBm over a 200 kHz bandwidth is necessary to avoid causing interference to WM from TVWS devices. This value accounts for body loss and hidden terminal margin. Correspondingly, the required SNR at the TVWS sensing receiver can be calculated based on the receiver's noise figure (NF). USRP's NF is 8 dB [31]in the COGEU frequency band of interest (622- 790 MHz). Considering that the thermal noise power spectral density (PSD) is -174 dBm/Hz, the TVWS receiver's sensitivity over 200 kHz is,

$$-174 + 10\log_{10}(200 \times 10^3) + 8 = -113\ dBm \tag{4-14}$$

Hence the TVWS receiver needs to detect signals with SNR at,

$$-126+113=-16\ \mathrm{dB} \tag{4-15}$$

The value -16 dB is used in [27]as a reference value for minimum performance for sensing algorithms.

4.3.2 False alarm and detection probabilities

Minimum requirements are ***P_d* higher than 90%** and ***P_{fa}* lower than 10% [27]**. Performance of a specific detection technique is usually characterized by plotting:

1. The probability of detection curve as a function of SNR for a given false alarm probability (between 0% and 100%) and sensing time.

2. The Receiver Operation Characteristics (ROC) curves, namely a plot of Pd vs. Pfa, given a sensing time.

4.3.3 Receiver Operating Curves (ROC)

The Receiver Operation Characteristics (ROC) curves, namely a plot of P_d vs. P_{fa}, a given SNR. As there's no possibility to determine the SNR, it was assumed that the received conditions were constant for the same place.

4.3.4 Sensing time

The choice of the available sensing time is crucial for the performance of the system. It is important that vacant frequency bands are quickly detected so that they can be used efficiently. If sensing time is too long, the data transmission duration reduces, thereby reducing throughput of TVWS devices.

For ED, sensing is made by successive averages of the spectrum. During the sensing time, a number Navg of FFT with size FFT_L are computed. So, the sensing time TD is the product of the number of average with the computation time for each FFT (without buffer overlapping),

$$T_D = N_{avg}.(FFT_L.T_S) \quad (4\text{-}16)$$

where $T_S = 1/\ f_S$ is the sampling time. A study is conducted to evaluate the optimum values of Navg and FFT_L for a constant sensing time.

Other sensing algorithm that do not require spectral averages, but are dependent on a recorded sample of the signal (such as covariance or eigenvalue based methods), are evaluated with a number of samples Ns corresponding to the total sensing time, in order to be compared with the ED algorithm.

4.4 Implementation

4.4.1 Dependencies

The sensing module relies on a software-defined radio (SDR), a GPS device and a host PC. The SDR platform is based on USRP2 hardware prototyping with a WBX daughterboard.

During sensing, the frequency scanning is fast enough to allow frequency hopping and sensing in less than 100 ms.GPS device is independent and is connected to the host PC by a Bluetooth connection. Since PMSE signals presence is not guaranteed in the demonstration sites, commercial tuneableFM wireless microphonesare also used, as primary users. This way, we can define a variety of sensing scenarios and measure the performance of sensing algorithms, for indoor and outdoor tests, under different propagation conditions. Wireless microphones operate in predefined TV bands of 30 MHz bandwidth, sub-divided in 24 channels, the maximum transmit power permitted is 50 mW. The WM set used is the equipment showed in Figure 4.3.

Figure 4.3: Professional Wireless Microphone set

4.4.2 Coding, Interface

The software application for PMSE sensing is built in LabVIEW. As explained in subsection 3.3Labview combines a graphical programming language with the capability to create user-friendly user interfaces, which makes it a preferred choice compared with other software solutions. This particular combination of hardware and software was chosen due to the recent development of USRP2 drivers for Labview[32]. Figure 4.4 shows a diagram of the sensing platform. As represented in the figure, the platform is composed by several components, a PC as a host, a USRP as RF front-end and a GPS device. There´s some different technologies and communication protocol evolved and all integrated by LabVIEW in one single program. Also, in order to increase speed and reduce complexity of the program, all sensing algorithms (CAV, BCED and ED) are coded in $C^{++}$and integrated as new Labviewfunctions.

The sensing module also connects to Internet accessing to a geo-location database, combining then, the geo-location database information with local sensing.

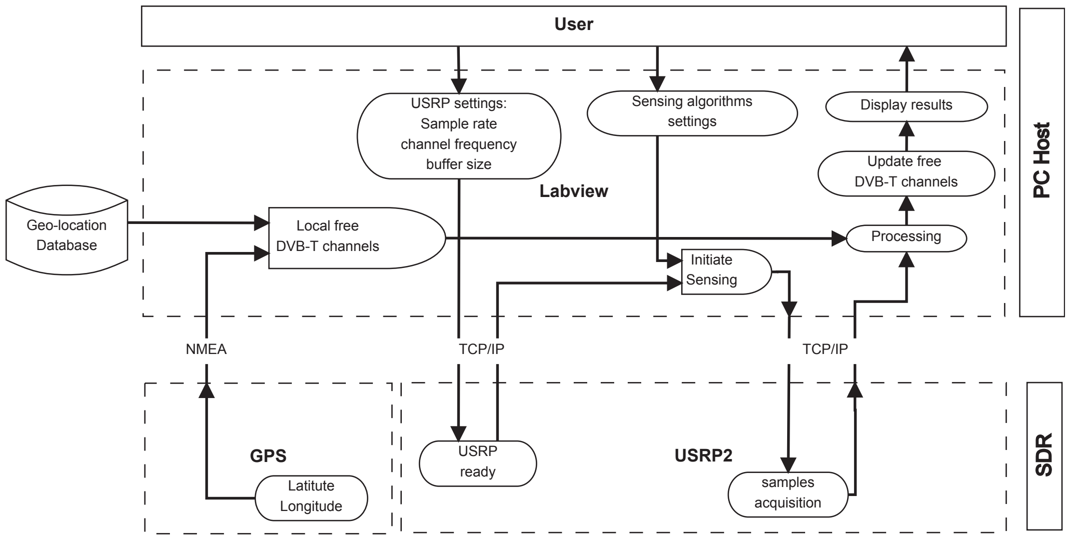


Figure 4.4: Structural and functional diagram of the sensing tool[36].

4.4.3 Control and Feedback

The sensing program is divided in three functional pages:

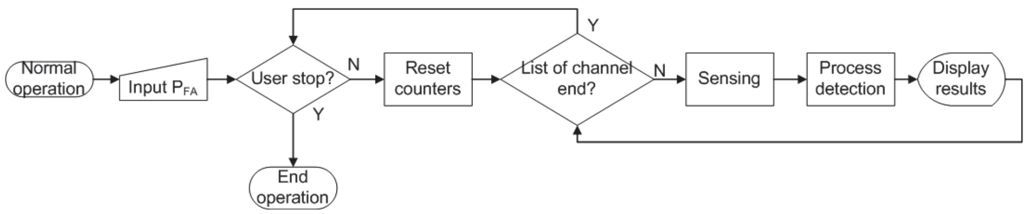
- **Pre-configuration**

This page is reserved for parameters that are only adjusted during start up, "e.g." enable or disable GPS receiver, FFT parameters, or input parameters for blind sensing algorithms.

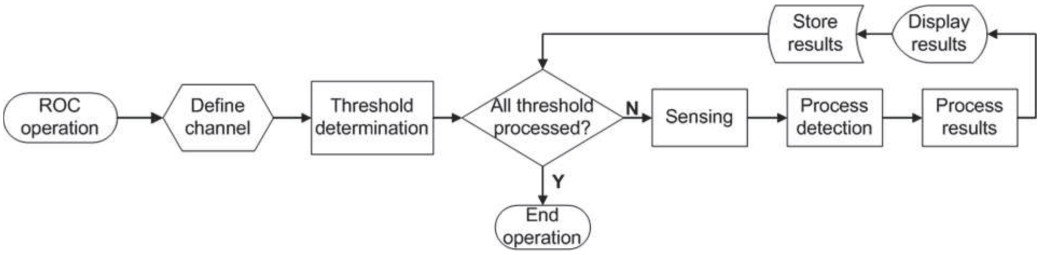
- **Setup interface**

This is the main setup page. As shown in Figure 4.6, the user may define operational modes: "Standard operations" when sensing is done for all available channels, or "ROC operation", when sensing is made only for the selected channel, varying the PFA. Figure 4.5a) and Figure 4.5b) shows a functional diagram for each method, respectively.

In normal operation, sensing is done from a list of available channels, sent by the geolocation database. Here, the P_{FA} must be entered by the user. If wireless microphones are present in one or more channels, they must be marked in the "Wireless Microphone Booking" bar (point and click over the green channel indicator, as depicted inFigure 4.8).



a)



b)

Figure 4.5: Flux diagram of sensing for a) Standard operations and b) ROC operations[36].

The ROC operation is performed using a default vector of P_{FA} values. The vector comprises a set of 8 values logarithmically spaced from 0.1% to 22%. Thresholds are defined using the method described in subsection 4.2.5(heuristic method) or can be loaded from a previous saved file. The measurement results are saved in spread sheet files for post-processing.

Figure 4.6: Setup interface of the PMSE sensing platform.

From the setup interface, the user can also define sensing parameters, such as detection threshold or sensing time. Following an initial configuration stage, the GUI triggers the communication process between the host PC and the USRP2. Local coordinates are acquired from a GPS receiver (if no GPS signal is available, coordinates can be inserted manually). The GUI includes a web browser window derationed to Google maps API and displays a map centred on the sensing device location. The preferred coverage area can be simulated in the map by introducing the coverage radius, this area is represented by a pink circle around the antenna. After a query to the DVB-T geo-location database, a list of all available TV channels is downloaded and displayed as LED indicators with different colours and symbols: red (cross symbol) means that the channels is already occupied by a DVB-T channel, and green (check symbol) means that the channel is free of DVB-T signals. Each channel reserved for PMSE usage is represented by a WM symbol. Also in the text box it's possible very the frequencies of the available channels and the respective max transmit power allowed, Figure 4.9.

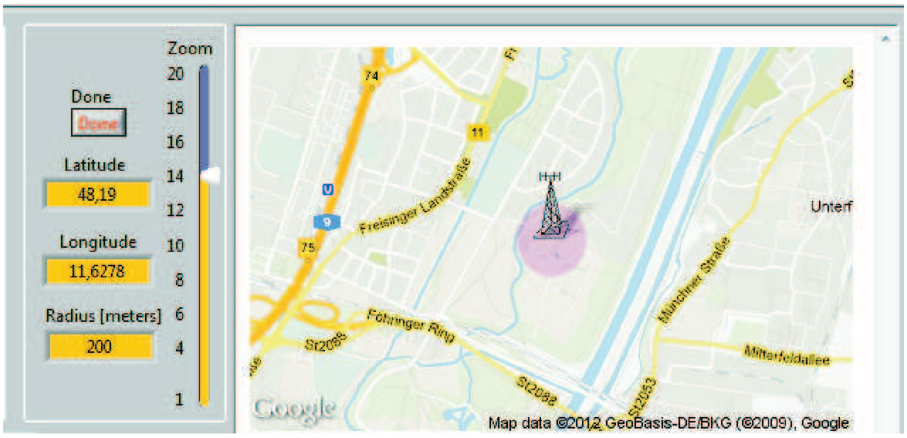


Figure 4.7: Google Map and the TVWS device location

Figure 4.8:WM booking bar

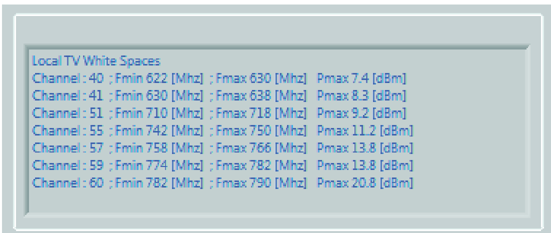


Figure 4.9: Local TV White Spaces channels and respective maximum transmit power

- **Sensing interface**

The sensing interface appears automatically after press the RUN button and the USRP is started. Depending on the set up the operations can differ. As explained, the first runs can be set to threshold calculations and in this case appears a frame with the histograms graphics, Figure 4.10. The histograms are updated every run, this makes possible to verify the detection evolution, even it´s possible reset and start over again. Mind that this operation must be done without PMSE signal present. When the operation ends, the thresholds are then determined as explained and user is prompted to continue. After this, the WM can be turned on and sensing is started.

Figure 4.10: Threshold determination

In standard operation the sensing is performed for all available channels and for each sensing algorithm, the result of sensing is compared to the respective threshold. If the result is above the threshold and if a WM is booked in that channel, status is set to ‘detection’ (colour black), and if there’s no previous booking of WM, then status is set to ‘false alarm’ (colour yellow). On the other hand, if the result from sensing is below the threshold and there is a WM booking for that channel, status is set to ‘miss detection’ (colour red), if there is no booking of WM, the status is ‘free channel’, (colour green), as depicted in Figure 4.11.

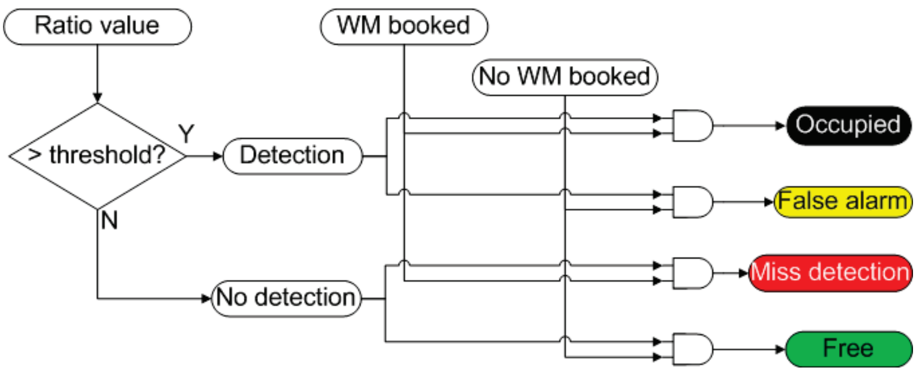


Figure 4.11:LED bar control logic[36].

This method is continuously repeated and produces statistical results, dependent on preliminary information about WM booking on free channels, i.e. without DVB-T signal: If a PMSE is booked for one channel, the measurement results for that channel, after sensing, will be ‘detection’ or ‘miss detection’. Otherwise, if no PMSEs are booked for that channel, measurement results will be ‘free channel’ or ‘false alarm’. All results from measurements are presented in real time bar graphs and also saved in a spread sheet file for post-processing.Table 4.1 resumes the colour code used and their meaning.

Table 4.1: Colour code used to identify sensing results

Colour	Status
Green	Free channel
Yellow	False alarm
Red	Miss detection
Black	Occupied Channel
Grey	Occupied with DVB-T

Also the status bar is actualized permitting a better perception of the sensing process. The Figure 4.13 shows the status bar where it is represented the sensing process to channel 51. The white rectangle indicates the channel being sensing, and the WM symbol above shows that a WM were booking for that channel.

The sensing GUI is represented in Figure 4.12. The sensing interface automatically presents the power spectrum for each DVB-T channel sensed, the total sensing time, the channel's number being sensed, the number of samples acquired, the thresholds and ratio values from each algorithms, and the SNR, as depicted in Figure 4.14.

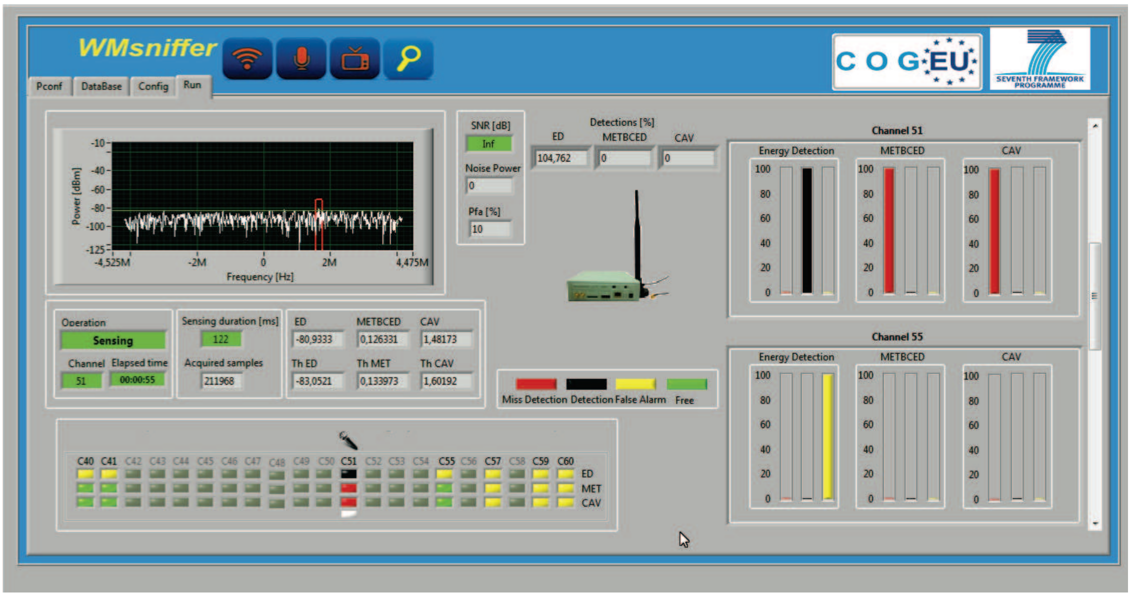


Figure 4.12: Sensing interface of the PMSE sensing testbed.

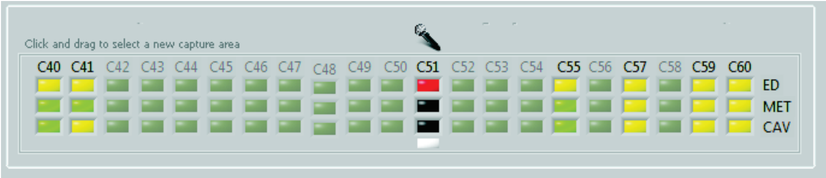


Figure 4.13: Status bar

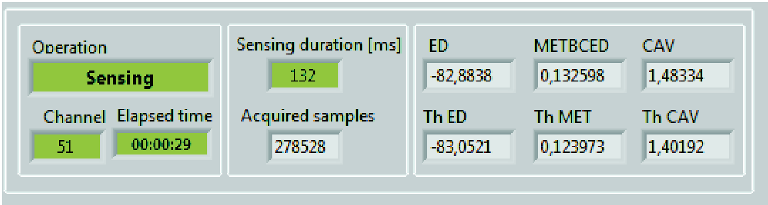


Figure 4.14: Display information of sensing parameters

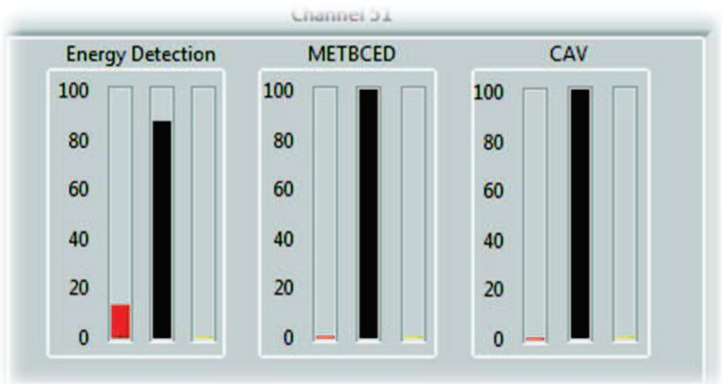


Figure 4.15: Statistics graphic - red->Miss Detection; black->Detection; yellow->False Alarm;

Figure presents the bar graph for statistics results for all algorithms.Each bar represent the percentage of probability of detection in black, probability of false alarm in yellow and the probability of miss detection in red.

4.4.4 GPS device

The GPS device connects to host by Bluetooth using the NMEA protocol. The coordinates acquired are in sexagesimal format and must be converted to decimal to send to Google Maps. The testgps.vi was developed to connect to GPS device, wait for the valid data and convert coordinates.

4.4.5 Geo-location database

The geo-location database is accessible through Internet. The host send a query to database including the location coordinates and wait for an answer, if valid information is available, database sends an OK as answer and host can download it as a xml file type, case no valid information available, then the answer is not Ok this means that the coordinates are outrange of database. In this case, the sensing must be performing for all channels.

4.4.6 SNR estimation

SNR in a channel is computed only if there is a WM detected. In order to estimate it, the following method is implemented:

1. Sum of the squared amplitude of all the samples with WM off, where only noise $u[n]$ is present;
2. Sum of the squared amplitude of all the samples with WM turned on, that is signal plus noise i.e. $x[n]$=$s[n]$+$u[n]$;
3. Computation of the SNR, in dB, using the following expression:

$$SNR = 10\log_{10}\left(\frac{x[n]-u[n]}{u[n]}\right) \quad (4\text{-}17)$$

This method assumes that the test conditions are constant.

4.5 Summary

In this chapter is described a PMSE sensing module which was developed for the TVWS transceiver based on three sensing algorithms; Covariance Absolute Value, Blindly Combined Energy Detection and Energy Detection (ED). It is presented an overview of the used algorithms and there implementation. Is described the implementation of the prototype. Also presents details about functionality.Is described the GUI details and functionalities, the implemented metrics and respective representation. The integration with the GPS device and the communication with the geo-location database are also resumed.

Chapter 5

5 Tests Measurements and Results

In this chapter is described the tests scenarios, set up and the procedures in order to evaluate the performance of the sensing module.

5.1 Scenario

The chosen scenario is the school floor, Figure 5.1. The primary system is located inside the auditorium, as shown in Figure 5.1. The sensing device was placed in two distinct places: inside the library, place L1, and outside the school walls, place L2. As shown in the Figure 5.1, there is no line of sight propagation between the WM and the sensing device. The distance between both locations and the wireless microphone is approximately 45 m. The auditorium was empty, but in the other areas, outside the auditorium there were people. The test was made in an ordinary school day.

5.2 Configuration

The WM was placed in the stage. In order to simulate a speaker there was used a radio device tuned and place near the WM. The WM was configured to operate in a frequency inside of the 48 TV channel.

The sensing device was set up for ROC operation. The channel selected to be scanned was channel 48, the antenna was placed in 1.5m high.

5.3 Experiment procedures

The test starts with the primary system off to enable the thresholds calculations. When the threshold calculation ends the WM is turned on in mute mode, i.e. only the carrier is transmitted. The sensing process starts and collects data during one hour for each of the 8 thresholds values, as explained in the previous chapter for ROC operation. The process is repeated but with the WM in speaker mode and also for each sensed place. This means that the duration of the test is above of 32 hours.

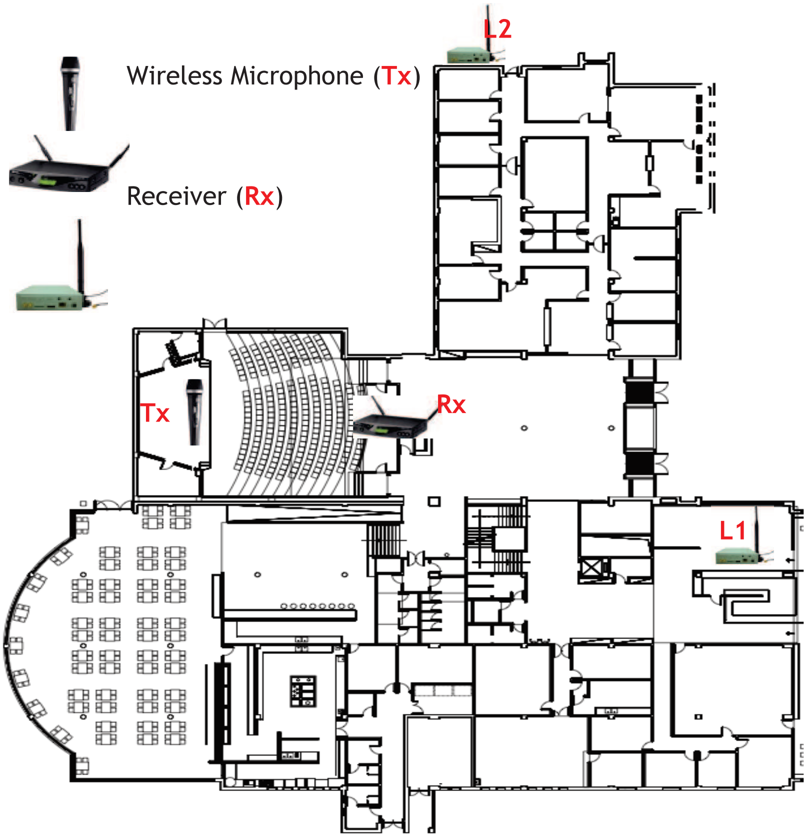


Figure 5.1: Building plant where field measurements were realized

Figure 5.2: The sensing module set up.

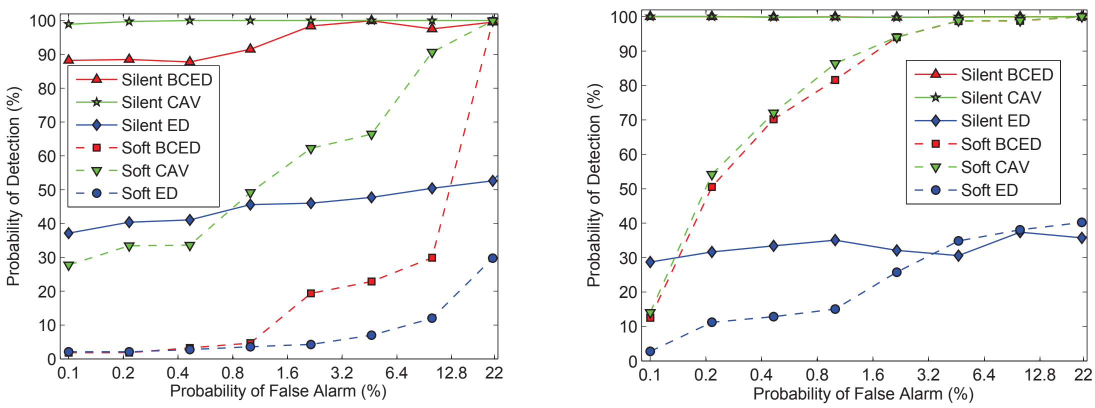
Figure 5.2shows the sensing module set up. Laptop screen is it is represented the database web page, in the big screen is pictured the GUI running. The USRP and two WM are also represented here.

Places more close to WM, give results of 100% detections in all cases and places far give a high percentage of false alarm.

5.4 Test results

The metrics evaluated in this test were the P_D function of P_{FA}, the ROC analyses. This analysis is enough to verify the performance of the device and also the algorithms implemented.

Erro! A origem da referência não foi encontrada. presents ROC for locations L1 and L2, and shows that WM in silent mode are easier to detect. This is due to the high peak correlation of the FM carrier without a modulation signal. Also, there is a significant improvement in the P_D in all scenarios and locations, using blind detection algorithms instead of ED algorithm.



a) b)

Figure 5.3: ROC for location L1 a) and L2 b)

As despite in the **Erro! A origem da referência não foi encontrada.**,the location L1 represents a worth case were detection is made with difficulty, but as can be seen blind algorithms performs better results.

5.5 Summary

This chapter refers to the experimental tests in order to evaluate the performance of the prototype and algorithms. The sensing module was evaluated in practice in a real setting,the blind detection algorithms were found to out-perform the ED algorithm. This practical evaluation confirmed the simulation results reported in [23].

Chapter 6

6 Conclusion Future Work

The project proposal was design, develop and test a radio device able to connect a geo-location database. Based on geo-location database information it must be able to perform sensing and find PMSE devices.

The developed prototype is based on USRP technology as RF front end and LabVIEW software. As described, the prototype here present is resumed to the sensing module, but is also one of the important modules, as is this module that implements the decision of the channels to use for communication and is this module responsible for the non-interference with primary users.

This sensing module is able to communicate with a geo-location database thought Internet, based on its own position coordinates and process sensing over the available channels. The sensing module detects WM signals making use of advanced sensing algorithms.

Some problems were solved during the implementation. The acquiring data from USRP is faster than the rest of process then buffer overrun occurred and the USRP communication gives error and break. This problem was solved by introduce a technic of flush the buffer every acquired cycle and also reduce the processing time, by choosing appropriate functions. Developing the algorithms in C++ also reduces the processing time and help reducing the buffer overrun problem.

The sensing module was evaluated in practice in a real setting,the blind detection algorithms were found to out-perform the ED algorithm. This practical evaluation confirmed the simulation results reported in [23].

6.1 On-going work

In following versions, the prototype will be updated with identification of the central frequency and bandwidth of multiple WMs present in a DVB-T channel. This feature is crucial for spectrum shaping and spectrum aggregation techniques, allowing coexistence between TVWS devices and PMSEs systems. Furthermore, communication protocols between all the different elements will be adapted to improve reliability and scalability of the testbed.

6.2 Tx integration

The sensing module is prepared to integrate the transmitter module. There is no dependence on software platform. Preliminary tests were made integrating sensing module with transmitting module and the TX module is built in IRIS platform. But there still a lot of work to complete this task.

6.3 Publications

This work generates the following publication:

R. Dionísio, J. C. Ribeiro, J. Ribeiro, P. Marques, J. Rodriguez, "**Cross-platform Demonstrator Combining Spectrum Sensing and a Geo-location Database**", Future Networks & Mobile Summit (FUNEMS 2012),Berlin, Germany, 4-6 July 2012.

Presented in “Future Network and Mobile Summit 2011”, on June in Warsaw, Poland. Details available in http://www.av.it.pt/4TELL/news_Funems.html

Also it was presented in the COGEU workshop“the Efficient Use of TV White Spaces in Europe” on November 10th in Munich Germany. Details available in http://www.av.it.pt/4TELL/news_cogeu_wshop.html.

The work here presented also is part of the COGEU periodic reports, Deliverables D2.1, D4.2, D5.1 and D5.3, available in http://www.ict-cogeu.eu/

Referencies

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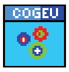
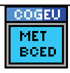
Annex A

1. List of used VI

VI is used in LabVIEW to designate Virtual Instrument. In order to reduce the complexity and to facilitate the interpretation the code can be grouped by functions or VI, these VIs are files that can also be used by other applications. In Table A1.1 is listed the VIs built and used in software.

Table A1.1: list of VIs used in the program

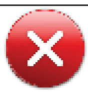
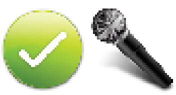
	testgps.vi	Used to connect to GPS device, acquire local coordinates and output them after conversion from sexagesimal to decimal.
	path.vi	This VI is used to generate a circle path over the Google map.
	LVcircle.vi	Generates a circle to use in path.vi
	xmlread.vi	Read the XML file sent by geolocation database.
	chfreq.vi	This vi is used to generate the frequencies table from the input channel array
	autocorr.vi	Compute the autocorrelation matrix, built in C^{++}
	toeplitz.vi	Generate the toeplitz matrix, built in C^{++}
	cav3.vi	This vi implements the last calculations of the CAV algorithm, it is used in cav.vi, built in C^{++}
	cav.vi	Implements the CAV algorithm

	METBCED.vi	Implements the MET-BCED algorithm
	contour.vi	Find the number of WM detected and the related central frequency and create a contour over the graphic
	COGEUsensing.vi	The main VI

2 List of controls and indicators

In order to create a personalised interface, some controls were made or customized as present in the next table.

Table A2.1: List of controls and indicators

	Dbacess2.ctl	This button is used to access to database
Boolean 2 	Micro3.ctl	This is an indicator and is used in the status bar and indicates that WM is booked.
	Micro5.ctl	Is used in booking bar and indicates an occupied channel by DVB-T.
	Micro4.ctl	Indicates a free channel, if a WM is booked it changes from the green check symbol to WM symbol.