Cognitive Spectrum Management in TV White Space: Libya as a Case Study

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2014

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The traditional spectrum allocation scheme is based on static allotment of frequency bands to applications and entities in specific geographical areas for extended periods of time. Telecommunications regulations, on the national and international levels, are established to protect these primary users from any interference and guarantee exclusive access to allocated spectrum. Such exclusive access model results in very low spectrum utilization while new applications are prevented from accessing the spectrum thus creating a spectrum scarcity problem [1]. Dynamic Spectrum Access (DSA) aims to solve this problem by allowing secondary users to opportunistically access the spectrum through Cognitive Radios (CRs) that can sense the spectrum and avoid interfering with the primary holders of the spectrum access rights. Regulatory bodies around the world are taking rapid steps towards realizing DSA and setting the rules for shared spectrum access.

TV White Space (TVWS) is the prime contender for spectrum sharing with standards now being developed allowing dynamic spectrum access of the unused TV spectrum for secondary applications through centralized Geo-location database. The Geo-location database framework is aimed at ensuring coexistence of secondary users with primary TV broadcasters and protecting the TV broadcasters and other incumbents like wireless microphone systems from harmful interference secondary users may cause. However, a comprehensive model for spectrum sharing that incorporates regulatory, application, and economical requirements into the spectrum management process and addresses secondary-to-secondary users' coexistence in conjunction with primary-to-secondary users' coexistence is yet to be proposed.

This work addresses this need by presenting a combined design and implementation of a Cognitive Spectrum Management System (CSMS) incorporating a Cognitive Framework for spectrum management in TV White Space. The system ensures both primary-to-secondary and secondary-to-secondary users' coexistence via a Geo-location Database System and a Spectrum Manager that allocates spectrum to competing secondary users while maximizing total spectrum allocation. A system implementation is conducted for the case of Libya were TV broadcasting stations' information is collected from regulatory sources and TVWS availability is estimated for parts of the country.

Acknowledgments

I would like to extend my gratitude to my supervisor, Professor Otman Basir, for his continues support and guidance throughout the making of this thesis. I would like to also recognize the support of the Canadian Bureau of International Education (CBIE) and the Libyan Ministry of Higher Education for giving me the chance to pursue my studies though the Libyan-North American scholarship program. Lastly, I would like to thank the Ministry of Communications and Information Technology in Libya for providing TV broadcasting data used in the TVWS estimation.

Dedication

To my parents, to whom I owe so much that can never be repaid

To my beloved wife, for without her support and love this work would not have been accomplished.

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Chapter 1

Introduction

1.1 Introduction

The communication spectrum is a scarce natural resource that must be effectively managed and regulated. The world's telecommunications regulatory body, the International Telecommunications Union (ITU), identifies spectrum management as a critical task of regional and national regulatory bodies in order to ensures equitable, efficient, and economical use of the communications spectrum [4]. Sound long term spectrum planning and management policies are key to maximizing the benefits to the national economy and ensuring healthy growth of the Information and Telecommunications Technology (ICT) sector and infrastructures. One of the main issues these policies and regulations must face is the problem of increasing demand on communications spectrum for new and existing applications. With the explosive growth of mobile and wireless technologies and the increasing traffic generated by these applications, the need for additional spectrum is higher than ever before. A report by Nokia Siemens Networks in 2011 predicts that mobile traffic will increase by 1000x folds by the year 2020 [5]. New, more efficient, digital communications technologies such as the Long Term Evolution Advanced (LTE-A) and 5G standards for mobile communications promise to alleviate some of that demand, but the same report indicates that a 10x fold increase in spectrum will still be needed.

Spectrum sharing through Dynamic Spectrum Access (DSA) and Cognitive Radios (CR) is identified as one of the ways to deliver this additional spectrum and solve the immanent spectrum scarcity problem. Through sensing of their surrounding communication environment, CRs are able to identify underutilized spectrum bands and intelligently and dynamically utilizing these spectrum holes, or white spaces, without interfering with existing users. However, in order to deploy such devices in any wireless ecosystem, comprehensive regulatory, economical, and technical frameworks must first be put in place to allow such dynamic spectrum sharing. In this context, the Geo-location database dynamic spectrum access framework represents an excellent model where communication spectrum can be opened to new applications while protecting existing ones from interference. The underutilized TV spectrum, called TV White Space (TVWS), is a prime candidate for such spectrum sharing with standards and regulatory rulings being issued in various parts of the globe.

This work presents the design and implementation of a Cognitive Spectrum Management System (CSMS) for spectrum management and sharing in TVWS. A cognitive framework is adopted for an adaptive design where the spectrum management system meets varying regulatory, economical, and technical requirements while ensuring coexistence between primary and secondary users of the spectrum. Libya is chosen as the subject of the system implantation and TVWS assessment where (and to the author's best of knowledge) no previous attempts to assess the availability of TVWS and the potentials of its utilization were made. The proposed design was implemented and the TVWS availability in test region of Libya was conducted using TV transmitter's data and elevation models utilization Longley-Rice propagation model. Finally, a spectrum allocation algorithm and a web-based interface were implemented for interactive access to the TVWS availability and spectrum allocation information.

1.2 Motivation

Utilizing the unused TVWS can help solve the spectrum scarcity problem and enable a wide range of new technologies and services from new back haul technologies for mobile networks and super-Wifi cells, to smart grid networks and remote sensing applications. TVWS holds the potential to bring much needed national economical and social advancements through advancement of the information and communications technology services and providing access to these services to all people. However before implementing TV white space technologies in any country, spectrum management and regulation issues must first be addressed. This work was undertaken in order to address these issues and provide a comprehensive study of TVWS regulation and potential implementation in Libya. The main motives of this work are:

1. Address the problem of spectrum management in Libya and propose comprehensive spectrum management solutions to accommodate for varying technological, economical, and regulatory requirements.

2. Assess the current state of the TV spectrum in Libya through studying the national spectrum plans and conducting radio propagation and analysis studies to quantify the availability of TVWS in Libya.

3. Instigate the Libyan public and official interest in TVWS technology through concrete results and engaging presentation of these results.

1.3 Contributions

The main contributions of this thesis are:

1. This work presents a novel design of a TV White Space management system based on an adaptive cognitive framework. The framework accommodates variations in regulatory, technical, and economical requirements while insuring effective spectrum management.

2. An implementation of the proposed system is conducted for the case of Libya including an implementation of a TVWS database system, a spectrum allocation system, and an interactive web-based interface.

3. To the authors best knowledge, this work represent the first attempt to analyze and estimate the availability of TVWS in Libya. The results obtained from this work are a cornerstone in any future efforts to implement TVWS technology in Libya.

4. A spectrum allocation system is implemented that allocated available TVWS to secondary users based on coexistence constraints for both primary-to-secondary and secondary-to-secondary users.

5. A web-based interface is implemented that allows users to query the system to check the availability of TVWS in any location in the studied area. In addition, an interactive spectrum allocation interface is implemented allowing user to investigate differ-

ent scenarios of spectrum allocation where multiple secondary users are requesting TVWS spectrum.

1.4 Thesis Organization

The rest of this thesis is organized into four more chapters. Chapter 2 will give an introductory background on related topics including spectrum management and access modes, cognitive radio and software defined radios, and TVWS. Chapter 3 is dedicated for the system design description for the encompassing cognitive framework and the cognitive spectrum management system. Chapter 4 will describe the system implementation including the implementation of the TVWS system, the spectrum management system, and the web-based interface. And finally, chapter 5 is dedicated for results, conclusion, and future work.

Chapter 2

Background and Related Work

2.1 Introduction

Shared spectrum access is a new paradigm in spectrum access and management that promises to alleviate the spectrum scarcity problem. In the exclusive use model spectrum is allocated to one primary user (PU) or application and no other user is allowed to operate in that spectrum to guarantee interference free operation for the PU devices. In the shared spectrum model on the other hand, secondary users (SUs) are allowed to operate in the same spectrum originally allocated to the PU as long as they do not cause any interference to the PU. While no guarantees of interference protection are granted to the SU, this grants the SUs opportunistic access to an otherwise restricted spectrum.

In order to ensure coexistence of PUs and SUs, two main technologies are needed: cognitive radios, and a spectrum database.

This chapter presents a brief background review on the main relative topics to this thesis starting with an overview of spectrum access models, then presenting the main concepts of cognitive radio, and finally presenting the definitions of TV white space and their access framework. A summary of related work is presented at the end.

2.2 Spectrum Access and Management

The International Telecommunications Union (ITU) is the world body tasked with regulating the global telecommunications resources and coordinating between regional and national regulatory bodies for effective management of all issues of telecommunications. The ITU Radiocommunications Sector (ITU-R) is the ITU sector responsible for keeping a global registry of spectrum plans and frequency assignments and setting the standards for global spectrum management policies. The ITU-R ensures that regional and national regulatory bodies operations are in line with the global spectrum policies and plans to avoid conflicts. Frequency assignments and allotments by regional regulatory bodies are reported to the ITU-R according to international agreements such as the Geneva 2006 (GE06) for VHF and UHF bands and the Geneva 1985 agreement for the VHF and FM Radio.

Advancements in wireless and mobile communications technologies have led to increasing demand for spectrum and existing regulatory framework need to meet such demand and open up the spectrum for new and innovative applications and services. Spectrum access models control the way services and application are granted access to communication spectrum and through studying existing models and improving them the spectrum access problem can be solved. Spectrum access models can be divided into the following categories:

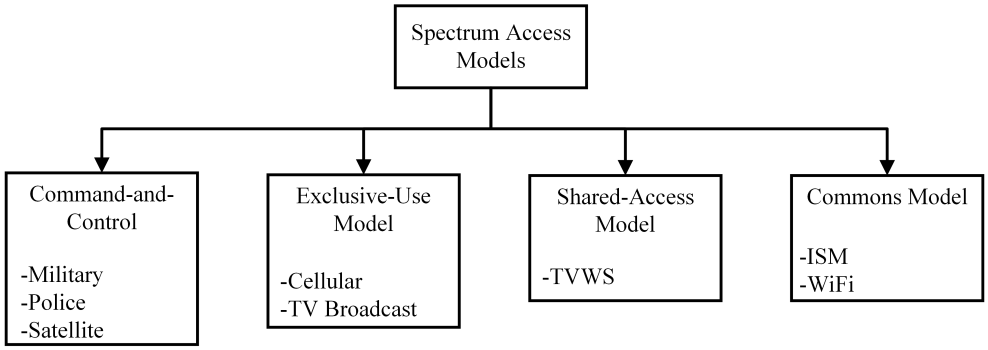


Figure 2.1: Spectrum Access Models

2.2.1 Command and Control Model

In this model, the regulator directly assigns specific bands to entities and applications. These entities have exclusive right to use the spectrum and are guaranteed protection from any interference. This approach is the main assignment model used by regulatory bodies around the world to divide the communication spectrum into specific bands and assign specific bands to services such as security and safety services including police, civil defense, and military services or to specific applications such as TV Broadcast, satellite, and mobile applications. Incumbents of these bands are labels "primary users" of the bands and are guaranteed interference-free operation from any other transmission.

2.2.2 Exclusive Use Model

In this mode, the incumbent is assigned a spectrum band and guaranteed interference-free operation for a limited (short-term or long-term) period of time. Assignment of this type is usually done through spectrum auctioning and other market-based mechanisms and involve lengthy processes generating large revenues for the regulating entity. Example of exclusive use assignment is cellular bands auctioning to different operators.

2.2.3 Common Use Model

The common use model is the most open approach to spectrum access no entity can claim ownership of the common spectrum. Access is unrestricted self-regulated to designated spectrum bands such as the Industrial Scientific and Medical bands (ISM) used by applications such as Wi-Fi. However, with common access comes the problem of degrading quality of service as no guarantees are in place for interference-free operation for users of the common spectrum. With increasing users and applications in the common spectrum congestion becomes a real problem

2.2.4 Shared Use Model

This model is a hybrid between the exclusive use and the common use model. In the shared use model access to an exclusive band is shared between a primary user (or application) and one or more users dubbed "secondary users". The primary user is still entitled to protection from harmful interference, while the secondary users in this access mode have no such guarantee. This model allows for utilization of assigned but unused bands in order to solve the spectrum scarcity problem. Spectrum sharing can be achieved through *spectrum underlay* or *spectrum overlay*:

1. Spectrum Underlay In spectrum underlay, the secondary user's signal is transmitted simultaneously within the same frequency bands as the primary user in such fashion as to not cause interference. the main mechanisms for spectrum underlay are *spread spectrum* and *Ultra Wide Band* communications. In spread spectrum the transmitted

signal is modulated on a wide range of frequencies either with frequency hopping or direct sequence methods as to not cause interference with the primary user. In UWB communications the signal is modulated on very large band range (>500MHz) with low transmission power. Spectrum underlay enables sharing of the spectrum over short ranges with low power.

2. Spectrum Overlay Spectrum overlay is a full spectrum sharing model where secondary users can fully utilize the spectrum when, and where, the primary users is not actively using it. In order for secondary users to use the spectrum in spectrum overlay mode they must first *sense* the spectrum to detect wither or not the primary user is transmitting at the current location and only transmit if no primary transmission is detect. Furthermore, the secondary users must refrain from further transmitting if they detect a primary transmission while utilizing the spectrum. These capabilities do not exist in conventional radios and in order to realize spectrum overlay sharing a new Cognitive Radio is needed.

2.3 Cognitive Radio

Cognitive Radio (CR) is a new communications paradigm that holds the potential to change the wireless communications word. First envisioned by Joseph Mitola in 1999 [6], a CR combines Machine Learning and Artificial Intelligence capabilities with configurable Software Defined Radio (SDR) to create a smart communication device that can selectively and adaptively change it's communications parameters according to changes in the surrounding environment. Therefore, CRs allow for the coexistence of multiple services (or users) in the same spectrum band by means of Spectrum Sensing (SS) and Dynamic Spectrum Access (DSA). In DSA the spectrum is shared amongst the incumbents of the spectrum (Primary Users or PU) and one or more Secondary Users (SU). SUs opportunistically and dynamically access the spectrum band whenever and wherever the PUs are not active. Successful coexistence is thus contingent on accurate spectrum sensing by SUs and correct identification of times and locations at which the PUs are not utilizing the spectrum. Failure to do so will result in harmful and unacceptable interference to the PU.

2.3.1 Cognitive Radio Definitions

Since it was first envisioned by Joseph Mitolla in 1999 [6], Cognitive Radio has generated wide spread attention among the research and professional communities for its potentials to revolutionize the wireless communications world. Cognitive Radio is viewed as a solution for the spectrum scarcity problem and a potential candidate for next generation wireless networks. Some definitions of cognitive radio from the literature include:

- An intelligent wireless communications system aware of its surrounding environment and adapts its internal state to statistical variations in the environment by adopting communication parameters and modulation strategies in an on-line fashion [2]
- A Cognitive Radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates [7]
- A Cognitive Radio is a radio that is able to sense, adapt, and learn from its operating environment [8]

From the multiple definitions above, a CR will have to perform a set of common tasks in order to fulfill its definition as a Cognitive Radio. These tasks are sensing, learning, and adaptation.

2.3.2 Basic tasks of Cognitive Radio

In order for a CR to achieve the promised intelligent communication and environment adaptation outlined in the definitions above, it has to perform the following tasks:

1. Spectrum Sensing (detection of spectrum holes)

2. Spectrum Analysis (detection of the characteristics of spectrum holes, channel-state estimation and predictive modeling)

3. Spectrum Access (transmit or not to transmit, select transmission parameters)

A CR system will continuously execute those tasks in what is known as the cognitive cycle. Figure 2.2.

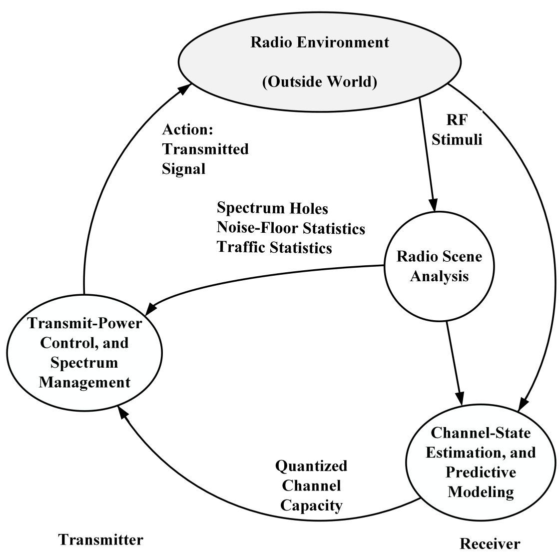


Figure 2.2: Basic Cognitive Cycle [2]

2.3.2.1 Spectrum Sensing

Spectrum sensing refers to the steps taken by a cognitive radio to perceive the communication environment parameters and determine its status. In order to achieve precise cognitive communications, the cognitive radio unit has to correctly sense if the spectrum is being used by the primary user or not. Failure to detect a busy channel will result in collision with the primary user's communication; alternatively, failure to detect an idle channel will result in missing a transmission opportunity and can thus decrees the communication throughput and efficiency.

Many techniques can be used to sense the usage of the spectrum. Some of the most cited methods are:

1. Energy Detection

   Energy detection is the simplest form of spectrum sensing and consists of estimating the power of received signal y. If P_y is greater than a specific threshold λ, then a signal is said to be detected. Otherwise the spectrum if free.

$$y(n) = x(n) + w(n)$$
$$P_y = \sum |y(t)|^2$$
$$Decision = \begin{cases} \text{Signl detected,} & \text{if } P_y \text{ is } >= \lambda \\ \text{No Signal Detected,} & \text{if } P_y \text{ is } < \lambda \end{cases}$$

   Energy detection however has many downsides. The decision accuracy is highly dependent on the threshold value and CR using energy detection only cannot distinguish between different signals, can not detect spread spectrum signals, and has been shown to perform poorly in fading environments [9].

2. Matched Filter

   As the name implies, a specific filter is used to match each signal to each expected waveform. This is the best possible detection technique were the signal is matched to a known waveform with high accuracy and low false alarm rate. The issue with matched filter approach is the high complexity and high power associated with matching different signals with different waveforms using a set of filters.

3. Cyclostationary Feature Detection

   Information is embedded in signals using modulation techniques resulting in periodicity in the signal or its features such as mean and variance. While Energy Detection uses the Power Spectral Density (PSD) to identify a signal from noise, the Cyclostationary approach utilizes the Cyclic Spectral Density (CSD) to differentiate signal from the Wide Sense Stationary noise (WSS). Moreover, each signal will have a different Cyclic Spectral Density and a Cyclic Auto-Correlation Function (CAF) thus differentiating different signals from one another.

   The CSD of a signal can be calculate as:

   $$S(f,\alpha) = \sum_{t=-\inf}^{\inf} R_y^{\alpha}(t) e^{-j2\pi f t}$$

   Where $R_y^{\alpha}(t)$ is the CAF and equals:

   $$R_y^{\alpha}(t) = E[y(n+t)y^*(n-t)e^{j2\pi\alpha n}]$$

   The CSD value is peaked at the cyclic frequency α. The detection accuracy is increased with increasing the number of features. However, that comes with a cost of increased complexity. Hardware Cyclostationary implementations are mentioned in the literature [9].

4. Multi-technique based approach

   Multiple spectrum sensing techniques can be combined to estimate the spectrum occupancy. Using information fusion such as Maximum A posteriori Probability (MAP), this approach can maximize detection accuracy while minimizing false detection rate[10].

2.3.2.2 Spectrum Analysis

In the spectrum analysis stage, the cognitive unit constructs a predictive model to predict how long can spectrum holes be available for in the future based on the sensing data of the previous step. Analysis can be distributed or centralized. In distributed analysis, each nodes models the environment independently of other nodes, while in centralized analysis nodes in the CR network send their perspective of the environment to a central analysis node that based on a predictive model computes the frequency holes characteristics and channel statistics and this information is then propagated back to the nodes.

2.3.2.3 Dynamic Spectrum Access

After spectrum holes are sensed, and their future characteristics have been probably determined, CRs access the spectrum dynamically and opportunistically. Issues of coordination and competition arise from such dynamism. If multiple CRs detect the spectrum as being available and try to access it at the same time collision is inevitable . Therefore, techniques for coordination between multiple users are needed to avoid collision and to ensure maximum spectrum utilization. These techniques can be categorized into two main categorize:

1. Non-Cooperative Spectrum Access

In non-cooperative spectrum access each nodes tries individually to access the spectrum with different access strategies. Access strategy can be conservative or aggressive depending on false alarm and miss-detection probabilities. Game theory is an important tool in analyzing and optimizing non-cooperative spectrum access.

2. Cooperative Spectrum Access

   In cooperative spectrum access, a group of CRs cooperates to achieve the optimum spectrum sharing scheme. The cooperation can be centralized or distributed. In the centralized version, a central server maintains access information and fairly distributes available spectrum holes among secondary users 2.3. Distributed cooperative access, on the other hand, depends on cooperation of users by exchanging local information to form a global model of the environment 2.4.

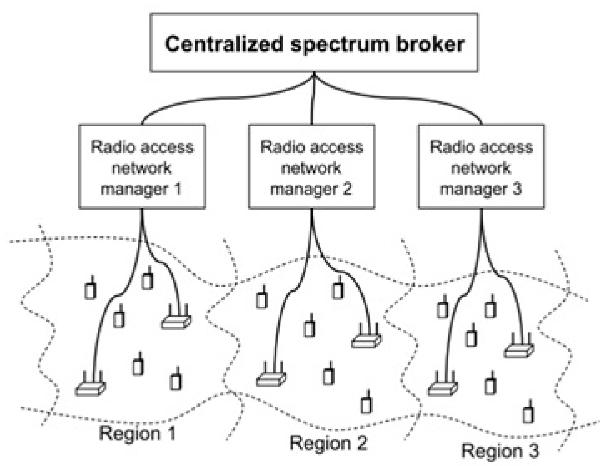


Figure 2.3: Centralized Spectrum Access [3]

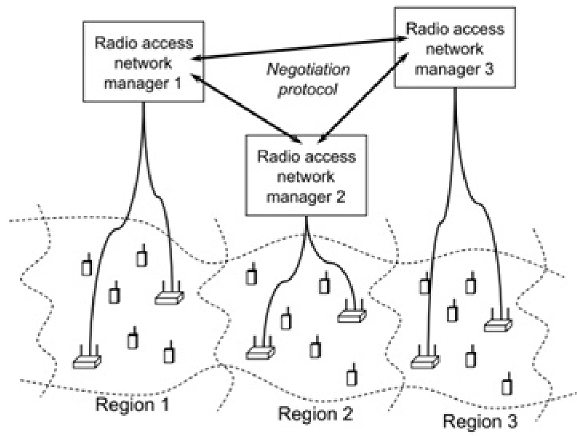


Figure 2.4: Distributed Spectrum Access [3]

2.3.3 Software Defined Radios

In order for a radio system to perform the tasks of a Cognitive Radio, it has to modify its operating parameters in real-time according to variations in the environment. These variations include:

- Varying the operating frequency
- Varying the modulation technique
- Varying the transmission power
- Varying the communication technology

Performing all of these reconfigurations requires a highly flexible architecture that can adapt to the environment. Software Defined Radios (SDR) provide such flexibility and are as such seen as an excellent candidate for Cognitive Radio implementation. In SDR most of the signal processing from modulation, demodulation, coding, and synchronization is performed by software and the hardware is reduced to basic radio functionalists such as ADC/DAC conversion and filtering in order to maximize programmable and flexibility. The main blocks of SDR are displayed below.

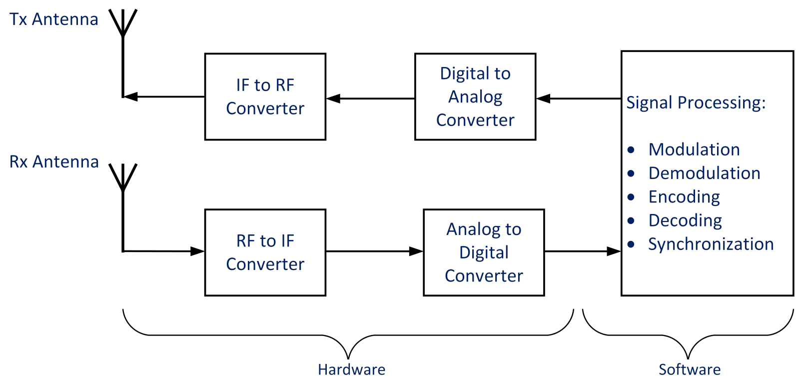


Figure 2.5: Example Architecture

Multiple SDR implementations are available for consumers and researchers. The most commonly used SDR platform for research use is the the Universal Software Radio Peripheral (USRP) developed by Ettus research [11]. The unit incorporate FBGA based circuitry for fast signal processing. Daughter boards can be connected to the main unit to enable transmission and reception of in different frequency ranges. The down side of the platform is it cost.

One other popular and simple SDR implementation is the family of SDR receiver dongles based on the RTL2832U chipset by Realteck. The chipset was originally developed for DVB-T reception however it was soon discovered that dongles with the RTL2832U are basically SDRs[12]. The dongles provide basic radio front-end functionality and supplies a Q/I signal data that can be fed to a PC or an embedded system running any SDR software. The Q/I data provides full representation of the signal and is thus sufficient for any signal processing the SDR software will do. Figure 2.7 below shows the Q/I signal representation.

Figure 2.6: Universal Software Radio Peripheral (USRP) with daughterboard

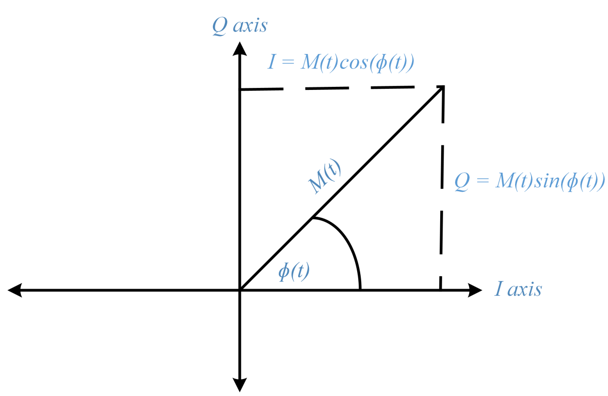


Figure 2.7: Q/I Signal Representation

Figure 2.8 below shows the block diagram of the TERRATEC RTL-SDR receiver dongle and its main components. This particular model uses an Elonics E4000 tuner chip that supports reception of frequency ranges from 48MHz to 2.3 GHz. The received signal is selected using the tuner and then converted from analog to digital and supplied to the USB port as a Q/I signal sampled at a rate of 2.5M samples per second.

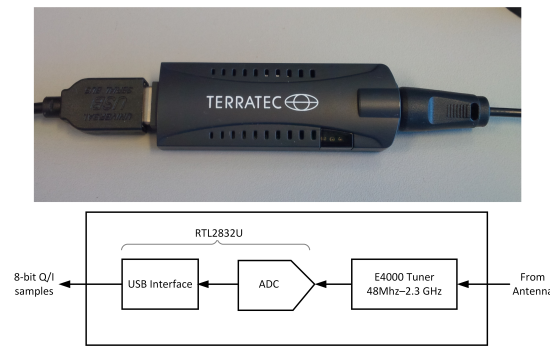


Figure 2.8: TERRATEC STL-SDR Receiver Dongle

2.4 TV White Space

2.4.1 What is TVWS?

TV White Space (TVWS) refers to the underutilized frequency bands in the VHF and UHF (Very High Frequency and Ultra High Frequencies respectively) that are traditionally allocated to terrestrial TV broadcast services. In most regions of the world much of this white space is in the range of 47-790MHz. The availability of these bands varies widely in size and location from country to country and from region to region. The term white space originally referred to the guard bands deliberately left blank between analogue TV channels to avoid interference. The term has become more reminiscent of the nature of the TV spectrum after the transition from analogue to digital TV broadcast in many regions and countries resulted in wide ranges of these bands being unused and usually referred to as *Digital Dividend*. While some of the Digital Dividend in some countries is assigned for mobile service, the nature of TV broadcast planning and frequency use still allows for opportunistic access of secondary devices to these bands without interfering with the primary TV broadcasters.

2.4.2 Why TVWS?

Harvesting this unused TVWS is of great importance because of the superior properties of the VHF and UHF bands. Devices transmitting in the VHF and UHF range require lower power and the signal can travel longer ranges compared to the higher frequencies such as the 2.5 GHz used for WiMax for instance. Current standards implementing TVWS such as the IEEE802.22 WRAN promise to provide coverage from a single base station for up to 30-100km [13]. In addition, VHF and UHF frequencies have superior propagation properties both indoor and outdoor where no line-of-sight is required for good reception. These and other characteristics make TVWS technologies a good candidate to provide broadband wireless information services to rural areas with minimum infrastructure investments.

In theory, CRs are capable of spectrum sensing and detection of PU activity to avoid interference. In practice however, much work still needs to be done before this capability is fully realizable. For that reason, regulators around the world are not yet allowing secondary use of the spectrum based on CR technology alone. As a result, a TVWS geolocation database approached is taken.

2.4.3 TVWS Geo-Location Database Model

A TVWS geo-location database (TVWS-DB) is a database of available TVWS channels that White Space Device (WSD) must consult in order to determine which bands are free (white) and which bands are not. The TVWS-DB is maintained by either the regulator or a licensed administrator. WSD can access this TVWS-DB directly through an administrator or a spectrum broker that not only facilitates access to the database, but also insures proper operations of secondary networks by means of spectrum management. The regulator maintains oversight over the entire process to ensure compliance of the TVWS-DB administrators and accuracy of its data. The next diagram outlines the relationship between the regulator, the database administrator or spectrum broker, the primary user, and the secondary users in TVWS applications.

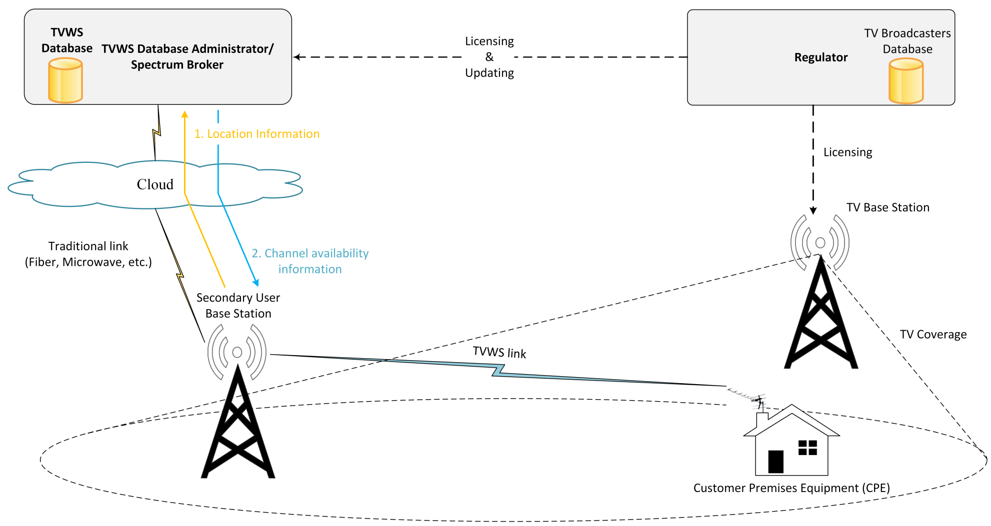


Figure 2.9: TVWS geo-location database access model

2.4.4 TVWS Standards

Multiple standard have emerged since the inception of CR and TVWS. Two main standard stand out as the main contenders for near-future implementations. These standards are listed below:

- IEEE 802.22, or Wireless Regional Area Network (WRAN), is an IEEE standard for rural areas. Base Stations (BS) consult a white space database (WSDB) to determine available channels and control Customer Premise Equipment (CPE) to avoid interfering with TV broadcasts in the UHF/VHF bands. BSs are also equipped with Cognitive Radio (CR) capabilities to further insure interference free operation. The IEEE 802.22 provides coverage for up to 30-100Km and is thus favorable contender to providing access to underserved rural areas with little infrastructure. Current versions of the standard promise rate of 23-31MB/s at ranges of 30Km [13]

- IEEE 802.11af, also referred to as WhiteFi or SuperWiFi, is another standard by IEEE targeted for the TVWS bands. Final approval of the standard is set for March 2014 [14]. Access Points (AP) are equipped with GPS capabilities to determine their position and consult with a regulator designated white space database (WSDB) to determine available channels and avoid inference. In addition, Cognitive Radio (CR) capability are also used to detect existing transmission and avoid interfering with them. The IEEE802.11af is a WLAN standard and is aimed to provide coverage up to 5Km. theoretical expected data rates vary from 24 MB/s for single channel and can reach up 568MB/s for multiple channels [14]

2.4.5 TVWS Applications

Many applications are envisioned for TVWS, some of them are:

- Wireless Access Technologies, such as:
    1. Extended wireless hot spots: or “Super Wi-Fi” where the range of a single AP can extend to many kilometers depending on the location
    2. Extended wireless back-haul: where many long-range virtual point-to-point connections can be established over white space to regular Wi-Fi access points to provide service to otherwise un-serviced areas
    3. Cellular offloading: where mobile operators can deploy White Space small cells in a multi-tier network to alleviate otherwise congested service areas.
- Machine to Machine (or M2M) communication, such as:
    1. Vehicular Wireless Networks (VANETs): where unlicensed White Space bands can be used for either Vehicle to Vehicle (V2V) or Vehicle to Access Point

(V2AP) communications without incurring the astronomical costs of acquiring dedicated spectrum.

2. Telemetry for Smart Grid applications: where utilities can control and monitor unbounded number of small meters without the need of additional infrastructure to connect all of them.

2.4.6 TVWS Regulation

TVWS represents the first step of the paradigm shift towards spectrum sharing as it proposed "license-exempt" operation of cognitive radio networks in the spectrum bands assigned for television broadcast service. A Geo-Location Data Base framework has been adopted by many regulators around the world where the secondary devices in the TVWS consult with a regulatory credited database that contains the TV broadcasting channels to avoid interference. This scheme is seen as the main facilitating scheme for device wanting to operate in the TVWS. The following is a summary of efforts by the ITU, FCC, Ofcom, and others, for accommodating TVWS devices and systems in their spectrum plans and regulatory policies:

- Global The International Telecommunications Union (ITU) has transferred the responsibility of regulating Cognitive Radio and TVWS devices over to the national regulatory bodies. The ITU World Radiocommunications Conference of 2012 (WRC-12) has concluded that "the current international regulatory framework can accommodate software defined radio and cognitive radio systems, hence dynamic spectrum access, without being changed. The development of systems implementing this concept, such as TV white spaces, is therefore essentially in the hands of national regulators in each country"[15]. The WRC-12 also recommends further studied and investigations of the effects of employing Cognitive Radio systems.

- The United States Much of the regulatory effort made towards enabling Cognitive Radio and TVWS has originated from the Federal Communications Commute (FCC) in the United States. The FCC has laid the grounds for a geo-database of TVWS for secondary access of TVWS based on Cognitive Radio technology. This scheme has since been globally recognized as the main contender for allowing new applications in bands such as the TV band. Since then, multiple such databases were credited by the FCC from several companies such as Google, SpectrumBridge, LS Telcom, and others

- Canada In August 2011, Industry Canada issued a consultation on the possible use of license-exempt TVWS devices in TV broadcast spectrum below 698 MHz. The 700MHz band is set to be auctioned and assigned for cellular mobile service in the 2014-2015 time frame. This may limit the potential for future TVWS applications in Canada

- The United Kingdom In December 2007, the regulatory body in the UK (Ofcom) agreed in principle to allow the operation of TVWS devices in the 470-790 MHz band on a license-exempt basis. In September 2011, Ofcom concluded a consultation on implementing geo-location, and as a next step will issue guidelines on the operating requirements for geo-location databases for prospective administrators. The UK is also in the process of determining operating parameters for its geo-location databases. In a recent consultation, six organizations expressed an interest in becoming a TVWS database provider

- The European Union CEPT and European Commission are working on the technical and regulatory conditions that would enable introduction of cognitive radios in the UHF TV white spaces. ECC report 159-53 provides technical and operational requirements for cognitive radio systems in the white spaces of the frequency band 470-790 MHz in order to ensure the protection of the digital broadcasting, and other existing services in the adjacent bands. The report is considering the potential benefit in using a combination of sensing and geo-location database to provide adequate protection to digital terrestrial television receivers [15]

- Trials in Africa

  - South Africa: Google announced a partnership with the Independent Communications Authority of South Africa (ICASA) and Carlson wireless to deliver wireless access to 10 schools through 3 base stations at the campus of Stellenbosch University's Faculty of Medicine and Health Sciences in Tygerberg, Cape Town

  - Kenya: A pilot project by Microsoft and the Kenyan government is reportedly delivering bandwidth speeds of up to 16Mbps to three rural communities which lack electricity: Male, Gakawa and Laikipia [15]

2.5 Related Work

Since the first introduction of Cognitive Radio (CR) by Joseph Mitola in 1999 [6], many contributions on the feasibility and applications of CRs have been published. Simon Hykin in [2] presents a comprehensive analysis CRs and the tasks needed for their realization. These features can be realized through Software Defined Radios (SDRs) and many platforms and implementations are now available for both researchers and commercial applications [16] [11] [12].

Through CR, Dynamic Spectrum Access (DSA) can be achieved allowing Secondary Users (SUs) to opportunistically and dynamically access spectrum that is assigned to Primary Users (PUs) while it is not being utilized. In order for SUs and PUs to coexist, SUs must possess CR capabilities for sensing the spectrum to determine spectrum availability before transmission in order to avoid interfering with PUs. For this reason, spectrum sensing has been the most researches aspect of CRs for a while with multiple proposals for spectrum sensing protocols and techniques that aim to achieve interference free operation of SUs in DSA [9]. Due to fundamental issues related to radio propagation and detection, problems such as the hidden node problem were a CR cannot detect a PU signal that is being blocked by natural obstacles raise real concern when it comes to PU protection from SU. For this reason, DSA frameworks has to exist to ensure coexistence between PU and SU in a Cognitive Radio Network CRN.

Many such frameworks for DSA are introduced in the literature. Some are distributed and rely on techniques such as cooperative spectrum sensing [9] where SU relay spectrum status information to each others to avoid accessing the spectrum while its occupied by the PU. However, for practical scenarios such as utilization of TV White Space, centralized approaches for DSA are proven to be more reliable. For this reason, the centralized geo-location database framework has been proposed and approved by the FCC and many regulators for DSA in TVWS. TV White Space (TVWS) is the underutilized spectrum bands in the manly UHF range of 470MHz to 790MHz. These bands are of great physical properties and highly desirable for wireless transmission. A centralized geo-location database model allows coexistence of SUs and PUs in the TV spectrum by keeping track of location-based channel availability information in a centralized database that can be queried by SUs before accessing the spectrum. For obvious reasons of varying regulations and operational conditions, TVWS frameworks and databases need to be developed for each country before secondary use of TVWS can be allowed.

TVWS estimation studies have been conducted in various parts of the world. In [17] the authors study the availability of TVWS in 11 European countries using the ITU-R P.1456 and the Longley-Rice (ITM) models. They concluded that almost 56% of the 470MHz-790MHz UHF bands are available with only co-channel protection. This number drops to 25% if adjacent channel restrictions are applied. The study only considered transmissions from TV stations. In [18] the authors present their results for TVWS availability in Italy and conclude that TVWS in Italy is available mostly in areas with light population density. A threshold-based approach is used in this study. Further studies are conducted for TVWS availability in India [19], Australia [20], and Japan [21]. All of these studies confirm the potential of TVWS technology in providing additional spectrum for existing and new applications but with varying degrees in each country.

To the author's best of knowledge, there has been no previous attempt to estimate the availability of TVWS in Libya or construct a TVWS access and management model in the country. This work aims to close this gap by presenting a comprehensive system design for spectrum management in TVWS based on an adaptive cognitive framework. In addition, TVWS availability is estimated in various test regions in Libya using radio propagation analysis and elevation models and a TVWS database is constructed.

Chapter 3

Proposed System Design

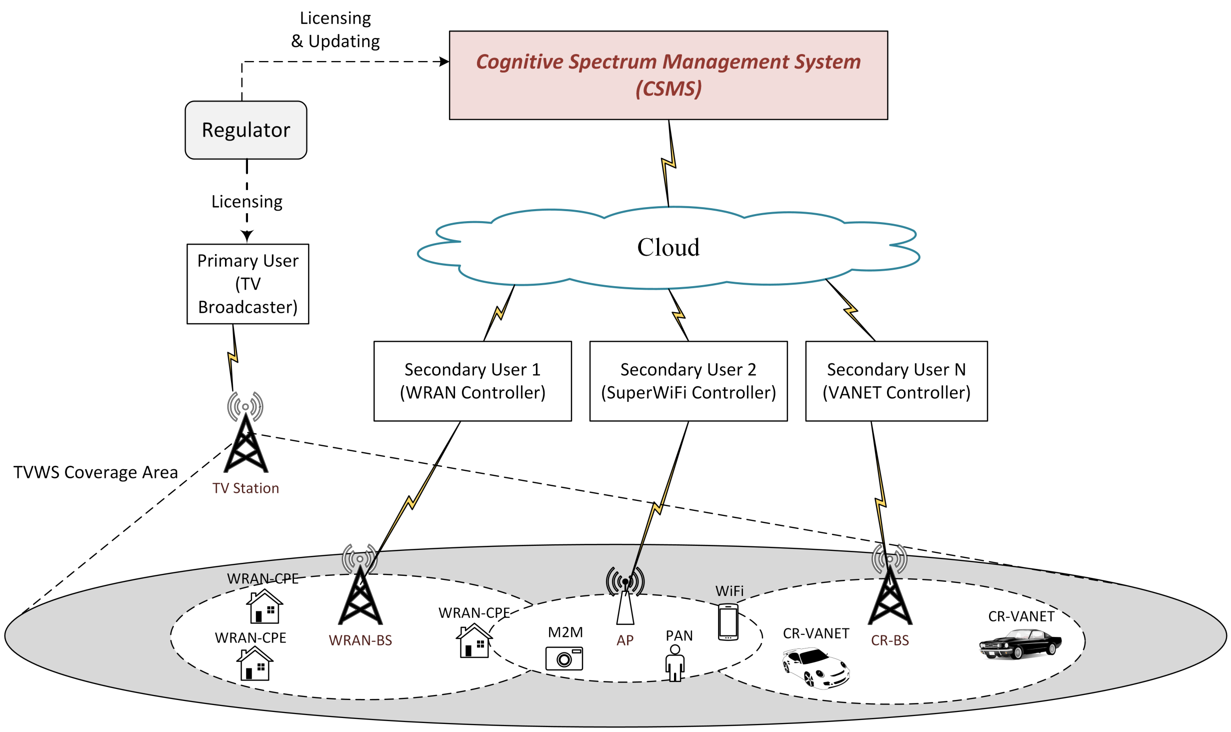
3.1 Introduction

This chapter presents the design of a Cognitive Spectrum Management System (CSMS) for spectrum management in TVWS. A cognitive framework is adopted to allow the system to adapt to varying regulatory, economical, and application requirements. Requirements are received and translated via a Requirement Translation Layer while a Network Interface Layer provide interaction with users. Multiple secondary users compete for spectrum access on secondary bases in a specified geographical area by submitting requests to the CSMS with their location coordinates. The CSMS utilizes the TVWS database and a spectrum manager to allocate spectrum to each secondary user while meeting coexistence requirements. The rest of this chapter is designed as follows: First a summary of system design assumptions is given followed by the details of the cognitive framework. The details of the CSMS design are outlined last.

3.2 System Design Assumptions

The proposed design is intended to be at the core of a centralized TVWS spectrum management framework that can be deployed by the regulator or a third-party management entity (spectrum broker or TVWS database administrator). The spectrum manager is authorized by the regulator to mitigate between independent entities attempting to utilize the TVWS in a geo-location database TVWS access model such as the one in figure 3.1.

The primary users are the TV broadcasters that must be protected from harmful interference. The secondary users are new applications attempting to utilize the TVWS through querying the TVWS database through the spectrum manager. We assume master base stations or network managers for the secondary users capable of managing customer terminal equipments in terms of operation frequency and power in order to determine the overall required resources and change the operational parameters of these equipments. The base station can connect to the spectrum manager through a conventional back-haul link and can then query the spectrum manager for available channels in its coverage area to meet users' demands. These assumptions are in-line with current IEEE802.22 WRAN [13] and IEEE802.11af Super-WiFi [14].



- TVWS: TV White Space
- CR: Cognitive Radio
- BS: Base Station
- AP: Access Point
- WRAN: Wireless Regional Area Network IEEE802.22 standard
- SuperWiFi: IEEE802.11af standard
- CPE: Customer Premise Equipment
- PAN: Personal Area Network
- VANET: Vehicular Area Network
- M2M: Machine-to-Machine communications

Figure 3.1: Spectrum Management in TVWS

3.3 The Cognitive Framework

The encompassing framework of our system is an adaptive cognitive framework based on a cognitive network model. In this model, end-to-end requirements are met within the system layers through a cognitive process that plans, decides and acts based on observations of the surrounding environment and interfaces to an adaptive network through an interface layer [22]. In our implementation, regulatory, application, and economical requirement are accepted through a Requirements Translation Layer (RTL). A Cognitive Process, implemented within the CSMS, receives translated requirements and end-to-end objectives and optimizes local parameters to meet those objectives. The CSMS interfaces to the Cognitive Radio Network of secondary users through a Network Interface Layer (NIL). Figure 3.2 below illustrated this Cognitive Framework for the CSMS.

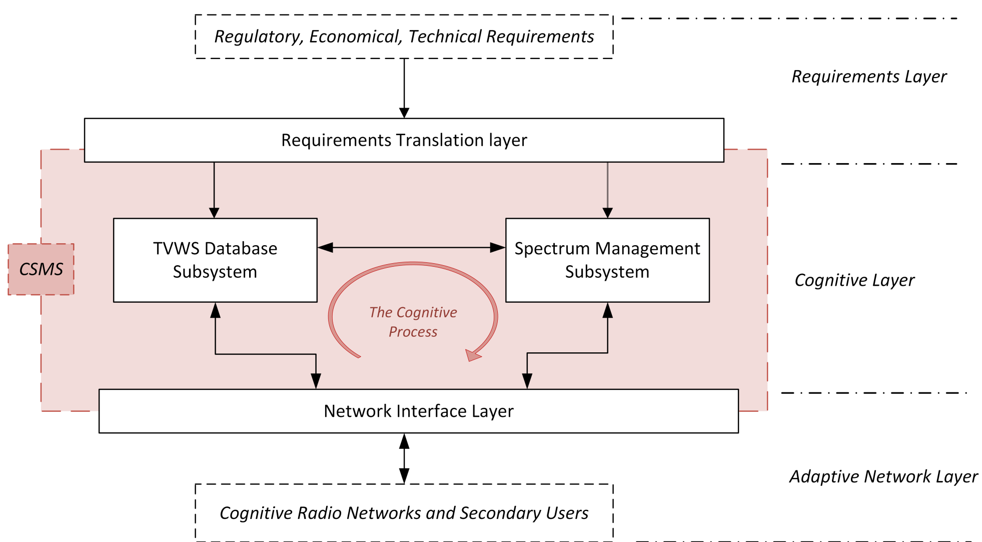


Figure 3.2: The Cognitive Framework

3.3.1 The Requirements Layer

The requirements flow is from top to bottom. Regulatory, application, and economical requirements are received and translated by the Requirements Translation Layer. The resulting parameters and objectives are then fed as inputs to the CSMS. Further detailing of these requirements is given below:

1. Regulatory Requirements

   Regulations for spectrum sharing are set by the regional and global regulatory bodies to ensure coexistence between the primary and secondary users of the spectrum. In TVWS, the regulator sets the general framework for secondary usage of the TV spectrum that ensure protection of the TV broadcast and other applications in the spectrum such as wireless microphone devices and astronomical radios from harmful interference white space devices may produce. Examples of regulatory-set requirements include:

   - The criteria of determining TVWS including minimum threshold for acceptable TV signal reception below which a channel can be deemed as white space
   - The maximum allowable transmission power for secondary fixed and mobile devices in the TVWS that insures no interference to neighboring primary receivers
   - The protection contours of primary transmitters inside which no secondary transmission is allowed
   - The maximum allowable antenna heights for secondary users
   - Any other criteria that the regulator may set to ensure protection of primary services and users

These requirements must be set within a regulatory framework for secondary spectrum access in TVWS. The details of such framework entail licensing and legal procedures that are beyond the scope of this work. However, the flexibility offered by the proposed cognitive framework should allow for easier adoption of the CSMS to different regulatory frameworks.

2. Application Requirements

   Multiple applications and standards are proposed to operate in the TVWS. The most prominent of which are the WRAN IEEE802.22 and Super-WiFi IEEE802.11af. Each standard has a different set of characteristics and requirements. The CSMS must meet these requirements in order for secondary devices to operate probably in TVWS. These requirements may include:

   - Quality of Service (QoS) parameters such as: maximum delay, minimum throughput, and minimum bandwidth for each connection
   - Maximum number of secondary terminal supported by each base station
   - Coverage radios of secondary user base station
   - Physical layer characteristics such as: supported modulation techniques, frame size, and data rates.

   The inclusion of these characteristics in the requirements set will allow the system to meet the demands of different secondary user to the best extent while protecting primary users from any interference.

3. Economical Requirements

   These are the rules governing the interactions between the primary users and the secondary users in the shared spectrum environment. Game theoretic algorithms and pricing schemes can be incorporated by the spectrum manager to efficiently and fairly allocate spectrum between competing users while meeting these requirements. These requirements may include:

- Spectrum sharing model (Auction, fixed price, variable price, etc.)
- Licensing prices for secondary use of spectrum in TVWS
- Spectrum prices
- Market model (monopoly, oligopoly, or competitive)

Economical factors are the main drive towards the adoption of spectrum sharing. While TVWS is seen mainly as license-exempt spectrum, introduction of pricing can have the effect of a control factor that will not only generate revenue, but can also improve the quality of service in a shared spectrum environment [23].

The Requirements Translation Layer accepts these high level requirements and interprets them into parameters that define the operation of the TVWS Estimator and the Spectrum Manager.

3.3.2 The Cognitive Layer

The cognitive layer is the core of the cognitive framework and where the requirements optimization is achieved in the “Cognitive Loop”. Different implementation of such loop are suggested in the literature. Mitola presented the “Cognitive Cycle” for Cognitive Radios in [6] where the environment is sensed and internal radio parameters are adapted based on intelligent planning and decisions steps. In [22] Thomas et. al. present a simpler OODA (Observe, Orient, Decide, and Act) for Cognitive Networks. The purpose of all different versions of these loops is to introduce intelligence to the system through iterative steps that mimic the cognitive process in humans.

The CSMS is implemented in this layer and a Cognitive Loop is formed from iterative interaction between the components of the CSMS to optimize the TVWS estimation and allocation process. The formed loops is adapt from the OODA loop presented in [22] and consists of the following steps:

1. Observe

   The CSMS collects information about the radio environment from regulatory sources (TV broadcasters' information) and (optionally) sensors on the ground in order to construct a full view of all transmitters in the managed area. This include information such as transmitters' locations, transmitters power, transmitters' antenna height, and any other radio environment data.

2. Analyze

   Using the collected environment information, the system estimates the coverage of each transmitter using propagation models coupled with elevation data in order to later determine spectrum availability at every location.

3. Decide

   In this step the CSMC determines if a specific frequency at a specific location is considered white space or not. This decision is made for all frequency channels for all possible locations in the managed area.

4. Act

   Here the system assigns the designated white spaces to secondary users requesting spectrum for the CSMS.

The figure below illustrates this cognitive loop.

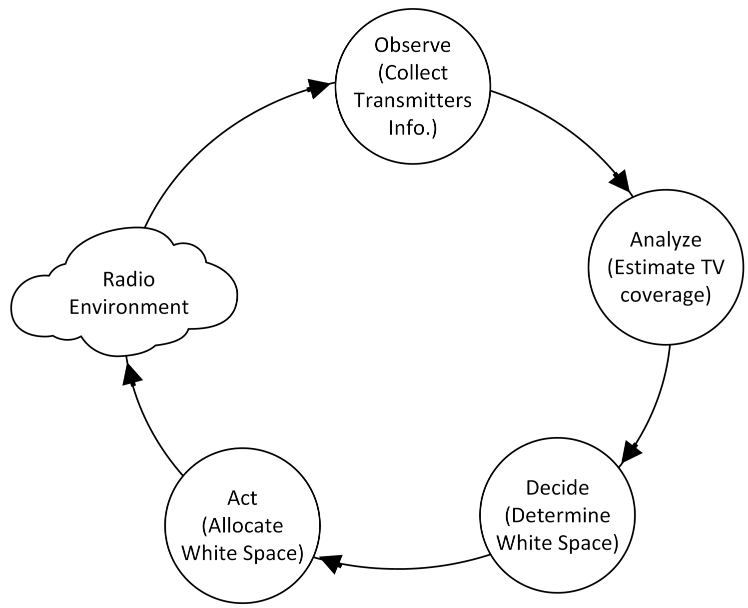


Figure 3.3: The Cognitive Loop

Further details on corresponding functions in the CSMS model implementing these steps will be given in section 3.4 of this chapter.

3.3.3 The Adaptive Network Layer

The system interfaces to cognitive networks that operate as secondary users in the TVWS domain. The interfacing is done through a Network Interface Layer (NIL). This layer provides three main functionalists:

1. Receive spectrum requests from the secondary users and provide the necessary interfacing to translate these requests and forward them to the CSMS.

2. Send spectrum assignments in response to the received requests to the secondary users.

3. Receive cognitive radios' sensing information of the surrounding environment to detect ongoing transmissions by primary users and report these sensing results to the CSMS. The TVWS Estimator in the CSMS can utilize this data to enhance its estimate of the available white space through fusion of information from the regulatory sources and sensing sources. The implementation of such fusion is out of the scope of this work.

3.4 The Cognitive Spectrum Management System

In a spectrum sharing environment where secondary users can access frequencies originally assigned to primary users who are not fully utilizing the band, a centralized database is essential to provide the necessary protection of primary users from harmful interference that secondary users may cause. However, a simple database approach may only ensure coexistence between primary users from one side and secondary users from another. In order to ensure coexistence between secondary users as well, a more comprehensive approach where a spectrum manager allocates white space to secondary users in a manner that does not cause interference between themselves is necessary. For this purpose, we design a *Cognitive Spectrum Management System* that comprises of a *TVWS Database System* and a *Spectrum Management System* to efficiently and effectively allocate available TVWS to secondary users while meeting high level requirements. Figure 3.4 below shows the full CSMS with interfaces.

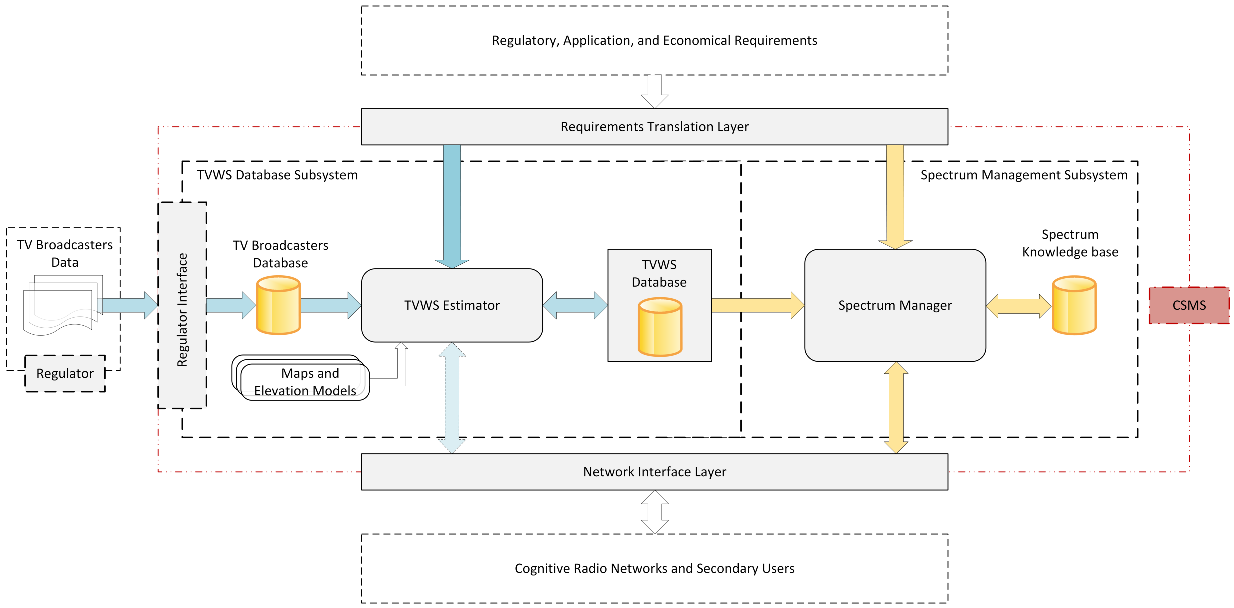


Figure 3.4: Cognitive Spectrum Management System (CSMS) Architecture

3.4.1 TVWS Database Subsystem

A comprehensive and adaptive design is adopted for the TVWS Database Subsystem where information from the regulatory sources on the state of the TV spectrum and broadcasting stations is gathered and inputted to the system periodically through a dedicated regulatory interface. This information is then used to estimate the availability of TVWS and populate a TVWS database with channel availability information for all locations on the map. This process is executed while meeting requirements collected through the requirements translation layer. This model allows the system to accommodate variations in regulatory rules from region to region such as changes in the TVWS estimation methodology, the received power threshold above which a channel is considered to be occupied, or the maximum allowed antenna height. A model of the TVWS Database System is presented in figure 3.5 below.

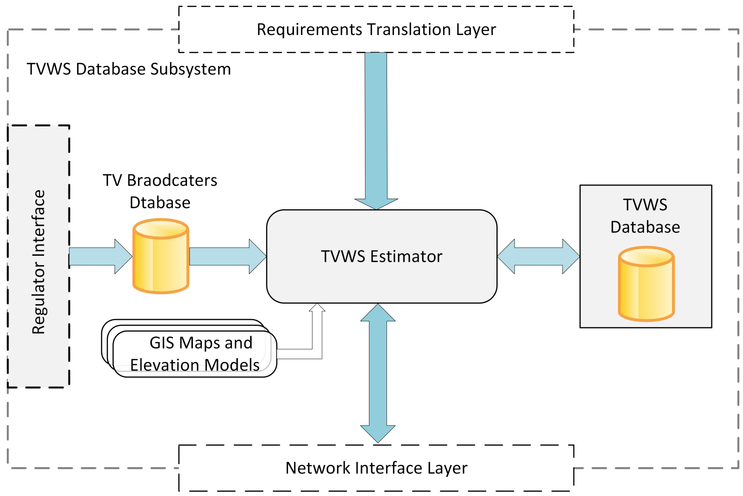


Figure 3.5: TVWS Database Subsystem

3.4.1.1 TVWS Database Subsystem Components

The database system consists of the following components:

1. Regulatory Interface

   An interface to the regulatory information sources such as TV broadcasting stations data and licensed wireless microphones and transmitter in the TV spectrum that must be protected from harmful interferences. Through this interface, regulatory data is updated periodically either on-line or off-line and translated from various formats supplied by regulators into a standard system format and stored in a repository for use by the TVWS Estimator. The TV Broadcasters Database contains up-to-date information on incumbent TV broadcasters such as:

   - Transmitters locations
   - Transmission frequencies

- Transmission power
- Antenna height
- Transmission type

And any other regulatory supplied data that is crucial in insuring protection of TV transmission.

2. TVWS Estimator

   To construct a full picture of the TV spectrum occupancy, a TVWS Estimator conducts extensive radio coverage calculations based on information obtained from the regulator on TV broadcasting stations stored in the TV Broadcasters Database. The estimator combines this data with geographical information and models such as elevation data, terrain type, clutter information, population information and any other data crucial in the radio coverage calculation. The results of radio coverage calculations are then used to predict the availability of TVWS in the geographical area to be administrated by the system. The TVWS availability data is then stored in a TVWS Database.

   The TVWS Estimator is interfaced to the network through the Network Interface Layer. This allows the network users to directly query the TVWS database or send channel sense data to the TVWS Estimator. This data can be used to augment regulatory information in order to better protect the primary users and enhance the channel availability information in the TVWS Database. Implementation of this aspect of information fusion is left to future work. More details on the design of the TVWS estimator algorithm will be given in subsequent sections.

3. TVWS Database

The TVWS Database is a pivotal component of the system and where channels availability information is stored. The database replied to queries of channel availability and supplies information such as:

- What channels are available for secondary use in the TV spectrum (White Space)
- Wither a specific channel in a certain location is available for secondary use or not
- What is the allowed transmission power at any available channel
- What is the total available spectrum at any specific location for secondary TVWS use This information is obtained by the Cognitive Spectrum Manager and is used to manage the TVWS spectrum.

3.4.1.2 TVWS Estimator Algorithm

Estimating the availability of TVWS depends heavily in regulatory set parameters and rules that define the protection regions for TV transmitters and received power threshold for acceptable TV reception for example. Different methods are adopted by different regulators. We adopt a threshold-based model and design an algorithm to estimate the availability of TVWS and populated the TVWS database.

In order to compute the availability of TVWS the designated area is first divided into a grid of k x k pixels as in figure 3.6. At each pixel, a virtual receiver is assumed with antenna height h_{rx}. For each receiver, a propagation model is used to predict the received signal strength from every possible transmitter on all frequency channels. If the predicted power from all possible receivers is below a specific threshold, the pixel is designated as white space for the current frequency channel. Algorithm 1 below explains these steps.

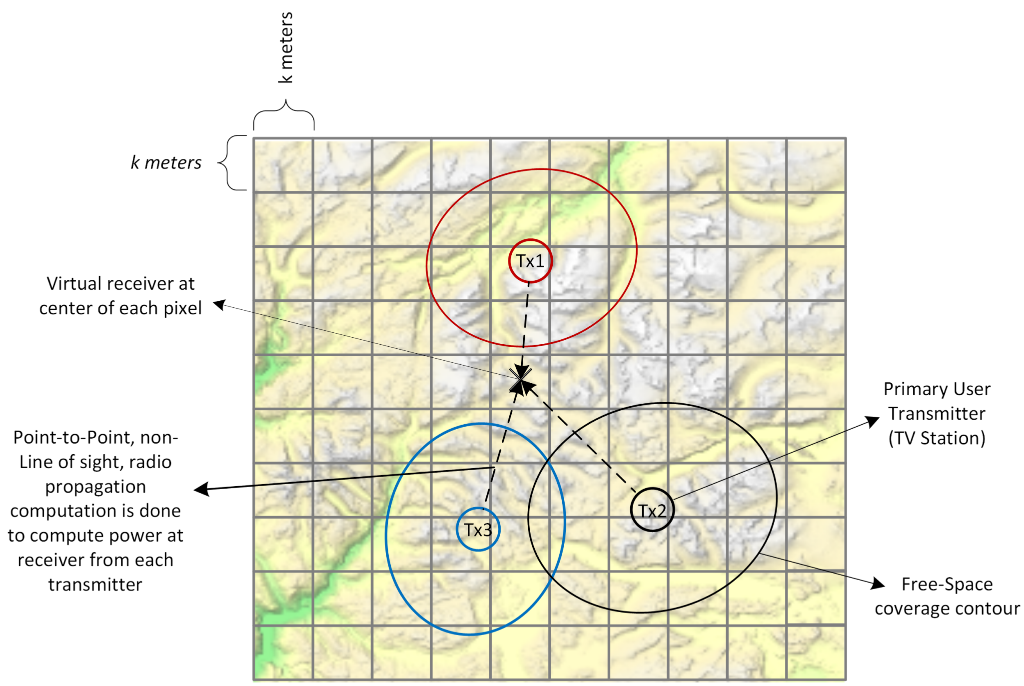


Figure 3.6: TVWS Estimation

```
Data: Receivers, Transmitters, Frequencies, DTM maps
Result: TVWS Database
initialization;
for All Frequencies do
    for all Receivers do
        for all Transmitters do
            Calculate received power at current receiver location;
            if Power >= Threshold then
                Not white space;
                Go to next receiver;
            end
            Designate pixel as white space;
        end
    end
end
```

Algorithm 1: TVWS Estimator Algorithm

3.4.2 Spectrum Management Subsystem

This is the second component of the CSMS and is responsible for managing the TVWS estimated by the TVWS Database Subsystem. Figure 3.7 below illustrates the main components of the system.

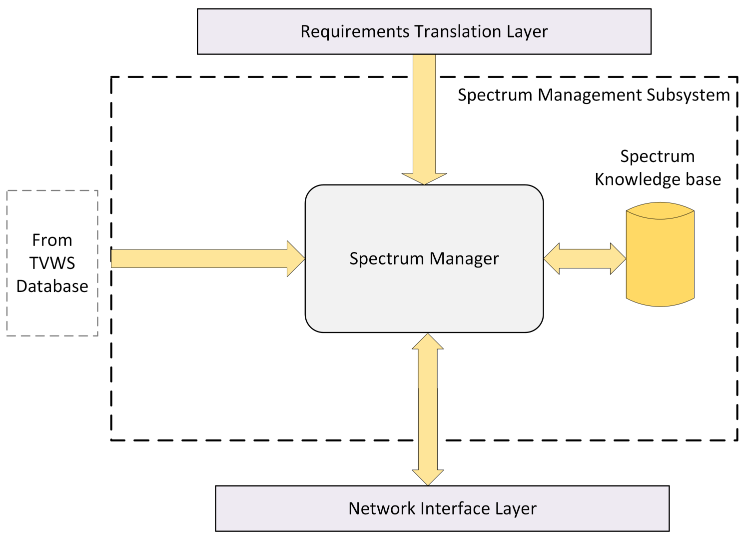


Figure 3.7: Spectrum Management Subsystem

3.4.2.1 Spectrum Management Subsystem Components

The spectrum management subsystem is comprised from a spectrum manager and a Spectrum Knowledge Base.

1. The Spectrum Manager

   The spectrum manager is responsible for distributing the TVWS spectrum amongst secondary users according to requirement conditions to meet two objectives:

- Primary-to-Secondary user coexistence
- Secondary-to-Secondary user coexistence

(a) Primary-to-Secondary User Coexistence

This is the main task of a TVWS management system and is achieved through utilizing the TVWS database. In order for primary and secondary users to coexist, primary users are entitled by regulatory rules to protection from any interference. Secondary users are permitted to operate within the TV spectrum as long as they do not cause interference to incumbents. As such, secondary users are not allowed to operate in geographical locations where any primary transmission is received. The spectrum manager achieves this protection for primary-to-secondary consistence by querying the TVWS database for a set of channels that are “available” for secondary use before any channels can be assigned to any secondary user. The database contains geo-location channel availability information estimated from regulatory data ensuring that secondary users only transmit in channels where there is no risk of primary users being affected by secondary transmissions.

(b) Secondary-to-Secondary User Coexistence

Secondary user’s coexistence amounts to different users being able to operate without affecting, and being affected, by one another while utilizing the TV spectrum on secondary-usage basis. The measure of secondary user’s effect on other secondary users can vary between applications and standards and can range from moderate interferences to sever congestion situations and performance degradation where no user is able to utilize the spectrum if no coexistence measures are in place. The Cognitive Spectrum Manager avoids these issues and achieves Secondary-to-Secondary user coexistence through a three-stage Spectrum Allocation algorithm.

2. The Spectrum Knowledge Base

   The knowledge base is used by the spectrum manager to keep an updated view on the spectrum conditions while performing spectrum assignment tasks. This includes obtaining the latest channel availability information from the TVWS database in addition to previous and ongoing channels assignments made by the spectrum manager. The knowledge base allows the spectrum management subsystem to perform real-time spectrum management without the need to wait for the TVWS database to be updated with new channel assignments.

3.4.2.2 The Spectrum Allocation Algorithm

The spectrum manager employs a three-stage spectrum allocation algorithm to distribute available TVWS spectrum amongst secondary users while meeting the coexistence requirements outlined previously. The algorithm maximizes channel allocation such that there will be no available channels that are un-allocated to secondary users.

The algorithm performs spectrum allocation in the following three stages:

1. Allocated non-shared channels

2. Allocate shared channels between conflicting users

3. Allocate shared channels between non-conflicting users

The algorithm results in all available channels allocate where no conflicting users (with intersecting coverage areas) being assigned the same channel. Adjacent channels are assumed non-conflicting.

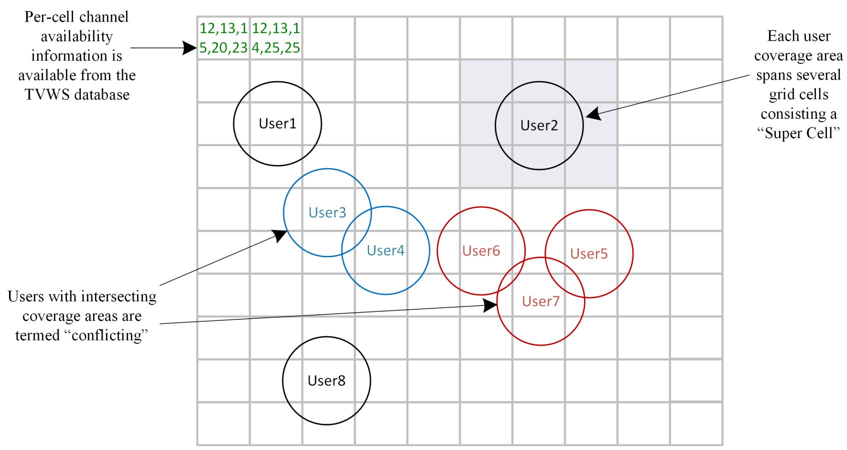


Figure 3.8: Spectrum Allocation

The following steps explain the details of the spectrum allocation algorithm:

1. Secondary Users (SU) wishing to access the TVWS spectrum submit requests to the Spectrum Manager containing their location information.

2. The TVWS database contains a grid G of m x m cells each with a unique cell number and with a set of available channels where no primary signal power is greater than reception threshold at the particular cell location.

$$Ch(Cell_i) = \{c \in C : P_j^c < t, \forall j \in T_p, \forall i \in G\},$$

Where:

C: set of all TVWS channels

G: set of all cells in grid

P_j^c: received power of transmitter j in channel c

t: TV reception threshold above which signal can be detected

T_p: set of all primary transmitters

3. Each secondary user is associated with a Super Cell (SC) consisting of all grid-cells within its coverage reach.

$$SC_i = \{ \; n \in G\text{:} \; \forall \; Cell_n \; \textit{where} \; SC_i \; \textit{signal is received} \; \}$$

4. The spectrum manager queries the TVWS database for channel availability for all cell within each users SC

5. The spectrum manager queries the knowledge base to double check if these channels have been allocated to secondary users previously

6. The set of common channels within an SC is designated as the Available channel set for each SU

7. Location information and coverage radios is used to calculate a Conflict Matrix (CM) to designate users with intersecting coverage areas

8. The spectrum manager performs the following three-stage algorithm:

   (a) Stage I: Allocate Non-Shared Channels. (Algorithm 2 below)

   (b) Stage II: Allocate Shared Channels Between Conflicting Users. (Algorithm 3 below)

(c) Stage III: Allocate Shared Channels Between Non-Conflicting Users. (Algorithm 4 below)

Stage I: Allocate Non-Shared Channels

```
Data: AvailableChannels, SharedChannels, Users, Channels,ConflictMatrix
Result: AllocatedChannels
initialization;
for user i ∈ Users do
    for channel c ∈ Channels do
        if ( c ∈ AvailableChannels(Users(i)) ) then
            shared = 0;
            for user j ∈ Users do
                if ( c ∈ SharedChannels(Users(i),Users(j)) && ConflictMatrix(Users(i),Users(j))
                ) then
                    % User i shares c with user j
                    shared++;
                    Break;
                end
            end
            if ( shared == 0 ) then
                %i does not share c with anyone
                AllocatedChannels(Users(i)) = AllocatedChannels(Users(i))+ {c} ;
                AvaialableChannels(Users(i))= AvailableChannels(Users(i))- {c} ;
            end
        end
    end
end
```

Algorithm 2: Spectrum Allocation Algorithm: Stage I

Stage II: Allocate Shared Channels Between Conflicting Users

Data: AvailableChannels, Users, AllocatedChannels, Clusters

Result: AllocatedChannels

```
initialization;
A. Initiate each user in a cluster
B. Create clusters of users with conflicting coverage areas:
C. Merge intersecting clusters
D. Allocate shared channels within each cluster:
for cluster n ∈ Clusters do
    TotalChannels = unoin(AvailableChannels(users ∈ Clusters(n)))
    while isNotEmpty(TotalChannels) do
        for user i ∈ Clusters(n) do
            C = intersect( TotalChannels , AvailableChannels(Users(i))) ;
            if ( C == empty) then
                continue ;
            end
            c = C(1); % select first channel;
            AllocatedChannels(Users(i)) = AllocatedChannels(Users(i)) + {c};
            TotalChannels = TotalChannels - {c};
        end
    end
end
```

Algorithm 3: Spectrum Allocation Algorithm: Stage II

Stage III: Allocate Shared Channels Between Non-Conflicting Users

Data: AvailableChannels, AllocatedChannels, Users, ConflictMatrix

Result: AllocatedChannels

```
initialization;
for user i ∈ Users do
    C = setdiff( AvailableChannels{Users(i)} , AllocatedChannels{Users(i)})
    if C is not empty then
        %channels are available and not allocated
        for channel c ∈ C do
            allocated = 0;
            for user j ∈ Users do
                if ( c ∈ AllocatedChannels(Users(j)) && ConflictMatrix(Users(i),Users(j)) ) then
                    % c is allocated to a conflicting user
                    allocated++;
                    Break;
                end
            end
            if ( allocated == 0 ) then
                %channel is not allocated
                AllocatedChannels(Users(i)) = AllocatedChannels(Users(i)) + {c} ;
                AvaialableChannels(Users(i)) = AvailableChannels(Users(i)) - {c} ;
            end
        end
    end
end
```

Algorithm 4: Spectrum Allocation Algorithm: Stage III

Chapter 4

System Implementation and Results

4.1 Introduction

This chapter will provide the implementation details of the CSMS decried in chapter 3. In order to validate the proposed design through concrete results, the system implementation is focused on the special case of TVWS management in Libya. Actual TV broadcasters data was obtained through regulatory bodies contained detailed transmitters information such as transmission frequency, transmission power, and antenna height. Radio propagation analysis was then conducted using Longley-Rice Irregular Terrain Model (ITM) and the ITU-R.P1546 propagation models coupled with elevation maps of Libya from NASA's Shuttle Radar Topography Mission (SRTM) [24]. The TVWS estimation algorithm described in 3.4.1.2 was used to obtain TVWS availability data in a designated test area of Libya. This data was then utilized to implement the TVWS spectrum management algorithm proposed in 3.4.2.2 and confirm the coexistence objectives.

Figure 4.1 below illustrates the different technologies and applications used in the implementation of the Cognitive Spectrum Management System. These include:

1. MATLAB
2. SPALT Radio propagation software
3. php/MySQL
4. Python
5. HTML/CSS/Javascript

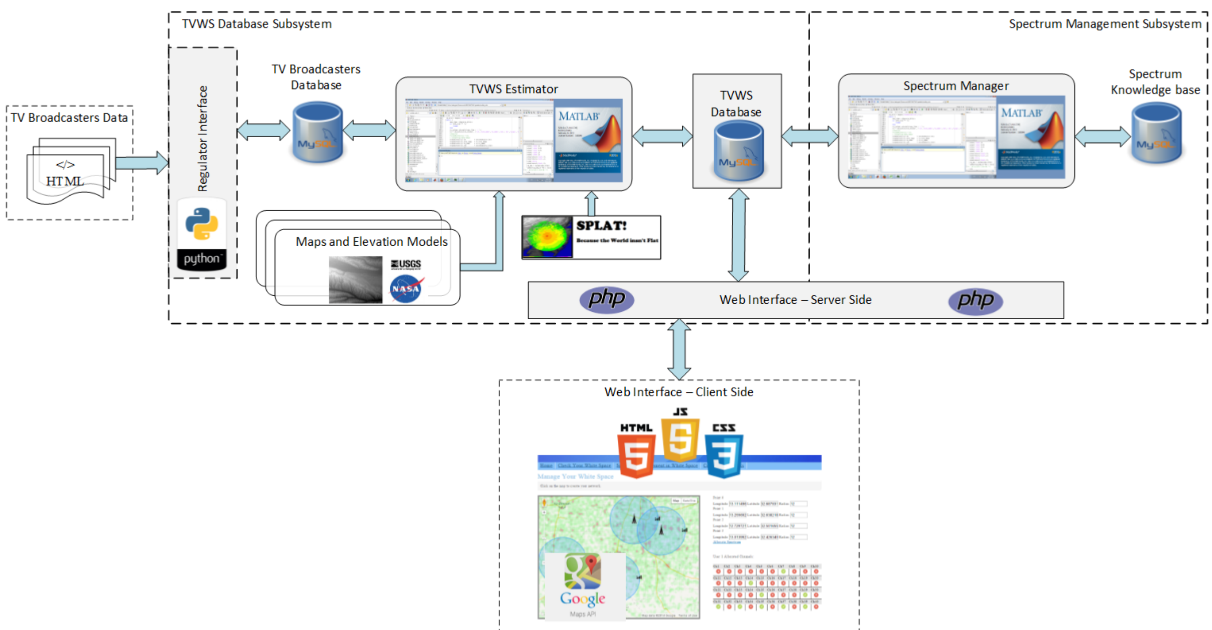


Figure 4.1: CSMS Implementation

The rest of this chapter is designed as follows: first a review of the TVWS regulation status in Libya is given followed by a summary of the data used to estimate the TVWS availability in the test area. Following that, a description of the implementation of the

TVWS estimation algorithm is given before a description of the spectrum management algorithm is outlined. A final section is dedicated to the detailing of the implementation of a web-based user interface.

4.2 TVWS Regulation in Libya

Libyan regulators are yet to adopt TVWS regulation governing the use and deployment of TVWS technology and devices in the country. Radio regulation in Libya is closely aligned with the ITU global and regional policies and regulations. Libya is in ITU-R Region-1 encompassing Europe, Africa, and much of Asia. Therefore, any future TVWS regulations and policies will be closely similar to that of ITU-R Region-1 countries. In 2013, the Libyan Ministry of Communications and Informatics (MCI) released the Libyan National Frequency Plan (LNFP) for public consultations and comments on future directions for national spectrum planning including the topics of spectrum sharing, cognitive radio, and TVWS [25]. According to the LNFP, the spectrum allocations in the VHF range from 47MHz to 230MHZ and the UHF range from 470MHz to 790MHz assigned for broadcasting services are as follows:

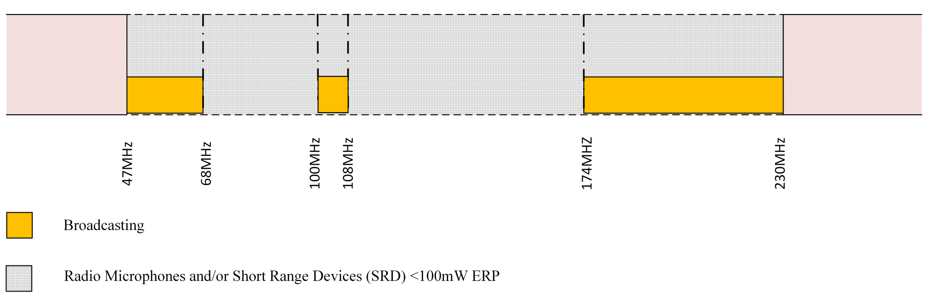


Figure 4.2: LNFP in 470-790MHz VHD range

It can be seen from figures 4.2 and 4.3 that TV broadcast bands are much more abundant in the UHF range than VHF range in Libya. Moreover, the bands in the VHF are more fragmented which adds more complexity to spectrum management and decreases the potential benefits of these bands. This analysis is consistent with ITU-R region 1 countries including the EU countries where more focus is given to the UHF bands as the primary

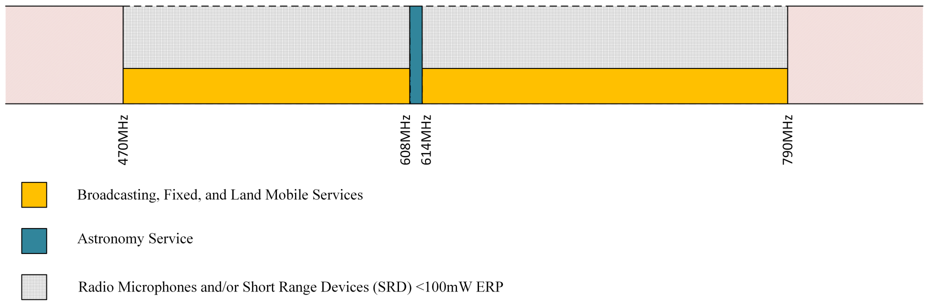


Figure 4.3: LNFP in 470-790MHZ UHF range

bands for TVWS. As such, any future implementation of TVWS systems in Libya will be similar to that in Europe and will most likely focus on UHF. However, the large geographical area of Libya and the low population density may allow for VHF bands utilization in TVWS thus increasing the potentials of TVWS technology in providing wireless access to rural areas throughout the country and hep in closing the digital divide. Extensive studies are needed to assess the actual availability of TVWS technologies and the potentials of TVWS technologies. This work is a contribution in this direction.

Before any implementation of TVWS technologies in Libya, a regulatory framework where TVWS devices can operated must first be established. The following are the key aspects of such framework:

1. TVWS bands must be identified by the regulator and clear characterization of the access rights to those bands must be declared.

2. Actual usage of TVWS bands must be clarified. According to information obtained from the ITU, there are about 343 transmitters in 68 sites across Libya in the UHF bands alone. However, most (if not all) of these stations are no longer operational as satellite TV is the main TV service in the country while transition to digital TV has not been completed yet.

3. Detailed specifications of TVWS database approval and administrator licensing procedure must be established

4. Licensing procedures for WSD and CR devices must be outlined

If such measures are taken by regulators in Libya, TVWS database administrators can start establishing concrete databases on the available bands. Once such a database is in place and administrators are accredited, TVWS networks trails can start and networks can be deployed.

4.3 TVWS Subsystem Implementation

The TVWS subsystem is one of the two main subsystems of the CSMS. The system design details are given in section 3.4.1. The implementation of the TVWS subsystem is focused on the case of Libya and is broken down into the following steps:

1. Data Collection and Translation

2. Field Strength Calculation

3. TVWS Estimation

4. Database Population

Figure 4.4 below illustrates the different technologies and applications used in the implementation of the TVWS subsystem.

Consequent sections will provide more details on each step of the implementation process.

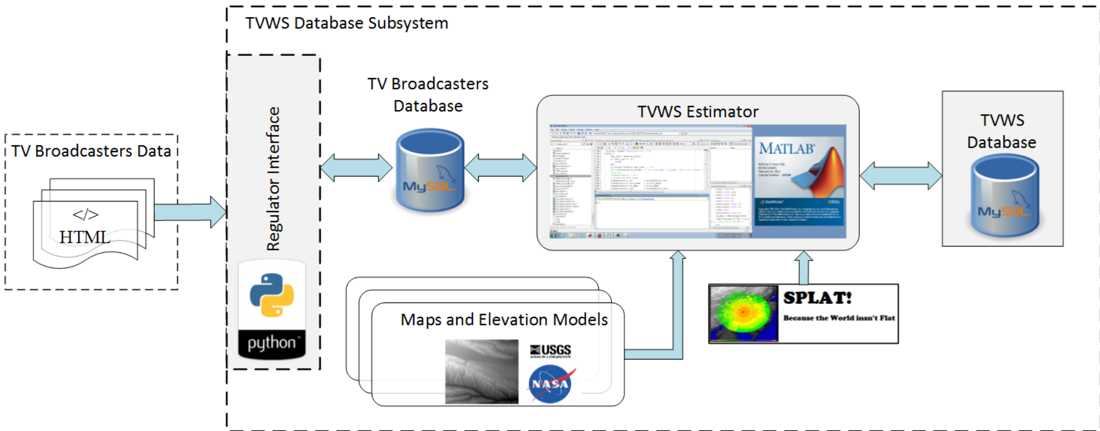


Figure 4.4: TVWS Subsystem Implementation

4.3.1 Step1: Data Collection and Translation

TV broadcasters' data were obtained through regulatory bodies containing transmitters parameters such as:

1. Transmitter's coordinates
2. Transmit power
3. Transmit frequency
4. Transmitter antenna height Above Ground Level (AGL)

This data was collected in HTML format and a Python script was written to extract the data and translate it into a TV Broadcasters Database implemented in MySQL.

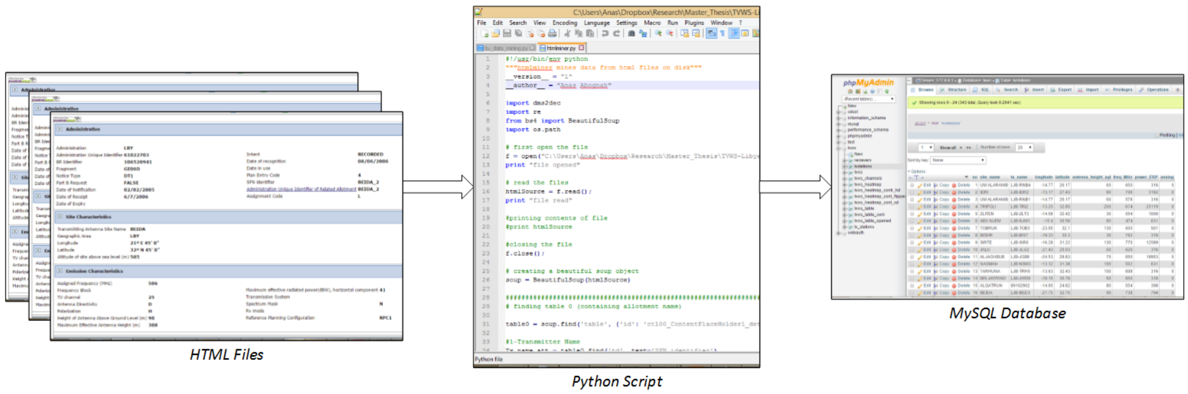


Figure 4.5: Extraction of TV Transmitters Data

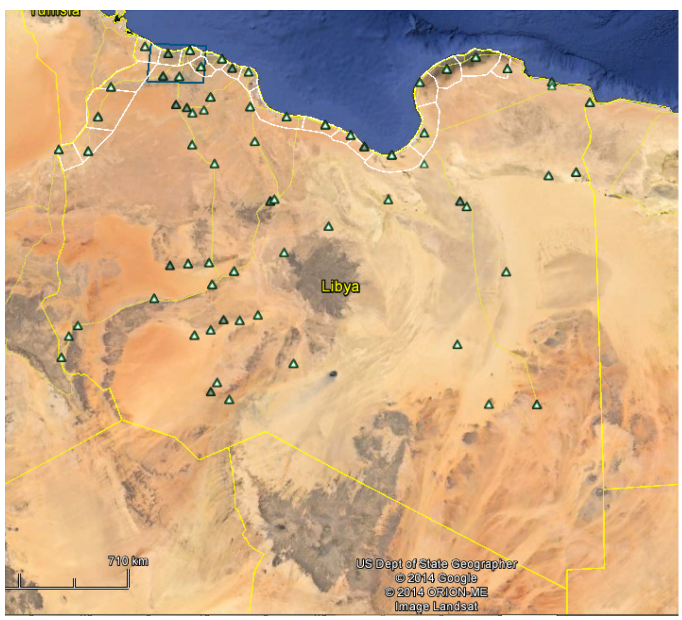


Figure 4.6: Map of Libya with all TV stations

In addition to TV station data, elevation maps were obtained covering the test area in the western part of Libya. The elevation maps used are the NASA's Shuttle Radar Topography Mission (SRTM) elevation maps available through the US Geographical Survey (USGS) site [26].

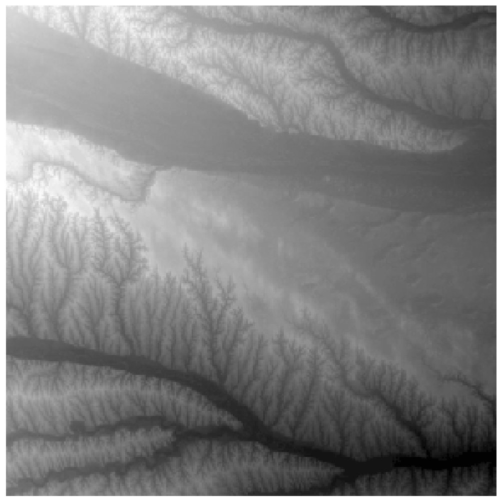


Figure 4.7: SRTM map tile (lighter pixels indicate higher grounds)

4.3.2 Step2: Field Strength Calculation

MATLAB was used to implement the TVWS Estimation algorithm described in 3.4.1.2. The program utilizes the TV broadcasters' database constructed earlier in order to compute the Field Strength (dBuV/m) at each receiver in the test area from each transmitter in the database. The Irregular Terrain Model (also called the Longley Rice model) [27] and The ITU-P.1546 citeITU-P154 propagation models where both used to predict the received power at each receiver.

1. Field Strength Calculation with the Longley-Rice Irregular Terrain Model (ITM)

The ITM model is a radio propagation module for frequencies from 20MHz-20GHz developed by A.G. Longley and P. L. Rice in the 1960s. The module incorporates statistical signal analysis with terrain information to predict median signal strength in terms of received power (dBW) and field strength (dBuV/m). Figure 4.8 shows an example point-to-point non-line-of-site analysis between two sites one in Tripoli and one in Sorman west of Tripoli. The analysis is executed using SPLAT radio propagation analysis tool [28]

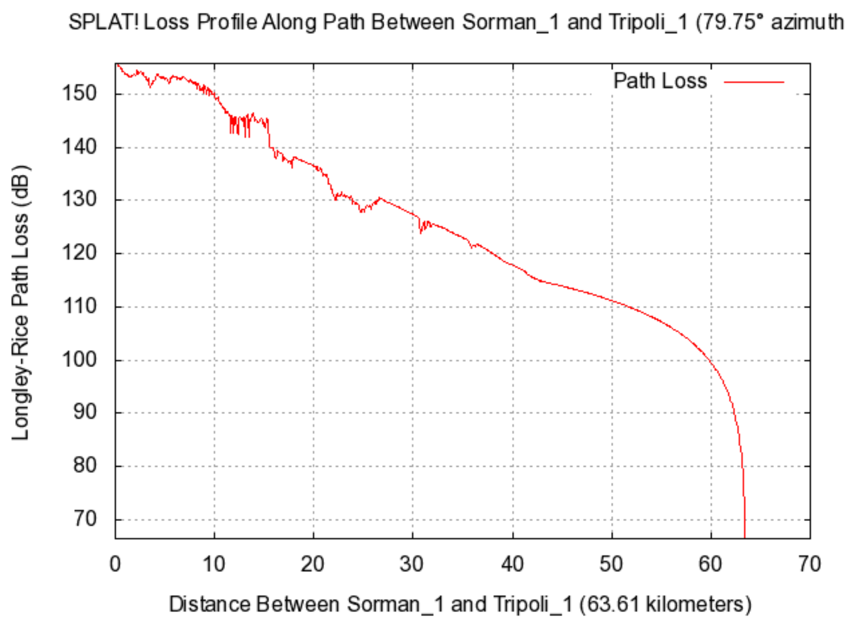


Figure 4.8: Pathloss with Longley-Rice ITM model

An-open source tool called SPALT [28] was used to perform the path loss computation based on the Irregular Terrain Model (ITM). The program also incorporate atmospheric and environment parameters into the calculation in accordance to the standards of TV broadcast planning and radio propagation. Table 4.1 below shows the parameters used in the radio propagation analysis.

Parameter	Value	(Unit/Meaning)
Earth Dielectric Constant	15.000	(Relative permittivity)
Earth Conductivity	0.005	(Siemens per meter)
Atmospheric Bending Constant	301.000	(N-units)
Radio Climate	5	(5 = Continental Temperate)
Fraction of situations	0.50	(50% of locations)
Fraction of time	0.50	(50% of the time)

Table 4.1: ITM model parameters for radio propagation analysis using SPALT

2. Field Strength Calculation with the ITU-P.1546 Propagation Model

   This model is published by the International Telecommunications Union (ITU) and is recommended for use for terrestrial TV broadcast coverage prediction for frequencies in the range of 30MHz-3GHz. The model is based on a set of field-strength curves for different frequencies, antenna height, and distances with equations for interpolation and extrapolation for a range of these values. Figure 4.9 below show an example of these curves for frequency of 600MHz.

   The curves are numerically generated and incorporate elevation metrics to take the terrain effect into account. The main parameter for terrain effect is the Height Above Average Terrain (HAAT). HAAT is computed as the elevation average of evenly spaced points taken on a path 3-15Km from the transmitter to the receiver. A minimum 50 of such points in the direction of the receiving antenna are selected and the average of their heights is computed.

   The different height parameters usually involved in radio propagation are illustrated in figure 4.11 below.

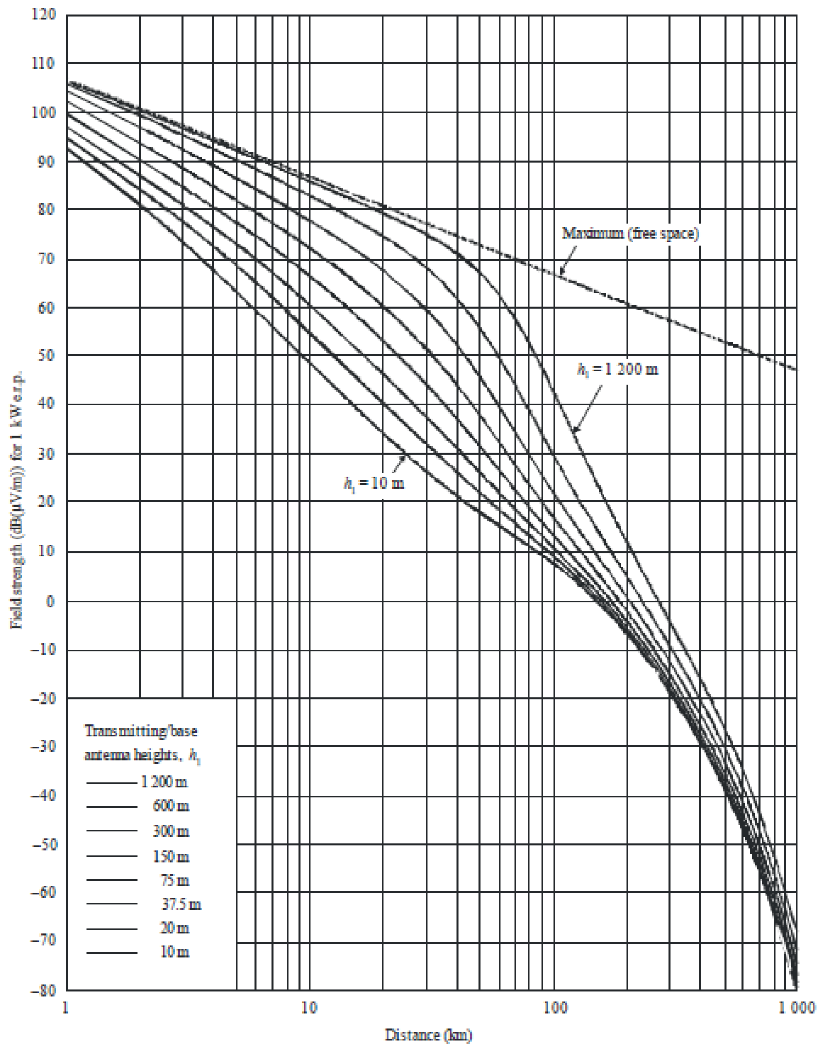


Figure 4.9: ITU-P.1546 Field Strength curves for 600MHz

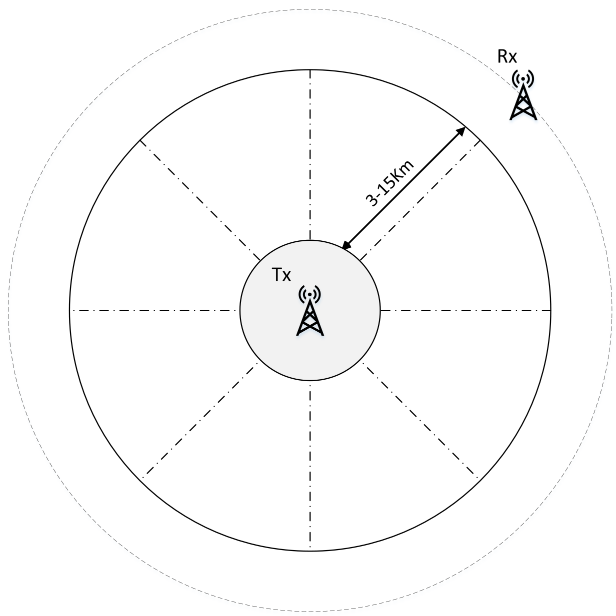


Figure 4.10: Height Above Average Terrain (HAAT) calculation

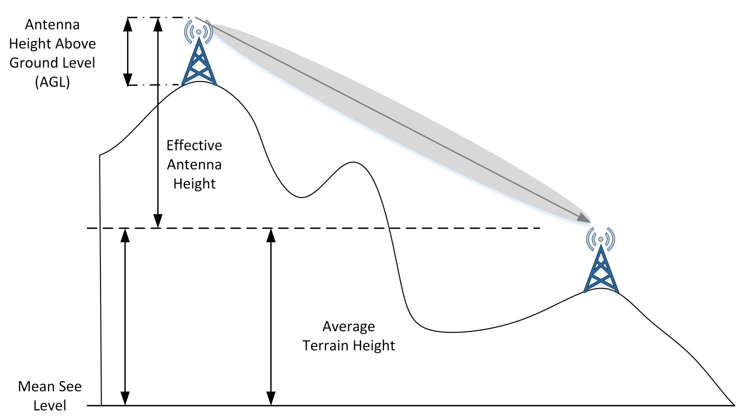


Figure 4.11: Different height measurements in radio propagation analysis

4.3.3 Step3: TVWS Estimation

The TVWS estimation algorithm adopts a threshold-based approach were the estimated field strength at the receiver is compared to a thresholds based on minimum acceptable location probability. Location probability in TV broadcast planning represents the probability of successful signal reception in a small area (usually 100m by 100m). This probability is critical in determining the coverage area of each transmitter and thus defines the area of service. Table 4.2 below shows different location probabilities for different service types with corresponding minimum field strength values of the received signal based on GE06 agreement [29].

Location Probability	Minimum Field Strength (dBuV/m)	Service Type
99%	60	Mobile and Portable TV
95%	56	Fixed Digital TV
50%	48	Fixed Analogue TV

Table 4.2: Location probabilities and field strengths for different service types

A range of field strength thresholds can also be defined within a specific location probability value for differentiation between different classes of services or reception modes. The next table (table 4.3) shows different minimum field strength values for 95% location probability for different reception modes for digital TV.

The selection of the field strength threshold strongly affects the outcome of classification of pixels as white spaces or not. For our implementation, a conservative approach was taken to avoid affecting primary TV reception at any location. The selected thresholds in this implementation are the minimum values allowing for maximum protection for TV reception.

Reception Mode	Minimum Field Strength (dBuV/m)
Fixed Roof-Top Level	50
Portable Outdoor	67
Portable Indoor	76

Table 4.3: Field Strength for digital TV at 95% Location Probability

4.3.4 Step4: TVWS Database Population

The estimation results is used to identify which channels in what pixels of the grid are white space and which are not. This data is then used to populate a geo-location database of locations and corresponding channel availability information. The database is implemented using MySQL providing flexible administration and suitability for online applications. The web-based interface implementation utilizes this database.

location latitude	location longitude	Ch1	Ch2	Ch3	...	Ch40
32.071	12.315	1	1	0	...	1
32.080	12.314	0	1	0	...	1
..	..	..	..	..	...	..
32.977	13.710	0	0	1	...	1

Table 4.4: TVWS Database Table

4.4 Spectrum Manager Implementation

The spectrum management subsystem described in 3.4.2.2 is implemented and tested using MATLAB. The three-stage spectrum allocation algorithm ensures assignment of all available channels to secondary users with no conflicting users being assigned the same channel to ensure secondary-to-secondary coexistence in addition to primary-to-secondary coexistence.

The TVWS database provides channel availability information on a grid of cells each $1000m$ by $1000m$. In each cell of the grid, a secondary user can only access the channels indicated to be white space in the database. A secondary user's coverage area is assumed to be more than $1km$ in range which means that the coverage area of a single secondary users will span multiple grid cells. The range assumption in line with TVWS standards such as the WRAN ieee802.22 standard where the base station coverage range can reach up to $30Km$.

Based on these assumptions, the system model comprises of secondary users (base stations) competing for access to TVWS. The spectrum manager allocated TVWS channels to each user based on coexistence constraints such that only free channels are allocated and no conflicting users are assigned the same channels. The figure below shows the implementation of the spectrum allocation algorithm illustrating TVWS grid, super cells, and conflicting users clusters.

The following steps explain the implemented algorithm:

1. Secondary Users (SU) wishing to access the TVWS spectrum submit requests to the Spectrum Manager containing their location information and coverage radius. The default coverage radius is selected as 12Km.

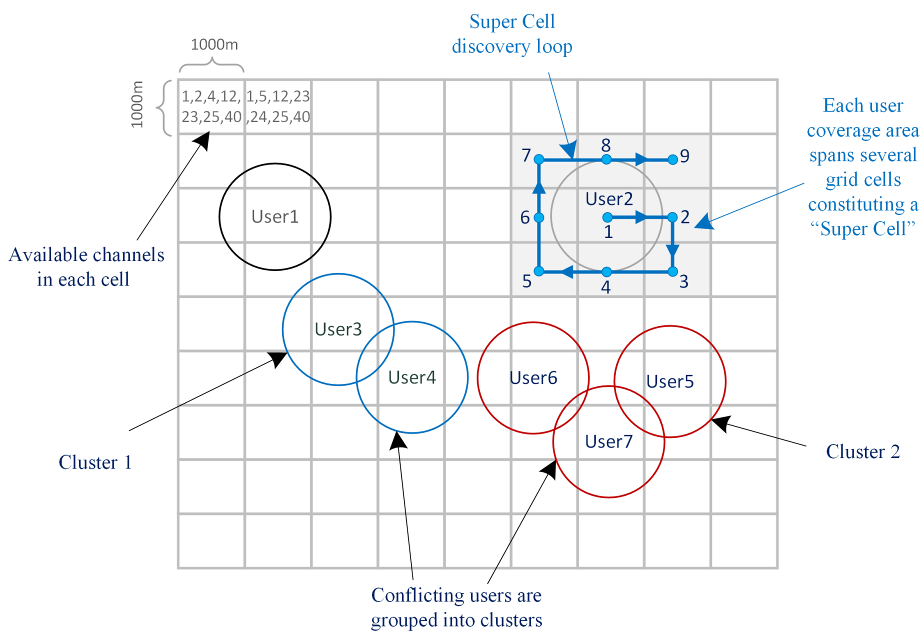


Figure 4.12: TVWS Allocation Algorithm Implementation

2. The TVWS database contains a grid G of 1000m x 1000m cells each with a unique cell number N and with a set of available channels.

3. Each secondary user is associated with a Super Cell (SC) consisting of all grid cells within its coverage reach. The radius of the SU coverage and its location are used to determine the set of grid cells comprising its SC through the following function:

4. The spectrum manager queries the TVWS database for channel availability for all cell within each users SC

5. The set of common channels within an SC is designated as the Available Channels set for each SU. The following function returns the set of available channels in an SU.

```
function C = getSharedChnls(SC , tvws_grid)
  % C = shared channels
  % SC = an array with cell numbers in grid covered by the SuperCell
  %tvws_grid = a grid of cells with available tvws chnls
  nChnls = 40; % Total number of channels
  n=size(SC ,2);
  CHNLS = zeros(nChnls,1);
  for i=1:n
      % For each cell in SC, Increment by 1 a channel that is avaialable
      CHNLS([tvws_grid{SC(i)}])=CHNLS([tvws_grid{SC(i)}])+1;
  end
  %If a channel is available in all cells , return it in C
  C = find(CHNLS == n);
end
```

Code 4.1: Deteccting Shared Channels

6. Location information and coverage radius is used to calculate an $(N$ X $N)$ Conflict Matrix (CM) where N is the number of users to designate users with intersecting coverage areas. Two users (i and j) are deemed conflicting if the distance between their centers is less than the sum of their radii. For each conflicting users $CM(i, j) = CM(j, i) = 1$. The following is the implementation of a function to calculate the conflict matrix.

```
function CM = getConflictMatrix(SCs,r,ro)
CM = zeros(size(SCs,2));
  for i=1:size(SCs,2)
     for j=1:size(SCs,2)
        if (i ~= j)
          d = getDistance(SCs{i},SCs{j},ro);
          if d <= 2*r
            CM(i,j)=1;
          end
        end
     end
  end
end
```

Code 4.2: Finding Conflict Matrix

7. After calculating the available channels, the super cells, and the conflict matrix, the spectrum manager distributes the TVWS channels between the secondary users by performing the three-stage algorithm described in 3.4.2.2. The following code segments are the implementations of the three stages of the spectrum allocation algorithm.

```
% STAGE I: Allocate non−Shared Channels
% 1− calculated shared channel sets between SuperCells
for i=1:nUsers
    for j=1:nUsers
        if CM(i,j) == 1 % if two SuperCells intersect
            SharedChannels{i,j}=intersect(AvailableChannels{i},AvailableChannels{j});
        end
    end
end

% 2− assign non−shared channels
sh = 0; % share count per channel
for i=1:nUsers
    usr = CForder(i); % get cells by conflict factor order (ascending)
    for j=1:nChnls
        c = Channels(j);
        if (ismember(c,AvailableChannels{usr})); % if channel is available
            for k=1:nUsers % for all other users
                if (CM(usr,k)) && (ismember(c , SharedChannels{usr,k}))
                    % are the two users in the same area (conflicting)?
                    % is c shared with this user?
                        %if yes: increment flag
                        sh = sh+1;
                end
            end
            if (sh == 0) % if c is not shared with anyone
                %1−add it to allocated channels of user i
                AllocatedChannels{usr} = [AllocatedChannels{usr} c];
                %2− remove it from AvailableChannels set
                AvailableChannels{usr} = setdiff(AvailableChannels{usr} , c);
            end
        end
    end
end
```

Code 4.3: Spectrum Allocation Algorithm STAGE I

```
% STAGE II: Allocate Shared Channels
% 1- detect clusters
Clusters = getClusters(Users, CM);

% 2- assign shared channels
for i=1:size(Clusters,2)

  Users = uniqueClusters{i};
  n=size(Users,2);
  TotalAvailableChannels = [];
  for i=1:n
    TotalAvailableChannels = union(TotalAvailableChannels , AvailableChannels{Users(i)});
  end

  while(~isempty(TotalAvailableChannels))
    for i = 1:n
      C = intersect(AvailableChannels{Users(i)},TotalAvailableChannels); % get available channels
      if (isempty(C))
        continue; % exit if no available channels
      end
      c = C(1);   % get one channel
      C=C(2:end); % remove channel from set
      %allocate channels to user
      AllocatedChannels{Users(i)} = [AllocatedChannels{Users(i)} c];
      %remove allocated channel from total available channel set
      TotalAvailableChannels = setdiff(TotalAvailableChannels , c);

    end
  end
end
```

Code 4.4: Spectrum Allocation Algorithm STAGE II

```
% STAGE III: Allocate Shared Channels between non−Conflicting Users
for i=1:nUsers
    % find channels available and not yet allocated
    T = setdiff(AvailableChannels{i} , AllocatedChannels{i});
    if (~isempty(T)) % if not empty
        for j = 1:size(T,2)
            c = T(j);
            allocated = 0; % flag if channel is allocated
            for k=1:nUsers
                % is c allocated to any other conflicting user?
                if (ismember(c , AllocatedChannels{k}) && CM(i,k))
                    % if yes, rais flag.
                    allocated = allocated+1;
                end
            end
            if (allocated == 0) %if channel is not allocated
                %allocate c to user i
                AllocatedChannels{i} = [AllocatedChannels{i} c];
                %remove channels from available list
                AvailableChannels{i} = setdiff(AvailableChannels{i} , c);
            end
        end
    end
end
```

Code 4.5: Spectrum Allocation Algorithm STAGE III

4.5 Web Interface Implementation

A web-based interface is implemented to allow interactive access to TVWS availability data and spectrum management system. The interface was implemented with the objectives of providing a platform to promote TVWS technology in Libya and engage stakeholders from regulators and service provides to researchers and end users. The web interface consists of the TVWS Database Interface and the Spectrum Management Interface.

The web interface was developed using HTML/CSS technologies with database and algorithmic implementations implemented using PHP/MySQL. Interactive features were realized through utilizing JavaScript techniques such as JQuery and AJAX.

4.5.1 TVWS Database Interface

The TVWS database interface provides access to the TVWS availability information at any location in the studied area in Libya. Users can check which channels are available and whcih channels are not available for secondary use by TVWS devices in the UHF range (470MHz-790MHz). The main features of the TVWS database interface are:

1. Interactive map Libya for visual inspection of TVWS availability. Users can click on the map to view available channels in any location
2. Reverse geo-location return the address information of the clicked map location
3. A visual table displays channel availability information in the chosen location
4. Total available spectrum is calculated based on the available channels. Each channel is assumed to be $8MHz$ wide.

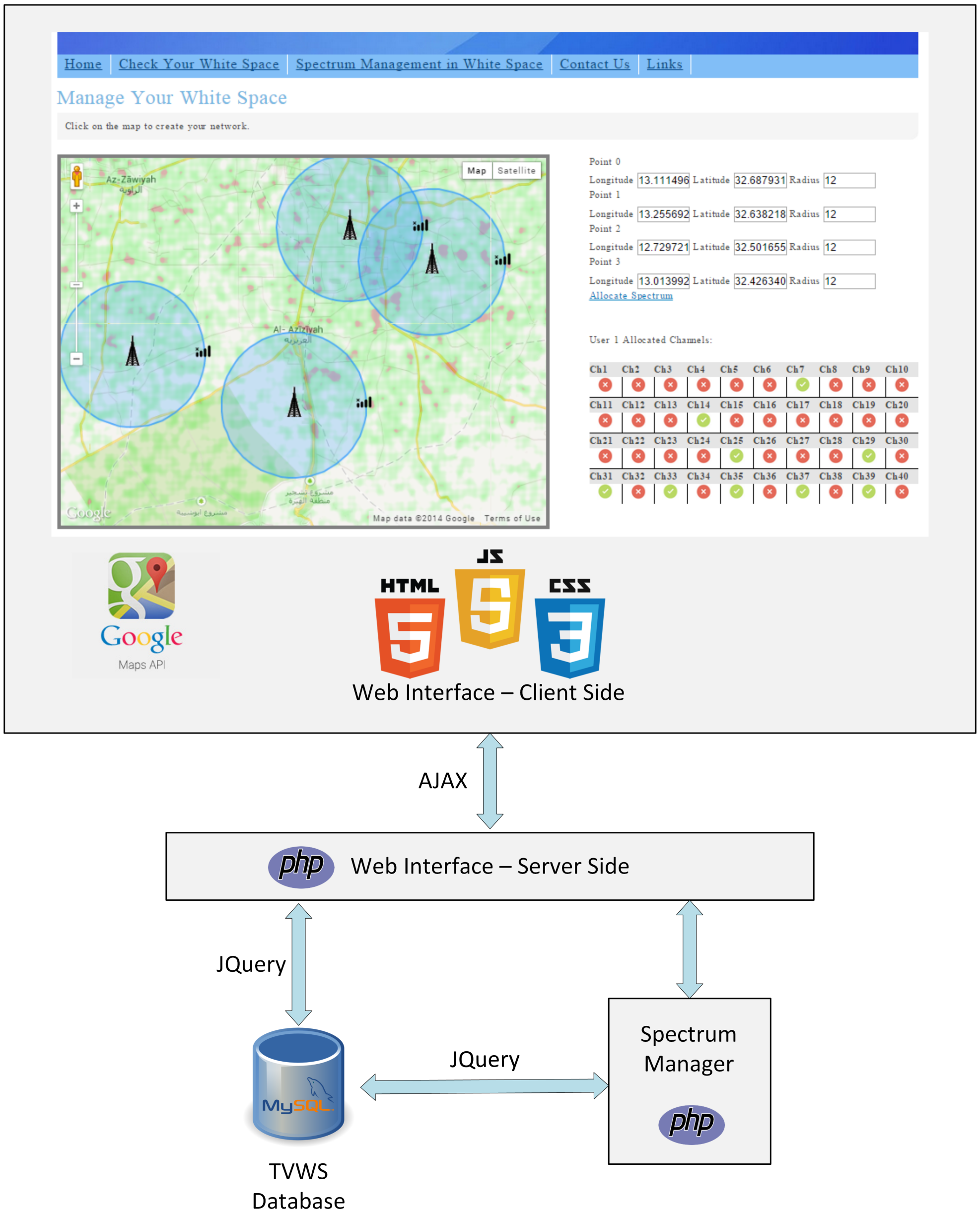


Figure 4.13: Web Interface Implementation

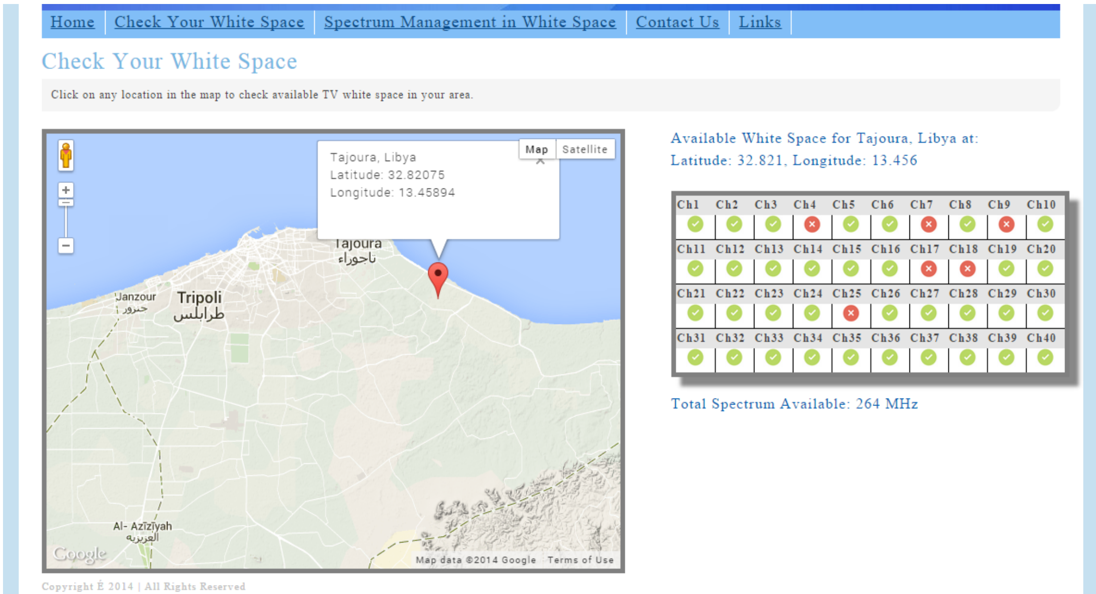


Figure 4.14: TVWS Database Interface

4.5.2 Spectrum Management Interface

A spectrum management interface was also developed to allow access to the TVWS spectrum manager described in 4.4. The interface provides an interactive way to manage spectrum allocation between multiple secondary users. A scenario were this interface is useful is for a provider to check the overall available spectrum for a group of base stations in a TVWS network.

The main features of the spectrum management interface are:

1. Interactive map allows positioning of multiple base stations at any position by clicking on the map canvas

2. The placed base stations can be moved and the radios of expected coverage of each tower can be changed by simply dragging an icon.

3. An interactive form shows the vales for each tower's coordinates and radios while its moved.

4. After the user is satisfied with the positions and coverage radii of the towers, she can click on "allocate spectrum button to call the spectrum allocation algorithm that allocates spectrum between the base stations.

The following figure shows a screen shot of the spectrum management interface.

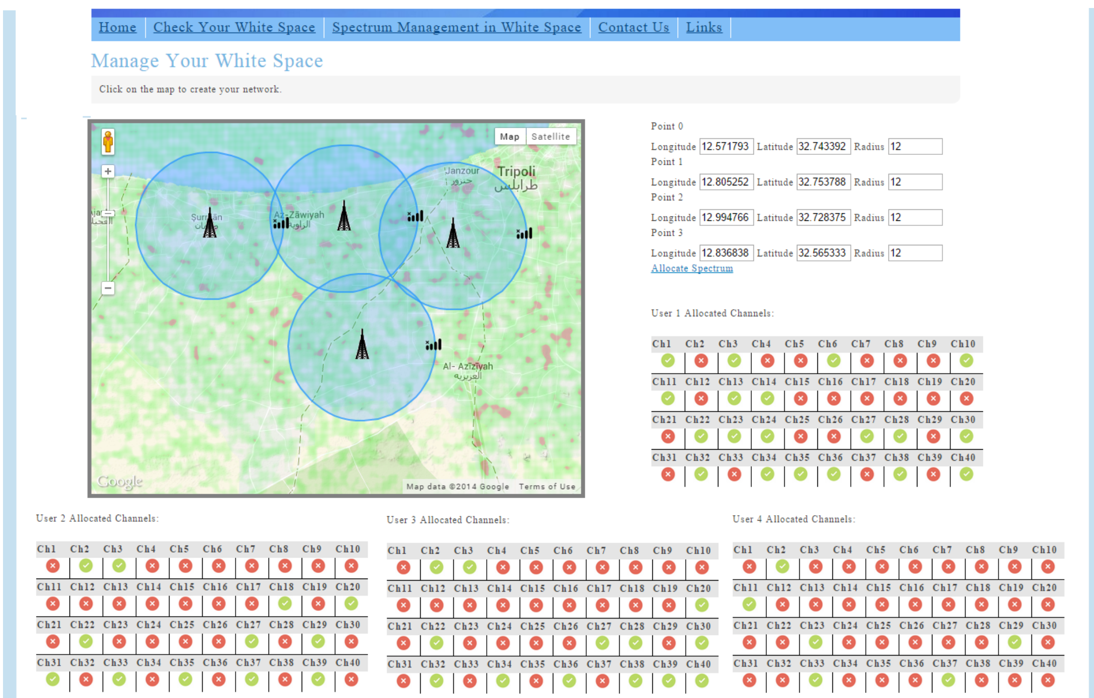


Figure 4.15: Spectrum Management Interface

4.6 Results

The implemented system was used to assess the TVWS availability in Libya using TV transmitters' data obtained from the ITU databases and the regulator of Libya. The data included around 343 TV stations in the UHF range from 470MHz to 780MHz providing TV coverage for the towns and cities of Libya. The assessment was conducted on two test areas:

1. Test Area 1

   A smaller area encompassing the capital city of Tripoli and the western mountains of "Jabal Nafosa". This area is of the most populated in the country and features interesting mix of terrain from coastal urban environment to mountainous rural terrain. The area contains five sites for primary analogue TV stations each consisting of multiple transmitters in the UHF range (470MHz-79MHz). Figure 4.16 below shows a map of this area.

2. Test Area 2

   A larger area covering the entire western coastal area of Libya. This area covers multiple large cities (Tripoli, Misurata, Azzawia, ...) were heavy TV coverage limits the availability of TVWS but also includes rural areas and smaller towns were TVWS is found to be abundant. Figure 4.17 below shows a map of this area.

The test areas were divided into a grid of pixels of 1000m by 1000m each. A receiver is assumed at each pixel and the received signal strength in term of Field Strength (dBuV/m) was measured from each transmitter in the area. If the maximum signal strength is below a certain threshold, the pixel is deemed as white space. The process is repeated for each

Figure 4.16: Test Area 1

Figure 4.17: Test Area 2

frequency. The Irregular Terrain Model (ITM) and the ITU-P.1546 propagation models were used to predict the received field strength at each location in the test area. Below are the results obtained using each of the two models.

4.6.1 Irregular Terrain Model Results

The table below shows the percentage of total available channels in the UHF range of 470MHz to 790MHz in test area 1 at different threshold level. Each threshold level corresponds to the minimum field strength for different primary service below which reception of the service becomes unacceptable. For instance, field strength at a receiver for analog TV below 48 dBuV/m renders the service unacceptable. As the threshold level increases (when going from fixed to mobile service for instance), the percentage of available TV channels for secondary use will also increase. This is a direct result of the fact that increasing the threshold level corresponds to decreasing the protection margin of the primary service, thus resulting in more channels being available for secondary use.

Primary service type	Threshold (dBuV/m)	TVWS availability (%)	Number of average available channels	Average spectrum available (MHz)
Fixed Analog TV	48	58.37	20.41	163.27
Fixed Digital TV	56	62.89	22.03	176.28
Mobile TV	60	65.05	22.89	183.17

Table 4.5: TVWS availability results with Longley-Rice (ITM) propagation model

Figure 4.18 below shows a heatmap of test area 1 with the total available channels at each pixel represented by a color from the range shown.

Figure 4.19 below shows different heatmaps for the field strength values at different channels. The locations of individual TV stations sometimes are apparent in these maps.

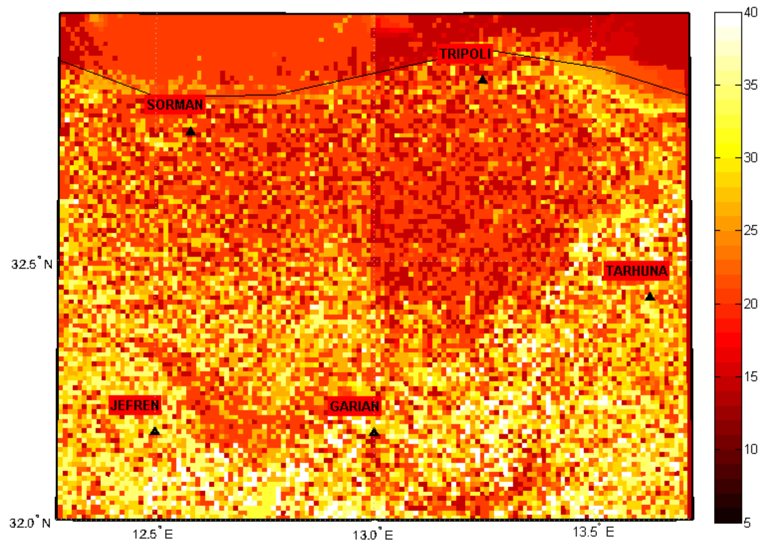


Figure 4.18: TVWS heatmap of Tripoli area using Longley-Rice (ITM) model

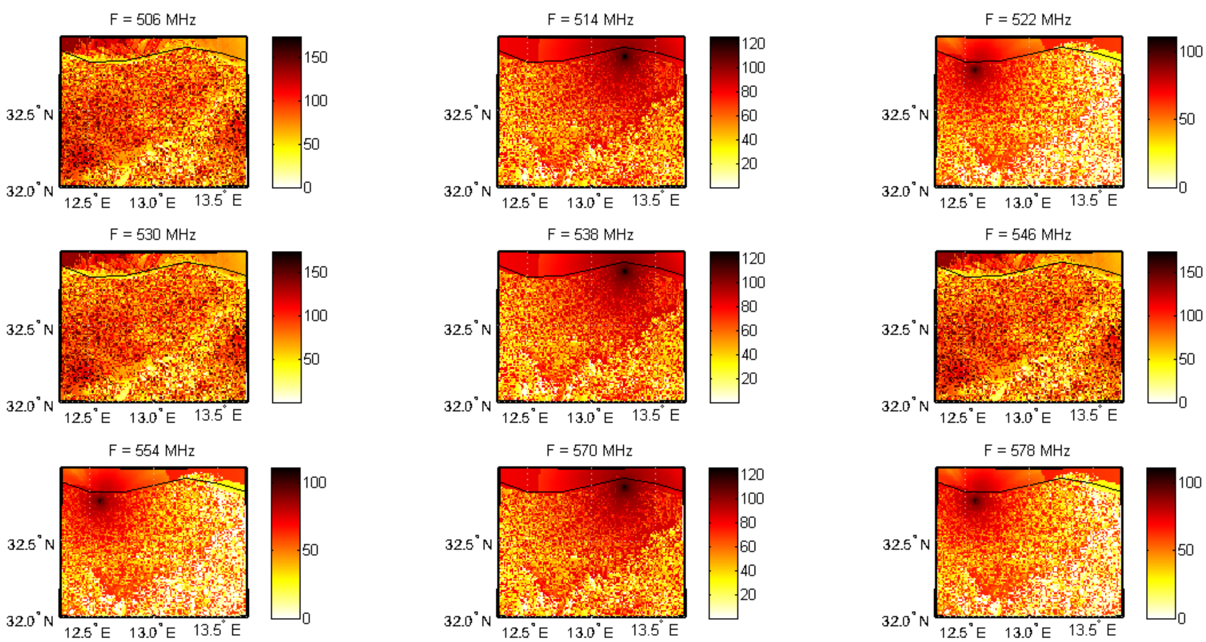


Figure 4.19: Heatmaps of field strength values for different channels (ITM model)

4.6.2 ITU-P.1546 Model Results

The ITU-P.1546 propagation model was also used to predict the signal strength and TV coverage at each pixel in the test areas. The table below shows the percentage of total available channels in the UHF range of 470MHz to 790MHz in test area 1 at different threshold level. As in table 4.5, each threshold level corresponds to the minimum field strength for different primary service below which reception of the service becomes unacceptable.

Primary service type	Threshold (dBuV/m)	TVWS availability (%)	Number of average available channels	Average spectrum available (MHz)
Fixed Analog TV	48	60.63	24.25	194.02
Fixed Digital TV	56	69.49	27.79	222.35
Mobile and Portable TV	60	74.22	29.68	237.50

Table 4.6: TVWS availability results with ITU-P.1546 propagation model

We notice that the percentages of total available TVWS channels using the ITU-P.1546 model are much higher than those obtained with the ITM model. This can be attributed to the statistical nature of the ITU model and the fact that the ITM model captures the effect of the terrain more that the ITU model.

Figure 4.20 illustrates the availability of TVWS channels in test area 1 as predicted using the ITU-P.1546 model.

The second test area on which the assessment was conducted included the entire western coastal region of the country. Due to computational complexity of the ITM model, and due to time constrains, only the ITU-P.1546 model was used to assess the TVWS availability in this area. Figure 4.22 below illustrates the results from the assessment with the pixels color coded to correspond to the total available channels at each location.

The above-mentioned results are highly encouraging and assure the way for TVWS

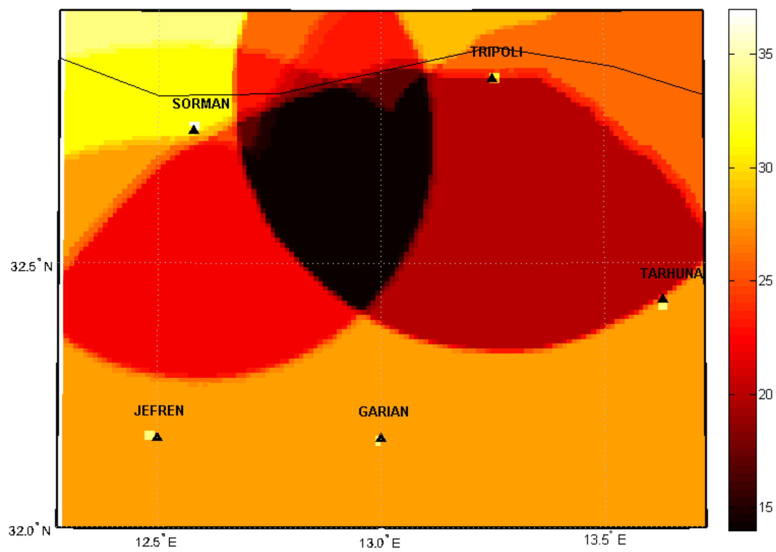


Figure 4.20: TVWS Availability in Tripoli area using ITU-P.1546 propagation model

technology implementation in Libya. While these results do not consider neighboring channels protection and protection of other primary services in the TV spectrum such as wireless microphones, it is worth mentioning that the TV transmitters data used are highly conservative and include all stations registered by the Libyan regulator with the ITU notification database according to the GE06 agreement. This data does not include operational status information in these stations and due to the fact that Libya is going through the transmission from analog to digital TV, most of these analog stations are off-line. Especially that satellite TV remains the most popular TV service in the country and a small portion of the population (if any) rely on terrestrial TV services.

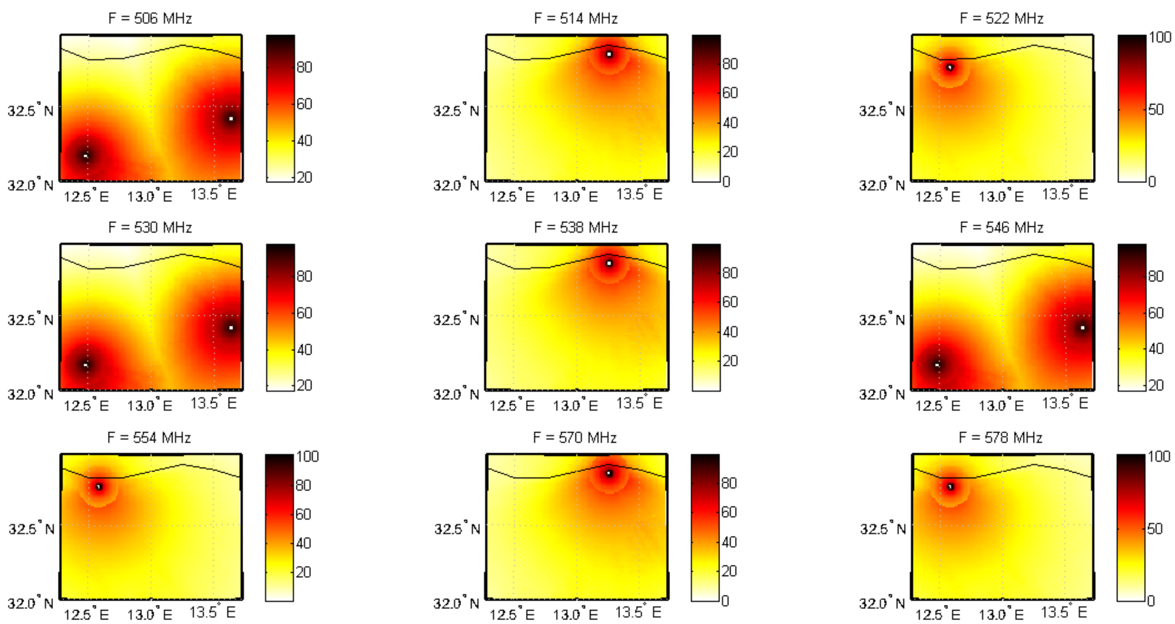


Figure 4.21: Heatmaps of field strength values for different channels (ITU-P.1546 model)

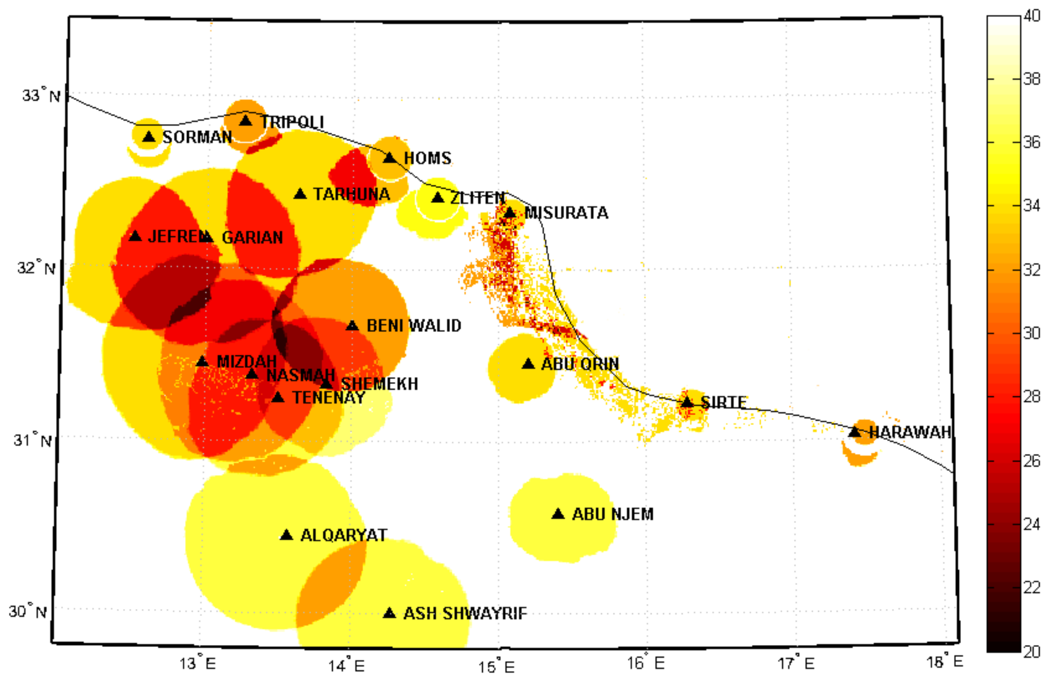


Figure 4.22: TVWS availability in the western coastal area of Libya (ITU-P.1546 model used)

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Spectrum management is a key aspect of next-generation wireless communication systems' implementation and operation. With the forecasted spectrum crunch, a new prospective for spectrum management based on open, shared, and dynamic spectrum access is required. Spectrum regulators and wireless network operators need to adopt new frameworks for shared and dynamic spectrum management in order to ensure the continuous improvement of information and communications services essential to national and international economic growth. TV White Space is the first realm for such shared spectrum access and the geo-location database framework ensures coexistence of primary TV broadcasters and microphones with secondary users of TVWS.

In this work, we presented a comprehensive system design for spectrum management in TVWS based on a geo-location database model and a cognitive framework. The cognitive framework allows the system to adapt to varying requirements ensuring flexibility and feasibility of real-world implementation. While the ge-location database model ensures interference-free operation of the primary TV broadcasters. Furthermore, the presented design ensures coexistence between secondary users by avoiding allocating the same free channels in TVWS to conflicting users while maximizing channel allocation.

The proposed system was implemented with Libya as the main target. TVWS availability in Libya was investigated through radio propagation analysis using TV broadcast stations' data and elevation models of the country. The Longley-Rice (ITM) and the ITU-P.1546 propagation models were used to assess the received signal strength from each transmitter at every possible location in the designated test areas in the country. Locations were the signal strength fell below the minimum threshold for correct reception were deemed as White Space and were designated for use by secondary applications. For all the tests performed in the most populated areas of the country no less than an average 58.37% of total channels were available over all locations with minimum average available spectrum of 163.27MHz. This percentage in found to reach as high as 74.22% of available channels with average available spectrum of 237.50MHz with higher TV reception quality thresholds. These results are highly promising and motivating for adoption of TVWS technology in Libya.

5.2 Future Work

Due to time constraints and resources limitations, some aspects of the system design and implementation are left for future work. Some future work is yet to be done on the ground in Libya with measurements and trials in order to complement the work done in this thesis.

5.2.1 System Design and Implementation

Some of the future work that can be done on the system design level is:

1. The implementation of the Requirements Translation Layer to translate regulatory, technical, and economical requirements to system parameters for TVWS estimation and management. Natural language processing algorithms and machine learning techniques are some of the tools useful in implementing such layer. However, before such layer can be implemented firm and concrete measurement translation guidelines must first obtained especially for regulatory requirements.

2. Investigation of other spectrum allocation techniques and algorithms such as demand-based spectrum allocation algorithms and economical frameworks for spectrum auctioning and leasing. The proposed and implemented spectrum allocation algorithm is targeted at maximizing spectrum allocation while ensuring primary and secondary users' coexistence. Demand-based spectrum allocating algorithms can incorporate conflict resolution techniques (such as game theory) or optimization-based technique to optimize a set objective (such as meeting the spectrum demand) while complying with a set of restrictions (such as coexistence constrains, QoS constrains, etc...).

3. The proposed and implemented TVWS estimation algorithm does not take into account the effect of secondary transmissions on the total SNIR at each receiver location. Secondary transmitters with considerable transmission power will have a non-negligible effect on nearby TV receivers and may degrade the signal reception. While this affect was considered in our implementation by taking the most conservative of thresholds when designating TVWS areas, it is still more robust to incorporate the effect of secondary transmitters in the initial computation of the Field Strength.

However, this will largely increase the computational complexity of the TVWS estimation and greatly increase an already high computation time required to obtain the availability results.

5.2.2 TVWS in Libya

This work is the first step towards TVWS adoption in Libya and much work still needs to be done before actual implementation can be realized. The results obtained through simulation are highly encouraging especially when we take into account that the country has not yet completed the transition from analog TV to digital TV and much of the considered transmitters in this study might actually be off-line. This means that the results obtained through this work in terms of TVWS availability in Libya are highly conservative. However, before actual implementations can be rolled-out the following work must be done:

1. Conducting measurement-based studies of the availability of TVWS in Libya and comparing these measurements with the simulation data in order to confirm/correct the results of this work.

2. Commissioning a trail project in Libya to demonstrate the viability of the proposed system in TVWS spectrum management with multiple base stations transmitting in TVWS in a specific test area in Libya.

3. The results obtaining from simulation, measurements, and trials can then be used by the regulator to establish a regulatory framework for TVWS access and ensuring protection of TV broadcasters and primary services in the TV spectrum from interference by secondary users

5.2.3 Work Extension and New Applications

Spectrum management in TVWS is still an active research field with great potentials for many new and existing wireless communication applications. Extension of this work can be done to address the problems associated with TVWS access and management in new applications such as Vehicular Ad-Hoc Networks (VANETS), small cells and femto cells, and smart-grid applications. Issues such as mobility management in VANETS over TVWS are still open for new contributions.

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