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Real-Time Implementation of Spectrum Sensing Techniques in Cognitive Radios

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Real-Time Implementation of Spectrum Sensing Techniques in Cognitive Radios

by

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Real-Time Implementation of Spectrum Sensing Techniques in Cognitive Radios

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Declaration of Co-Authorship and Previous Publication

I. Co-Authorship

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

Chapter 3 and 4 of the thesis was co-authored with Aarron Younan, Danilo Corral-De-Witt, Jose Matamoros, Faroq A. Awin and Esam Abdel-Raheem under the supervision of professor Kemal Tepe. In all cases, the key ideas, primary contributions, experimental designs, data analysis, interpretation, and writing were performed by the author, and the contribution of co-authors was primarily through the provision of hardware setup and data collection. Arooj Fatima contributed to the background study and hypothesis modeling; Aarron Younan contributed to the data collection and graphing results; Danilo Corral-De-Witt, Jose Matamoros, Faroq A. Awin and Esam Abdel-Raheem provided feedback on refinement of ideas and editing of the final manuscript.

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II. Previous Publication

This thesis includes [1] original papers that have been previously published/submitted for publication in peer reviewed journals, as follows:

Thesis Chapter	Publication title/full citation	Publication status
Part of Chapter 3 & 4	Corral-De-Witt, Danilo, Aarron Younan, Arooj Fatima, Jos Matamoros, Faroq A. Awin, Kemal Tepe, and Esam Abdel-Raheem. "Sensing TV spectrum using Software Defined Radio hardware." In Electrical and Computer Engineering (CCECE), 2017 IEEE 30th Canadian Conference on, pp. 1-4. IEEE, 2017 .	Published

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Abstract

Wireless communication requirements of higher sampling frequencies and bandwidth are ever increasing. For this purpose, exploitation of underutilized spectrum bands was one the challenging research targets. Cognitive Radio (CR) is a promising solution to overcome the "limited bandwidth" issue. Software defined radio (SDR) is the enabler of CR. The aim of the thesis is to adopt the vacant TV channels for secondary users. Spectrum sensing prototype has been proposed to detect TV white space (TVWS). The prototype has been developed using Universal Software Radio Peripheral (USRP) and examined to sense TVWS in the real time world. The conducting analysis of obtained measurements showed the state of unoccupied spectrum bands in the UHF band ranges from 500 MHz to 698 MHz in the urban area of Windsor, Ontario, Canada. Two different spectrum sensing techniques namely, the energy detector, and pilot-tone detector were employed to get the result with minimum computational complexity. Experiments show that the presence of incumbent users can be easily detected using the spectrum sensing techniques mentioned in the thesis. The experimental results have demonstrated the validity of the proposed prototype.

Dedication

Dedicated to,

My beloved parents: Syed Akhlaq Hussain and Syeda Fatima

My kind aunts: Kaniz Ishtiaq, Narjis Fatima, Naseem Fatima and Meraj Fatima

My sister: Alina Akhlaq

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I would also like to pay my special regards to the University of Windsor for providing me the opportunity to study in this institute. The last but not the least I would like to thank my family and friends to tolerate me and for always being there for me during my study period.

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List of Abbreviations

ATSC	Advanced Television Systems Committee
AWGN	Additive White Gaussian Noise
BPF	Band-pass Filter
BW	Bandwidth
CR	Cognitive Radio
CS	Cyclo-Stationary
CSV	Comma Separated Value
dBi	decibels isotropic
dBm	decibels in milli-Watts
DTV	Digital Television
ECC	Electronics Communication Commission
ED	Energy Detector
EIRP	Effective Isotropic Radiated Power
FCC	Federal Communications Commission
FDM	Frequency Division Multiplexing
GPS	Global Positioning System
GSM	Global System for Mobile communication
GUI	Graphical User Interface
IP	Internet Protocol
ISM	Industrial/ Scientific/ Medical
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
NI	National Instrument

OFDMA	Orthogonal Frequency-Division Multiple Access
OSI	Open System Interconnection
PC	Personal Computer
PHY	Physical layer
PU	Primary User
QoS	Quality of Service
RF	Radio Frequency
RSS	Received Signal Strength
SDA	Software Defined Antennas
SDR	Software Defined Radio
SNR	Signal to Noise Ratio
SU	Secondary User
TCP	Transmission Control Protocol
TDM	Time Division Multiplexing
TPC	Transmission Power Control
TV	Television
TVWS	Television White Spaces
UHF	Ultra High Frequency
UK	United Kingdom
US	United States of America
USRP	Universal Serial Radio Peripheral
WiCIP	Wireless Communication and Information Processing lab
WiMax	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

Chapter 1

Introduction

1.1 Background

Wireless communications is an integral building block of modern communications. With the advancement of technology, the demand for radio spectrum has increased tremendously. There are more users of bandwidth as compared to the capacity of radio spectrum. The Industrial/ Scientific/ Medical (ISM) band has been successful to manage most of the Wireless Local Area Networks (WLANs) so far but the interference is becoming a nightmare for the communication industry. The overcrowding in the vital band of communications opens a gateway to find a better spectrum management techniques. There is a need for an autonomous technique which is efficient enough to sense the radio spectrum in its surroundings.

A Software Defined Radio (SDR) is capable of managing the spectrum. In the previous kind of radios, the spectrum was divided either by Frequency Division Multiplexing (FDM) or Time Division Multiplexing (TDM) in which particular amount of spectrum has been dedicated to the specific user even if the user is inactive, the spectrum is considered occupied. SDR is capable enough to evade the "limited spectrum" assumptions of these kinds of radios in many ways including spread spectrum and ultra wide band techniques, Software Defined Antennas (SDAs), Cognitive Radios (CRs), etc. SDRs along with the SDAs are enablers of CRs.

Joseph Mitola III first proposed the concept of CR, and as per his definition a radio which is smart enough to make its decision based on its surrounding environment, analyze the past communications and do transmissions based on the current state of the environment can be referred to as CR [1]. A CR can be termed as an "Intelligent Radio" which has the capability to make decisions in the real-time environment.

1.1.1 Motivation

Natural disasters such as earthquakes, floods, and hurricanes often cause great loss of human lives. According to the United Nations Relief Web, more than 750,000 people have died across the globe during the past decade [2]. Besides the deaths caused by the disaster, a large number of people suffer or even die due to delay in getting rescued or necessary support. During any disaster, different relief teams step forward to offer their services. Each team setup their communication system to coordinate their efforts. Overcrowding of spectrum causes problems due to interference. Moreover, during mega disasters, communication infrastructure is often severely affected, and it is hard to re-setup a system with limited resources.

In situations mentioned above, the capability of CR can be utilized to set up a communication system. A CR will detect its surrounding environment, setup a secure communication system which will not interfere with its neighboring radios. CR occupies a channel for a certain amount of time and can communicate with neighboring radios. In this way, a CR will allow its surrounding co-operating radios to utilize the same spectrum.

The need for a real-time signal processing increases while dealing with the catastrophic situations. There is a minimum time for a user to analyze the communication system and make decisions accordingly. CR is capable of analyzing the situation in the real-time along with the SDR and SDA. One of the benefits of a CR is to use it to setup a communication network which is a combination of multiple CRs. In this way, the underutilized channels can be efficiently used.

1.1.2 Problem Statement

Fast and reliable communication in case of natural disaster is a crucial aspect of saving human life from loss. To setup, a communication system which is efficient enough to overcome the interference problems while utilizing the limited bandwidths is an important task.

The foremost step before setting up a communication system using CR technique is to detect the presence of the incumbent user in the spectrum. In a case of disastrous situations, computational complexities need to be avoided while identifying the primary users. There is also a need to demonstrate the effectiveness of the system with a prototype.

1.1.3 Use of Television White Spaces

Disastrous situations such as hurricanes, floods, earthquakes, etc. affect the communication infrastructure badly. The Industrial/Scientific/Medical (ISM) band is populated by different Bluetooth, WiFi, GSM, etc. bands in the vicinity. Moreover, many unlicensed band users also interrupt this popular band. The use of ISM band increases during such catastrophic situations. The advent of digital switch-over in the Television (TV) band opens a gateway to many underutilized channels. These channels are referred to as Television White Spaces (TVWS). These channels can be utilized for various communication purposes.

TVWS have been preferred over other various frequency bands found in the vicinity because an enormous amount of TV spectrum is still unoccupied. The use of TVWS to cater the communication needs in such situation has been proposed in this thesis. TVWS has been chosen to serve the purpose since this band has been considered as the most underutilized band in the spectrum. The proposed research demonstrates the idea that these bands can be used to setup a communication system during disasters.

1.1.4 Thesis Objectives

The goals of the thesis include:

i. Building a prototype that can perform real-time spectrum sensing using Universal Software Radio Peripheral (USRP) 2901.

ii. Studying the behavior of TVWS available in Ultra High Frequency (UHF) band ranges from 500 MHz to 698 MHz to determine which TV channel band can be exploited for this purpose.

iii. Implementing the IEEE 802.22 standard on the proposed prototype.

The thesis is intended to establish a prototype using USRP to detect the white spaces present in the TV spectrum. The major step to setup a CR based communication is spectrum sensing. Various spectrum sensing techniques that have been implemented in the thesis are obtained from the literature. The spectrum sensing techniques adopted in this thesis will be used to detect the presence of the incumbent user of the spectrum. The selection of an efficient technique which has less computational complexity is the primary objective. The efficiency of the method can be measured by its probability of detection (P_d) and the probability of false alarm (P_f). The data is collected in real-time with a USRP hardware and GNU Radio software.

1.1.5 Thesis Contributions

In this thesis, TVWS has been selected as a candidate spectrum band for our spectrum sensing prototype. The prototype uses a USRP 2901 hardware and GNU Radio software to obtain results of spectrum sensing. The setup was build in Wireless Communication and Information Processing (WiCIP) lab.

The prototype has been examined using simulated signals, which were generated using MATLAB and GNU Radio software platform. Then, verification of the validity of the proposed prototype has been done by employing the prototype in real world measurements. Data for real world measurements have been also analyzed in order to determine the TVWS in the target spectrum band (i.e., from 500 - 698 MHz).

Different spectrum sensing techniques (i.e. energy detection and pilot-tone detection) have been implemented to detect the presence of incumbent users. The detection has been verified by adopting different threshold and calculated its P_d and P_f under different SNR scenarios while following IEEE standard.

1.2 Thesis Organization

The thesis is organized as follows. Chapter 2 presents the literature review on CRs as well as SDRs. The highlighted techniques of spectrum sensing are also the part of the chapter. Finally, the CR standard IEEE 802.22, as well as the communications system using CR, is presented.

Chapter 3 presents the research methodology in detail. It provides an experimental setup for detecting TVWS. Equipment and parameters used for testing and implementing the proposed prototype are also considered. An overview of sensing algorithm used in the thesis is also presented in this chapter. Generation of the simulated ideal signal to examine the proposed prototype is considered. Furthermore, conducting to the simulations, the performance metric has been discussed and employed to verify the validity of the proposed prototype.

Chapter 4 gives design examples and achieved results of conducted experiments. It illustrates the data which has been captured using USRP. The simulated data can also be observed in this chapter. The chapter demonstrates the experimental results of the proposed prototype and analysis of the attained experimental results are also considered in this chapter.

Chapter 5 includes the conclusion and future scope of the proposed algorithm.

Chapter 2

Literature Review

2.1 Introduction

The natural frequency spectrum is not enough to accommodate the increasing number of wireless communication users. The need for fast communication with higher data rate devices is one of the most significant concern to be taken into account in coming years. The CR concept provides a viable solution to the problem. According to the definition given by Federal Communications Commission (FCC): "Cognitive radio: A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability and access secondary markets." [3].

A generic CR is implemented over an SDR. In RF communications, SDR along with the SDAs are the enablers of the cognitive radios. SDRs are the capable paradigm of managing and optimizing the spectrum efficiency. A typical CR is shown in Figure 2.1.

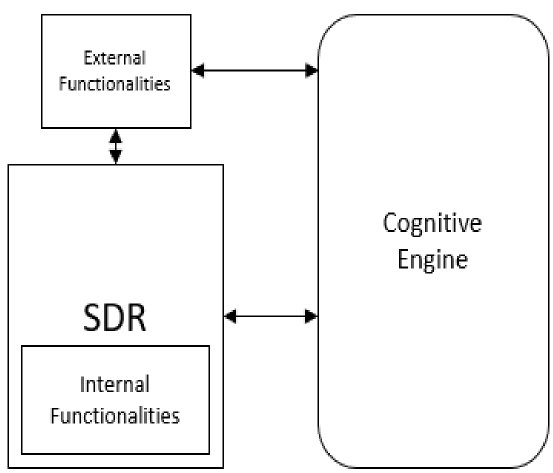


Figure 2.1: A Typical Cognitive Radio

SDR can be interfaced with a wide variety of networks including Zigbee, WLAN, WiMAX, Bluetooth, etc. SDR structure is not only in use to optimize the spectrum efficiency but also to overcome the “limited spectrum needs,” as presented in the literature. The chapter is based on the literature review of previous implementations of CR to scan TVWS, but before describing it, this chapter presents the basics of CR. At first, an introduction to SDR is presented. The fundamentals of the main units of SDR and relationship between SDR and CR is given in this chapter.

The functions of CR along with their significant examples will be explained in detail. The CR standard IEEE 802.22 will be discussed along with the communication protocols of CR. Finally, a literature review of previously implemented prototypes, as well as their outcomes, are mentioned.

2.2 Software Defined Radios

According to the concept of SDR, the radio in which most or all of the hardware components which were previously physically implemented including filters, amplifiers, modulators/demodulators are now implemented using the software on a Personal Computer (PC) or embedded system. A simplified version of an SDR is presented in Figure 2.2.

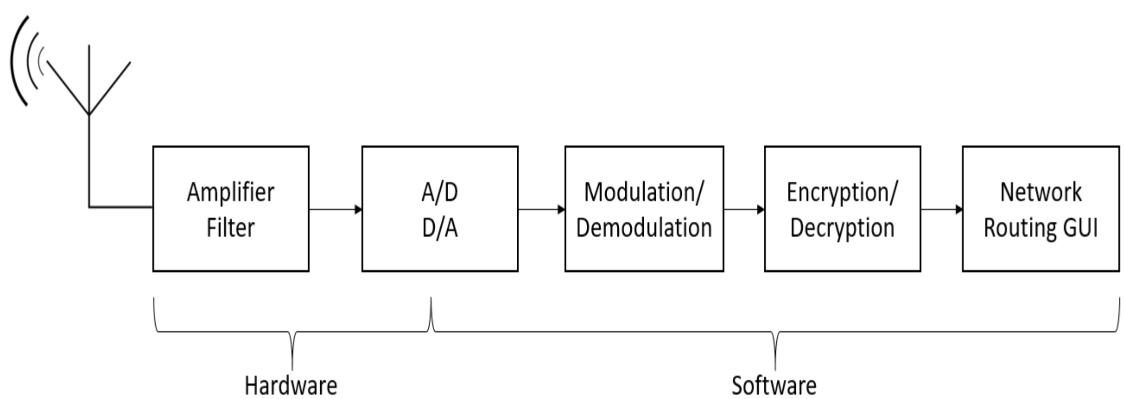


Figure 2.2: A simple Software Defined Radio

SDR is responsible for performing the internal and external sensing, (i.e., it deals with the inner layers of the OSI and TCP/IP models) and forms a connection between each layer. The upper layer functionalities in Figure 2.1 show a relationship between the SDR and SDA. In addition to SDR, CR has an advantage of sensing the environment in real-time. SDR initially was considered as the promising solution for interoperability, seamless global connectivity, multi-standard and multi-mode issues [4].

2.2.1 Software Defined Radios: A Platform for Cognitive Ratios

The need for higher computational and intelligent functionalities as well as emerging demand in high Quality of Services (QoS) given by the service providers leads to the CR technology. As provided in the definition given by FCC, a CR has the capability to adapt the radio parameters and can change itself accordingly. SDR has shown the flexible communication functionality by using the fixed analog circuits and components. Based on this, a CR needs to be designed around SDR. According to one definition, "A CR is an SDR that is aware of its environment, internal state, and location, and autonomously adjusts its operations to achieve designated objectives [4]."

SDR presents a very flexible platform for an implementation of a CR. It can operate flexibly with different bandwidths over a wide range of frequencies. An ideal SDR consists of three central units such as reconfigurable digital radio, a software tunable analog radio and a software tunable antenna. The primary function of digital radio is to optimize the different waveforms. Software analog radio front end is there to perform functions such as RF filters, Power Amplifiers, Low Noise Amplifiers, etc. The impedance synthesizer along with this unit is there to ensure the optimized performance of the antenna. The ideal SDR architecture is shown in Figure 2.3:

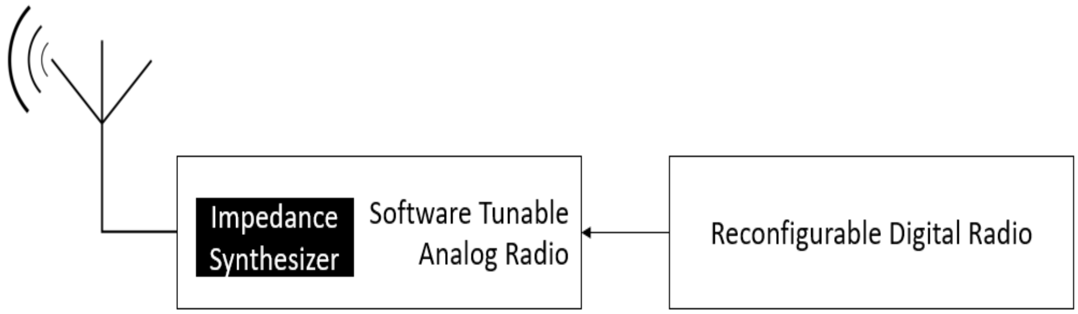


Figure 2.3: A Generic Software Defined Radio

2.3 Main Functions of CR

A CR can perform tasks autonomously by using functionalities such as self-managing, self-optimizing, self-monitoring, self-repair, self-protection, self-adaption, and self-healing to achieve its goals [1]. There are two main highlighting features of CR:

- Flexibility
- Potential gain in spectral efficiency

The RF spectrum is divided into:

- **Licensed Spectrum**: A licensed spectrum is alloted to a particular user by giving the administrative rights. The Licensed user is allowed to perform operations in this particular range. Spectrum management authorities give legal rights to the user according to which no other user is allowed to use this spectrum within the same geographic area.
- **Unlicensed Spectrum**: An unlicensed spectrum is an underutilized spectrum which has never been allotted to any particular user. An unlicensed user is the one who is

utilizing the unused spectrum of the ISM band. These users are authorized to use the band for a particular period without causing harmful interference to the other users if the band is unoccupied. According to FCC a user of unlicensed spectrum is allowed to transmit information which is less than 1 watt [5].

In a typical communication system, the user of licensed band is known as the *Primary user* (PU). The channel has been allocated to the PU regardless of its activity. *Secondary Users* (SU) are the one which uses the underutilized unlicensed or in some cases licensed bands of the spectrum. SU has the lowest priority regarding spectrum usage. The primary objective of the CR is to accommodate those SUs, to maximally utilize the available spectrum. The functionality of a CR is shown in Figure 2.4.

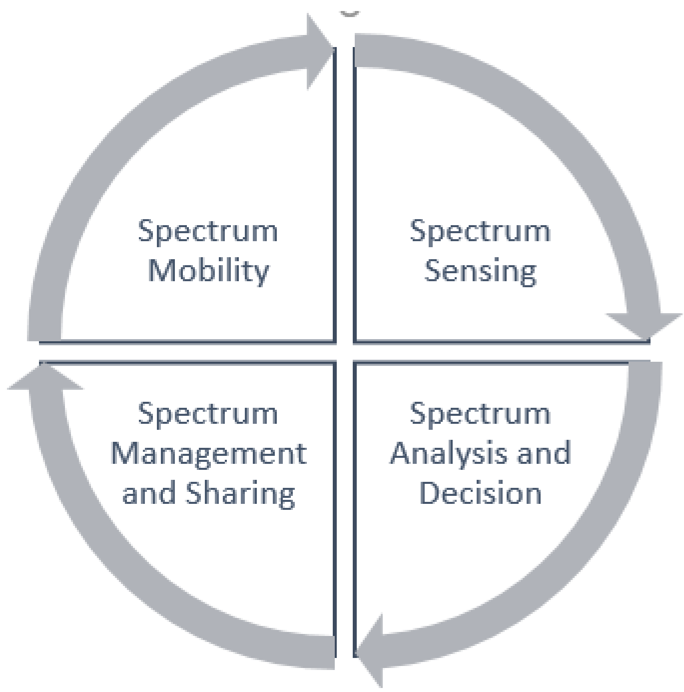


Figure 2.4: Main Functions of CR

2.3.1 Spectrum Sensing

Spectrum sensing is the key aspect of CR. Finding a spectrum sensing technique which requires shorter time to detect the presence of a signal is one of the main challenges in making CR efficient. The performance metrics of any technique can be estimated based on its detection accuracy, robustness and complexity. Spectrum sensing is modeled on the following hypothesis [3]:

$$Hypothesis\ 0\ (H_0) : Signal\ is\ Absent$$

$$Hypothesis\ 1\ (H_1) : Signal\ is\ Present$$

where,

$$\begin{aligned} H_0 &: x(t) = w(t), \\ H_1 &: x(t) = h(t)^* s(t) + w(t), \end{aligned} \tag{2.1}$$

x(t) is the Received Signal Strength (RSS) of the signal, *w(t)* is the Additive White Gaussian Noise (AWGN) [6], *s(t)* is the received signal and *h(t)* is the channel gain.

The performance of any sensing techniques can be estimated by calculating its probability of detection P_d and probability of false alarm P_f [7]. For a system to be efficient, ideally the P_d should be high, and P_f should be low. The performance probabilities will be further discussed in Chapter 3.

Several Spectrum Sensing techniques have been proposed in the literature [3, 4, 7–11]. Among the most notable ones are the energy detection based spectrum sensing, pilot-tone detection scheme, cyclo-stationary based spectrum sensing, matched-filter detection schemes. Some of the techniques illustrated in Figure 2.5 are presented here.

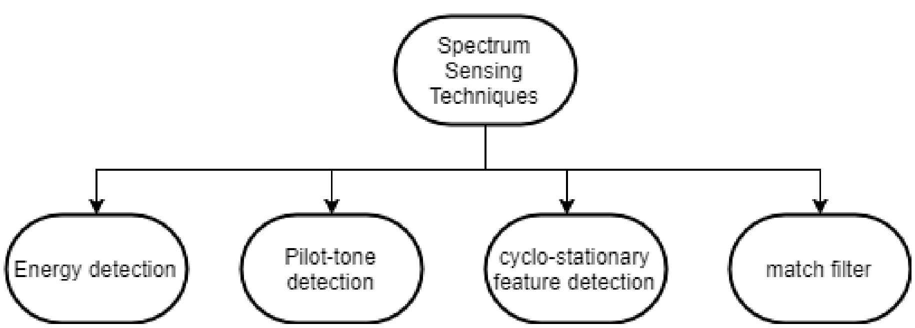


Figure 2.5: Various Spectrum Sensing Techniques

i) Energy Detection Spectrum Sensing Technique

Energy Detection spectrum sensing technique is the most popular scheme to detect the presence of PU. It works on the simple principle of estimating the strength of the incoming signal. This technique has the lowest computational and implementation complexities as the detector does not need to know about the incoming PU signal [12].

A simple Energy Detector (ED) can be based on the detection criteria which can interpret the presence of an incoming signal by comparing its signal strength with a predefined threshold value:

$$d = \begin{cases} 0 & \gamma < \lambda \\ 1 & \gamma \geq \lambda \end{cases} \tag{2.2}$$

where λ is the predefined threshold and γ is the energy of the incoming signal. The selection of the λ is critical in this scheme as the selection is sensitive to noise bench of the signal. If λ is considered high then signal with low power will be miss detected by the system simultaneously with low λ, there is a high probability of detecting the noise which can give rise to Signal to Noise Ratio (SNR) penalties [13]. According to [4], the AWGN in Equation (2.1) has the power of σ^2 and bandwidth $\boldsymbol{B}$ Hz.

In a conventional ED, the energy of the signal is computed over a given time period T equivalently over N samples:

$$T = NT_s, \tag{2.3}$$

where T_s is the sampling period of the signal.

The SNR (ρ) of the signal can be computed over a certain time period considering the signal and complex conjugate signal product as mentioned in Equation 2.4 [7].

$$\rho = \frac{\alpha^2}{\sigma^2(t_2 - t_1)} \int_{t_1}^{t_2} s(t)s^*(t)dt, \tag{2.4}$$

where α is the magnitude and σ^2 is the variance.

Limitations: Noise above a certain level cannot be estimated in ED. Once the value of SNR drops below a certain point the scheme can no longer efficiently detect the signal, irrelevant of increased sensing time [10].

ii) Pilot-tone Detection Scheme

Another method to detect the presence of PU in a BW is by estimating the presence of a Pilot-tone in the spectrum. A transmitter places a pilot tone, and the receiver has complete knowledge about the location of this tone in the spectrum [10].

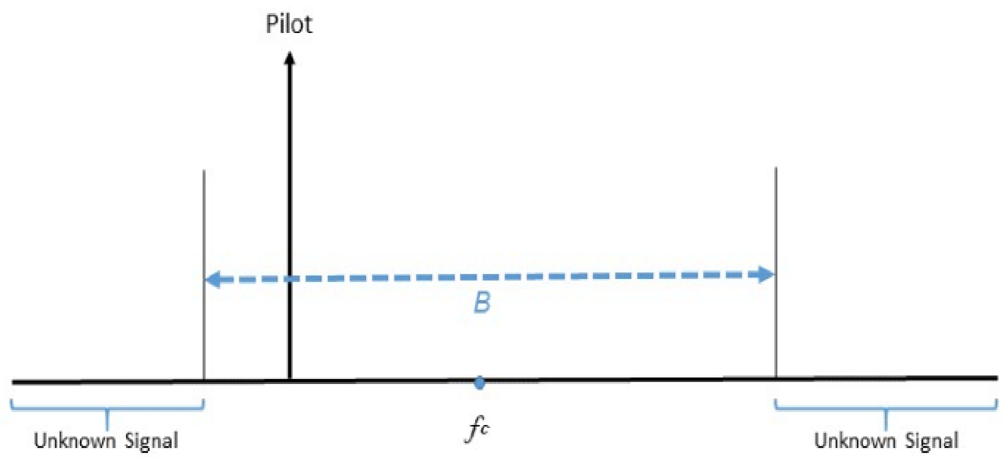


Figure 2.6: Pilot Signal in Spectrum

The pilot signal is detected in a digital domain, and hence the hypothesis for this will be:

$$\begin{aligned} H_0 &: x(n) = w(n), \\ H_1 &: x(n) = S_p(n) + w(n), \end{aligned} \tag{2.5}$$

where $S_p(n)$ is the signal with the pilot of power θ. The pilot data can be estimated using matched filter statistics which states:

$$T = \sum_n x(n) s_p^*(n). \tag{2.6}$$

where $x(n)$ is the received signal and $s_p^*(n)$ is the conjugate of received pilot signal.

The presence of the signal is detected by considering the statistics given in Equation 2.7. T_x represents the signal presence. The test statistics T is compared with a threshold λ. If T is less than λ then signal is absent, otherwise, present.

$$T_x = \begin{cases} 0 & T < \lambda \\ 1 & T \geq \lambda \end{cases} \tag{2.7}$$

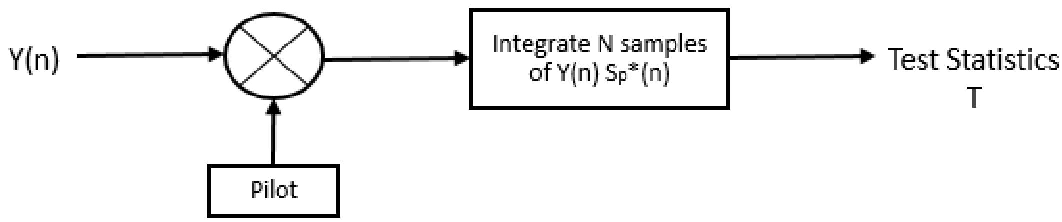


Figure 2.7: Pilot Detection

iii) Match Filter Detection Scheme

The technique with the highest P_d and also with the highest computational complexity is the matched filter detection scheme. To implement this technique, a user must have the complete knowledge of the incoming PU signal. The concept of matched filter according to [7] works by maximizing the SNR at the output of the filter. Mathematically, this is written as:

$$h(t) = \begin{cases} s(t-T) & 0 \leq t \leq T \\ 0 & elsewhere \end{cases} \tag{2.8}$$

The presence of PU can be estimated by passing the signal through a filter which will increase the useful signal strength at the same time will decrease the noise power [14]. If the signal is present there will be a clear, sharp peak or else if there is no peak then the signal is not present in the spectrum. The filter which can perform such function is known as matched filter.

The block diagram given in Figure 2.8 illustrates that the received signal *x(t)* will be added with an AWGN which will give the resultant signal (y(t)). The resultant signal along with the predefined signal will be given as an input z(t) to the match filter which will convolve the two signals and impulse response of the output signal will then be compared to the threshold λ for the PU detection to obtain test result T(x) [15].

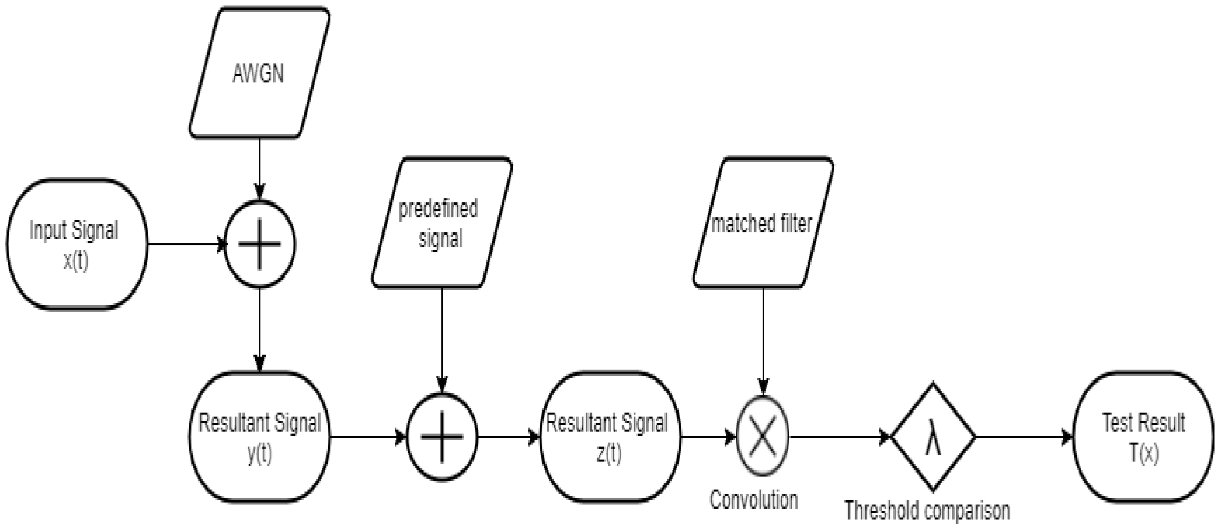


Figure 2.8: Block Diagram of matched filter technique

Matched filter scheme detects the presence of a PU by increasing the value of SNR. This gives the advantage to detect the signals with low SNR which are usually neglected in other schemes.

Limitations: Matched filter cannot be implemented in the case where the receiver does not have complete information about the incoming signal. Moreover, the computational complexity of this scheme increases the hardware complexities and hence is not a preferable scheme in so many cases.

iv) Cyclo-Stationary Spectrum Sensing Scheme

In wireless communications when an excess amount of BW is used, signals show very strong Cyclo-stationary (CS) feature based on modulation type, carrier frequency, and data rate. If the user knows certain characteristics of PU, then CS feature can be used to detect the presence of PU in the BW [7].

This technique has robustness in uncertainty in noise power and propagation channel [16]. To implement this technique user has to make a trade-off with the computational complexities. This method deploys the inherent periodicity of the modulated signals and hence guess the modulation scheme used by the PU. This increases the efficiency of the system [17]. The generic block diagram shows the basic working of the detection scheme in Figure 2.9. An input signal $x(t)$ is passed through a filter which will reduce the noise element present in the signal. The resultant signal will be correlated with the other captured signals and after performing signal correlation, the result will be compared to the predefined threshold λ to obtain the test statistics result $T(x)$ which will determine whether PU is present or not.

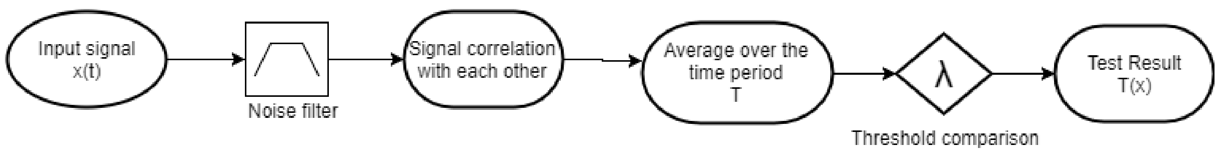


Figure 2.9: Block Diagram of CS detection scheme

Limitations: CS spectrum sensing technique needs sufficient amount of signals to detect the spectrum. In case if a number of observations are not enough, the detection performance will be compromised. Due to high computational and implementation complexities, the overall hardware complexities of the system increases.

v) Other Spectrum Sensing Algorithms

There is a variety of other detection schemes presented in the literature including the covariance based method in which the difference between the covariance of incoming signal and additive noise is used to detect the presence of the PU.

Eigen value based detection scheme is similar to the covariance based scheme. The Eigen value of the covariance matrix is computed and then compared to detect the signal. This scheme is based totally on the test statistics and does not require any information about the noise and hence also known as “fully blinded” detection scheme [7].

Another technique is wavelet based edge detection in which wavelet transform technique is used to detect the edges of the signal. Other techniques include spectral estimation method [18], filter bank method [19], etc.

2.3.2 Spectrum Analysis and Decision

A particular band of a spectrum has its own characteristics based on a number of users and frequency range. Spectrum sensing detects unused spectrum in the band but SU has the ability to choose the band which is suitable for it in terms of data security and availability of band as required by SU. Spectrum analysis also determines the path loss, interference, wireless link errors, layer delays, etc. [1].

The knowledge about the incoming PU is analyzed, and the decision is made on which band should be allocated to the SU. There are different models and approaches present in the literature which can be used to analyze the spectrum. One of the techniques uses Markov chain analysis [20]. The following aspects are analyzed by CR [21]:

- **Operating Frequency**: CR has the capability to analyze and adjust the operating frequency as required by the SU.
- **Modulation**: CR detects the modulation scheme and can adjust according to the need of SU. For example, communication where the minimal delay is required, CR increases the data rate at the same time neglect the bit error rate.
- **Transmission Power**: CR can adjust the transmission power according to its use. For example, if CR needs to accommodate a large number of SUs, it decreases the transmission power of each user whereas, if the number of SUs are limited then CR has the potential to increase transmission power accordingly.
- **Communication Technology**: CR has the aptitude to switch among different communication technologies.

2.3.3 Spectrum Management and Sharing

The information obtained after spectrum sensing and analyzing is then utilized for managing the spectrum. Spectrum management includes dedicating the specific band to a particular SU based on its availability and PU activity. If a certain band is available for a particular time period, but the PU of the band is showing unpredicted behavior, then it is the responsibility of the CR to switch SU to the band where PU activity is partially predictable. Selecting the most suitable spectrum for SU is the main responsibility of spectrum management protocol [21].

Spectrum sharing is an important aspect of CR. Sharing the spectrum requires a coordination with other users present in the spectrum. Sharing the spectrum can be threatening for SU if a malicious user is present in the system and it depicts the spectrum band as unoccupied and is actually trying to read the data sent by the SU. It will not only cause data loss for SU, but also it will be a threat for SU. Sharing spectrum with a malicious user can be harmful to SU as it can affect the data security of the SU.

2.3.4 Spectrum Mobility

Spectrum mobility is an important factor of CR protocols as SU is not privileged to use a certain band for a long time. Availability of licensed bands changes frequently over time. The major factor affecting mobility is the time it takes during spectrum hand-off [1]. This hand-off cause delay in various layers of the communication stack. While writing protocols for this aspect of CR, one must consider the sensing time taken by SU to detect the vacant band and also to vacate the band when PU becomes active. Otherwise, PU can face severe data loss due to interference. IEEE 802.22 put forth standards to avoid this interference by putting time constraints for SU. In this case, SU will not be able to use the band for a prolonged time, and the risk of interference can be minimized.

Spectrum mobility is the key aspect of CR to ensure the uninterrupted communication by implementing dynamic spectrum access [22]. The spectrum holes are the unused or underutilized spaces present in the spectrum. Spectrum mobility protocol interrupts an on going communication if PU becomes active. This protocol then switches to another channel to provide communication services to the SU. To provide QoS communication while ensuring a seamless communication is the task of spectrum mobility [23].

2.4 Cognitive Radio Standard: IEEE 802.22

IEEE 802.22 is the standard designed to deal with the white spaces present in the TV spectrum. IEEE 802.22 ensures a seamless communication of a cognitive user while causing no interference to a digital or analog user of the band. IEEE 802.22 was introduced initially to setup a communication system in rural areas while utilizing TVWS.

IEEE 802.22 deals with the Wireless Local Area Network (WLAN) as well as the physical (PHY) and Medium Access Control (MAC) Layer while ensuring the QoS to any data including audio and video traffic [24]. This standard is the modified version of IEEE 802.16 (WiMax) and 802.11a/g (WLAN) with a wider range for its user.

The key features of this standard include high data rate, long range, immunity to interference, extensive data coverage and the most of all it can be operated in the licensed as well as an unlicensed band [8]. The operating parameters are provided in Table 2.1.

Table 2.1: IEEE 802.22 Parameters

IEEE 802.22 Parameters	
Parameter	Specification
Range	30-100 km
Methodology	Spectrum Sensing to Identify free channels
Channel Bandwidth	6, 7, 8 MHz
Channel Capacity	18 Mbps
User Capacity	Up-link: 384 Kbps, Down-link: 1.5 Mbps

The communication regulatory authority has standardized protocols for TVWS operations in the USA and UK, according to which if a fixed device is operating at a particular geographic location; it can transmit power up to 1 W in one or multiple 6 MHz channel. Antenna gain of 6 dBi is allowed. The power spectral density should not be greater than 12.2 dB in any 100 KHz band. The effective isotropic radiated power (EIRP) of a portable device should not exceed above 100 mW

(20 dBm) and power spectral density should not be above 2.2 dB in a 100 kHz band. If a portable device is working adjacent to the licensed channel its power should be reduced to 40 mW while spectral density should be -1.8 dBm in a 100 kHz band. The sensing device should detect signal up to SNR value of -114 dB and should end the communication within 2 seconds [25]. The antenna parameters defined by IEEE 802.22 should have a gain of 0 dBi or higher.

2.5 Communication over Cognitive Radio

CR is designed to set up a communication system which meets the ideal concept of meeting the standards set up by FCC while ensuring the use of an underutilized spectrum of TVWS. It is designed to work efficiently with different layers of the TCP model. The SU should be able to set up a communication without causing harmful interruption to PU.

The CR standard IEEE 802.22 is designed to work with the Physical (PHY), Medium Access Control (MAC) and Network layer of the CR. This standard states that the total time of spectrum sensing, data transmission and spectrum vacating should not exceed 2 seconds. Moreover, during this time CR should continuously scan other vacant bands in the spectrum in case if PU wants to become active so that SU can be able to vacate the band without causing interference with licensed user.

The CR should provide data security for SU from the malicious users of the spectrum, as it can cause harm to the data transmitted by SU. Another concept given in literature states that a CR should be efficient enough to create its own system by setting up a communication between two SU's (i.e. one SU transmits the data, and another SU receives it and vice-versa.)

2.5.1 Cross-Layer Functionality of Networking Layers

The cross-layer functionality of CR in Network Interface layer of the TCP model is shown in Figure 2.10. The physical layer being on the bottom is directly related to all the external hardware including the RF antenna, SDA and other physical hardware which is useful for signal transmission and receiving. CR sensitivity is well-addressed if RF front-end sensitivity is increased. PHY layer is responsible for exploiting the digital signals for specific PU. The MAC layer, on the other hand, is in charge of spectrum allocation (i.e., it is responsible for spectrum analysis, spectrum management, and spectrum mobility.) Moreover, network cooperation where users share their spectrum sensing measurements is also part of this layer.

Each Internet Protocol (IP) layer supports different configurations which support various modes of operations of a communication system. The overall performance of each layer is obtained by tuning the configuration parameters with each other. The major challenges faced during the configuration of these layers include modularity, interoperability, imprecision, scalability, and complexity [26]. Cross-Layer Optimization also increases the computational cost of the system.

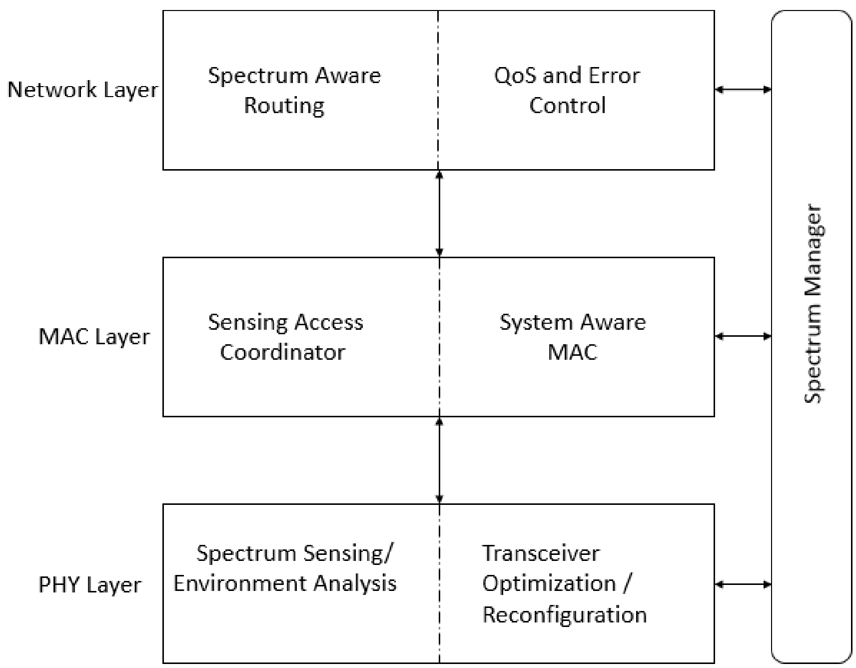


Figure 2.10: Cross-Layer Functionality of CR

2.5.2 IEEE 802.22 for Cross-Layer Functionality

IEEE 802.22 has put forth the standards to deal with different communication layers of OSI and TCP/IP model. These standards define parameters to adapt the radio operating characteristics to work in a real-time environment. The PHY and MAC parameters defined by IEEE Working Group are mentioned in the sections below.

PHY Layer

The service capacity to which a CR correspond is a total of PHY data rate of 18 Mbps in a 6 MHz TV channel [24]. The main objective of PHY layer is to keep the performance standard high at the same time the complexity should be low. IEEE 802.22 has defined high flexibility regarding modulation and coding. Another important issue to consider is the Transmission Power Control (TPC), according to the standard, the TPC dynamic range should be at least 30 dB. The key features are given below:

Table 2.2: PHY Layer Parameters

PHY Layer Parameters	
Parameter	Specification
PHY Transport	OFDMA
Modulation	QPSK, 16QAM, 64QAM
Spectral Efficiency	0.624 bits/s/Hz – 3.12 bits/s/Hz
Coding	Convolutional Code
Spectral Mask	802.22 has adopted the Spectral Mask requirements proposed by FCC.

MAC Layer

The CR-based MAC should be highly dynamic so that it can effectively respond to the changes in the operating environment. Robust data delivery is the major function of this layer besides medium access control. A CR channel can use any multiplexing scheme including frequency, time, code or any combination therein. Hence, the MAC layer protocol designing is complex as compared with any other standards such as WiMax, WLAN, etc. where the channel is predefined.

The other operations of this layer include switch channels, suspend/resume channel operation, and add/remove channels to protect the incumbent user [24].

2.6 Spectrum Sensing using SDR Hardware

SDR hardware is incorporated with a variety of functionalities. The hardware has the capability to perform functions such as analog to digital conversion and vice versa, modulation and demodulation, encryption and decryption, network routing using Graphical User Interface (GUI), etc. There are various hardware including Radio Television Luxembourg (RTL) SDR [27], USRP [28], etc. present to detect the spectrum. These hardware have previously been used with different antennas to achieve communication between SU while applying different CR techniques. A variety of vendors including NI, Ettus, RTL-SDR, etc. are producing SDR hardware. SDRs along with SDAs have been previously incorporated with softwares such as GNU Radio, Labview, etc. to achieve CR functionalities.

A scheme which estimates the energy of the PU using Wireless Open-Access Research Platform (WARP) boards is presented in [29]. The research implemented a communication system using two WARP boards, one board as a transmitter and the other as the receiver. The QPSK modulated signals were generated for system validation. The experimentation results were able to detect signals only up to -7 dB SNR.

Ettus USRP and antenna for spectrum sensing in convolutional neural networks along with the GNU Radio software was used to setup a prototype in [30]. Energy detection scheme for incumbent user detection is based on machine learning techniques such as K-means clustering while keeping the 10 dB SNR value fixed.

Two different spectrum sensing methods (i.e., covariance matrix and maximum-minimum Eigenvalue method) have been implemented in [31] for spectrum sensing. A Universal Software Radio Peripheral (USRP) was used to capture the real-time signals. This USRP was configured using GNU Radio software. The spectrum sensing under different SNR scenarios was discussed in this paper.

The literature review of examples motivated us for prototype implementation for scanning TV signals present in the vicinity. A variety of ideas has been presented in the literature to utilize TVWS for different uses such as authors in [8] represented the use of TVWS over CR to setup a communication system over Smart Grids. Authors in [32] implemented the cellular device to device communication while utilizing TVWS and proved that TVWS could be the optimal solution for communication setup without causing interference to the PU of the spectrum. The use of SDR hardware for channel scanning is also discussed in [33, 34].

A prototype using Labview and NI USRP was implemented in UK to scan 2.4 GHz ISM band [35]. Microsoft and Google are also studying TVWS. Microsoft has conducted the first ever study of TVWS under FCC regulations as mentioned in [36]. Another study was done to study the spectral occupancies in Auckland, New Zealand in which authors study the 806 - 2750 MHz bands [37]. The competitive study of TVWs in other parts of the world is mentioned in [38].

2.7 Summary

In this chapter, the literature related to the research was discussed. The SDR is the enabling technology to implement the CR in the real world. The CR has four main functions including, spectrum sensing, spectrum analysis and decision, spectrum management and sharing, and sharing mobility. Spectrum sensing is the most important feature of the CR. Different spectrum sensing techniques have been discussed in this chapter. The chapter also illustrated a brief overview about the CR standard IEEE 802.22. Moreover, the PHY and MAC parameters to design communication setup for CR have been discussed.

Chapter 3

Research Methodology

3.1 Introduction

TVWS is one of the best candidates as a solution to improve the spectrum efficiency. For this purpose, extensive research works have been done in [30, 33, 34, 38]. In practice, to implement the spectrum sensing in real world, three important steps were taken into consideration. These stages include a spectrum sensing prototype, examining the prototype using simulated signal and finally examining the prototype in the real world. The proposed methodology is explained in details as follows:

1. **Prototype establishment:**

   A prototype using USRP 2901 and GNU Radio was developed to capture the real-time TV signals. These signals were stored in a Data Base (DB).

2. **Real-time testing:**

   The stored data was tested to detect the presence of an incumbent user using various spectrum detection techniques.

3. **Simulated testing:**

   To test the validity of adopted spectrum sensing techniques, simulated signals such as ATSC, QAM, PSK, QPSK, etc. were generated using MATLAB and GNU Radio.

The spectrum sensing techniques were at first tested on simulated signals. These signals were generated in GNU Radio as well as in MATLAB. This chapter presents the prototype implementation using USRP 2901 in detail. The method to generate TV signals in MATLAB as well as signals having characteristics similar to TV signals such as Quadrature Amplitude Modulated (QAM) signal, Phase Shift Keying (PSK) modulated signal, Gaussian Minimum Shift Keying (GMSK) modulated signal and Quadrature Phase Shift Keying (QPSK) modulated signal produced by GNU Radio is also described in this chapter.

A review of pilot-tone detection scheme and its implementation as well as energy detection scheme and its implementation are considered. Filter designing technique to implement pilot-tone detection is also presented. The selected energy detection method for the detection of PU is also discussed.

The adopted method to test the performance of the proposed prototype is also considered.

3.2 Equipment and Parameters

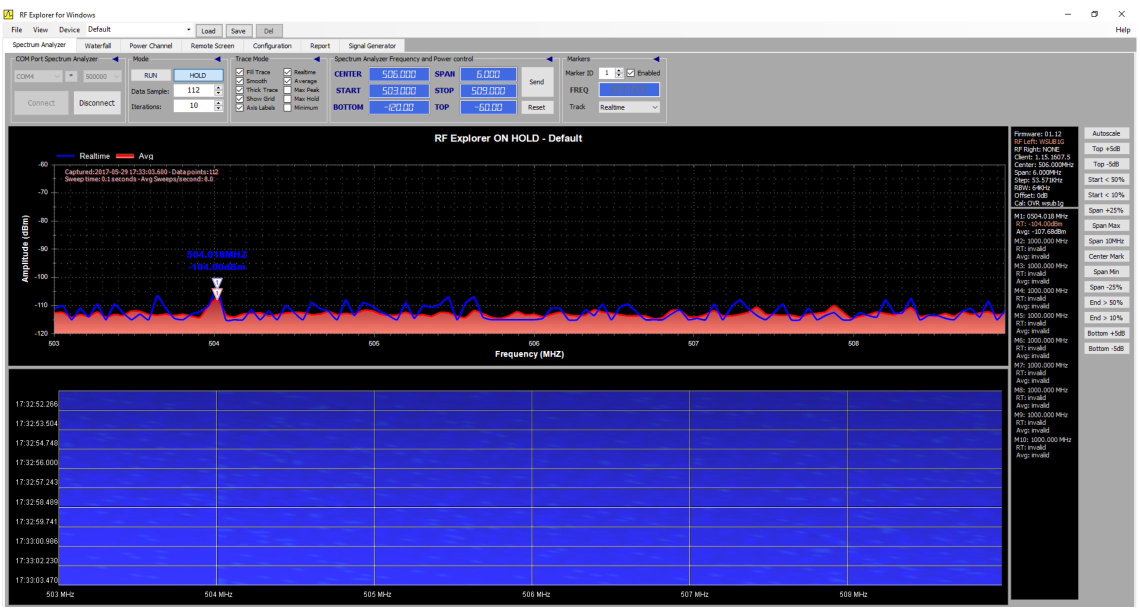
3.2.1 Radio Frequency Explorer

A simple hand held RF explorer as shown in Figure 3.1a was used to observe the spectrum. RF explorer has a variety of functions including Spectrum Analyzer, RF Generator, Wifi Analyzer, etc.

There are numbers of RF explorer present, but the one which was used to observe the presence of TV signals in the vicinity has a scanning frequency range between 240 MHz to 960 MHz. In Figure 3.1b, the observed signal is starting at 513.5 MHz and ending at 519.5 MHz with center frequency at 516.5 MHz is shown.

Initially, RF explorer was used to observe and record the readings but the readings obtained cannot be considered reliable enough as the data collected using USRP gave more refined and accurate results than data collected using RF explorer.

(a) RF Explorer



(b) Signal Observation in RF Explorer

Figure 3.1: RF Explorer Hardware and Software Overview

3.2.2 Universal Serial Radio Peripheral

A National Instrument (NI) USRP-2901 has been used to capture the signals in the vicinity. This unit has a capacity to capture signals ranging between 70 MHz to 6 GHz. It is a 2X2 Multiple Input Multiple Output (MIMO) device (i.e. it has ports for two receiver antennas, as well as, two transmitter antennas) Figure 3.2.

Figure 3.2: NI USRP-2900/2901

The communication applications which can be achieved using this tunable RF transceiver includes: TVWS, broadcast FM, low-power unlicensed devices (ISM), etc.

3.2.3 Antenna Parameters

The Antenna parameters are given below:

Antenna	Resonance
Omni-directional Mobile Antenna	144/440MHz
TV Antenna	500-700MHz
J-Pole Antenna	142MHz
GPS Antenna	Model No. GPA-02A

3.2.4 Spectrum Parameters

The spectrum parameters were specified by Industry Canada [39] states the rules to be followed while working with the TVWS. The TV channels measured in this thesis are from channel 19 to channel 51 excluding channel 37 which has been preallocated for radio astronomy. The frequency ranges between 500-698 MHz.

3.3 Experimental Setup

In this section, the thesis presents the process which was used to sense the UHF TV spectrum bands in the city of Windsor, Ontario, Canada and discusses some details of the resulting observations. The sensing platform implemented was composed of an SDR, *python* applications, GPS mobile antenna and UHF antenna. The prototype initially was mounted in a vehicle to dynamically detect spectrum bands, and the collected data is stored both locally and in a remotely located Data Base (DB).

Analysis of the obtained data exhibits the state of the unoccupied spectrum in the frequency range from 500 MHz to 698 MHz in the urban area of the city. The frequency range analyzed (500 - 698 MHz) is particularly appealing due to good propagation properties for long range communications as these channels are widely spread not only in Windsor, ON, but also to the adjacent areas [40].

3.3.1 Prototype Setup

The purpose of the prototype implementation is to setup a mobile hardware to dynamically sense and record TVWS in the city. A NI USRP 2901 is employed as the key functional prototype platform component; since this SDR device can provide a high accuracy sensing due to its receivers low noise figure of 5-7 dB [28]. The proposed measurement setup is divided into as: Data Collection Environment, and Data Visualization. Data Collection Environment is explained in this chapter while Data Visualization is part of Chapter 4.

Data Collection Environment

The flowchart of the experimental set-up has been shown in Figure 3.3. The steps of data collection environment have been explained below:

Hardware setup: The prototype consists of the following hardware elements:

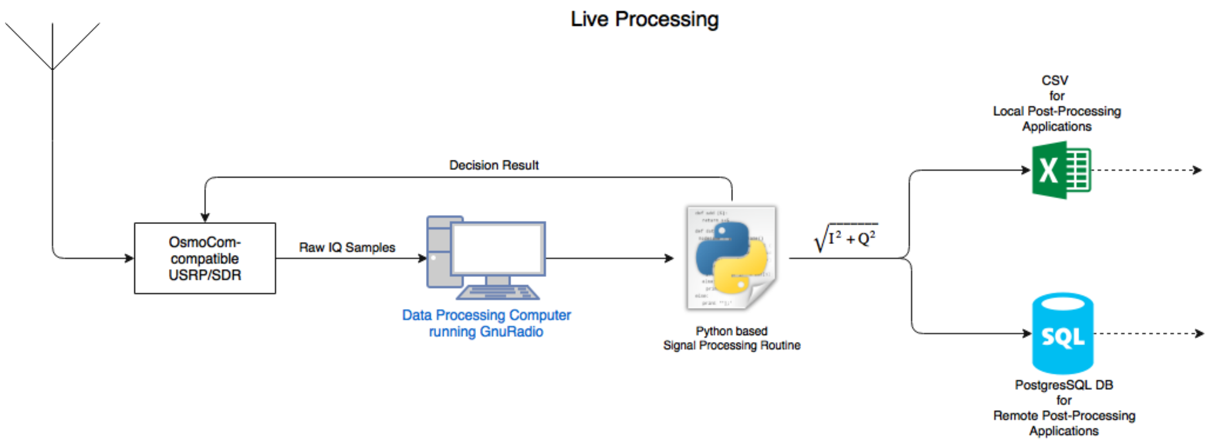
- NI-USRP 2901.

- Dual-Band 2 meters and 70 centimeters mobile antenna.
- GPS-Band active patch antenna model No. GPA-02A.
- WiFi Hotspot for database storage connection.
- Computer running Gnu Radio Python scripts.

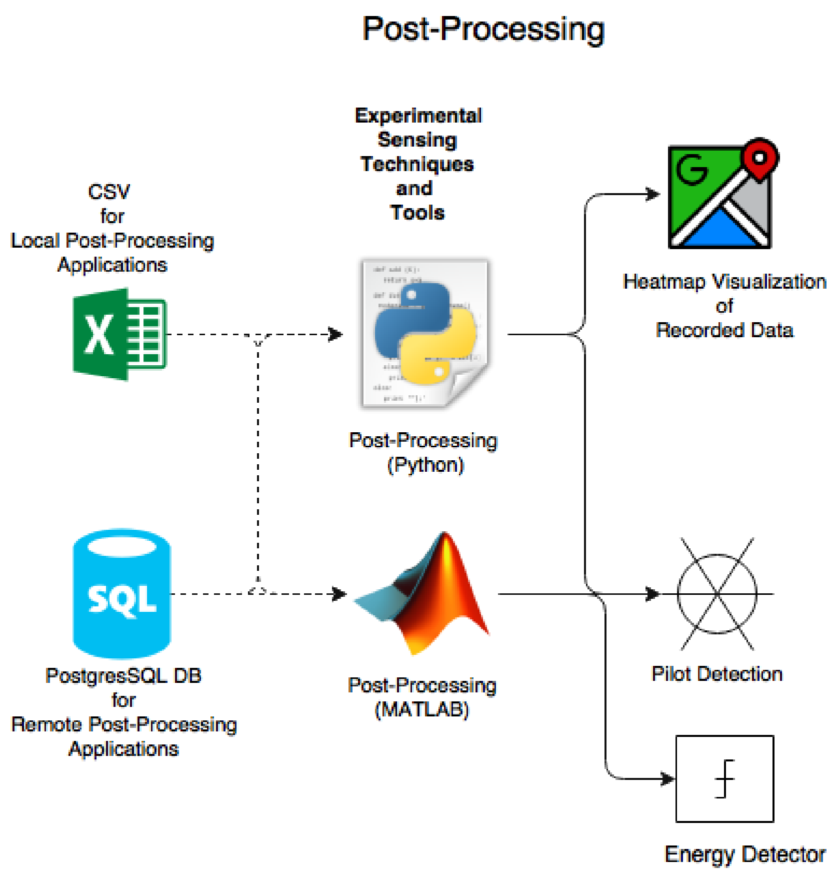
Data logging: The proposed algorithm for the signal collection environment is designed as two Python scripts which were developed to collect, record and report on the details of white spaces in the band; a script for data capturing and recording and a script to generate heat-map using Google Maps. The data-logging script is built using the GNU Radio signal processing framework. The readings are stored in a SQL database as a Comma Separated Values (CSV) file for use in the post-processing stage.

GNU Radio flow graph: GNU Radio is a software development toolkit which is utilized for the implementation of SDR and development of signal processing systems. GNU Radio companion is employed to create the skeleton of the data recorder script. The Osmocom Source block forwards the unprocessed IQ signal into two different blocks which process the signal further. The Probe Average Magnitude Squared block turns the incoming IQ stream into an object which is used to poll and measure various characteristics of the probed signal. This probe is, in turn, invoked using the Function Probe block. This block invokes a user-specified function and stores the output in a variable, which can be accessed throughout the *Python* script. The rate at which this variable is updated by the function probe block can be specified in the poll rate field of the function probe.

Data Storage: At the completion of each channel hop, the average strength corresponding to a given channel is recorded into both a CSV file and an online DB as is observed in Figure 3.3. This data is accessible using *dB Hero* SQL database client as well as *pgAdmin* database client. The data has been analyzed using *MATLAB* and *Python* programming tools.



(a) Detected signals pre-processing flowchart



(b) Post-processing flowchart

Figure 3.3: TVWS Detection Flowchart

3.4 Simulated Data Generation

The adopted spectrum sensing techniques have been examined using simulated signals generated using MATLAB and GNU radio. The generated data has an affiliation with the TV signals. The modulation schemes used to generate simulated data have been adopted by FCC and Electronics Communication Committee (ECC) while designing channel parameters for the USA and Europe respectively.

3.4.1 Data Generation using GNU Radio

The following signals have been generated using the software:

- **QAM Signal:** QAM is a digital modulation scheme. It conveys two analog message signals, or two digital bit streams, by modulating the amplitudes of two carrier waves, using the amplitude-shift keying (ASK) digital modulation scheme. The two carrier waves of the same frequency, usually sinusoids, are out of phase with each other by 90° and are thus called quadrature carriers.

  QAM is widely used in a digital TV and variety of communication systems [41].

- **PSK modulated signal:** PSK is the digital modulation technique in which the phase of the carrier signal is changed by varying the sine and cosine inputs at a particular time. PSK technique is widely used for wireless LANs, RFID and Bluetooth communications.

- **GMSK modulated signal:** GMSK is a form of modulation used in a variety of digital radio communications systems. It has advantages of being able to carry digital modulation while still using the spectrum efficiently. This signal is used in the variety of communications systems including GSM [42]. This technique is used in Europe but we are taking it here as an example.

- **QPSK modulated signal:** QPSK allows the signal to carry twice as much information as ordinary PSK using the same bandwidth. QPSK is used for satellite transmission of MPEG2 video, cable modems, video conferencing, cellular phone systems, and other forms of digital communication over an RF carrier [43].

Figure 3.4 shows the program to generate data for various modulation schemes. A vector source provides the input signal bits to the modulation blocks. These blocks are further connected to the file sinks, the blocks in which user allocate the specific location to store the generated data. The generated files are in the form of *.dat* extension and can be visualized in Chapter 4.

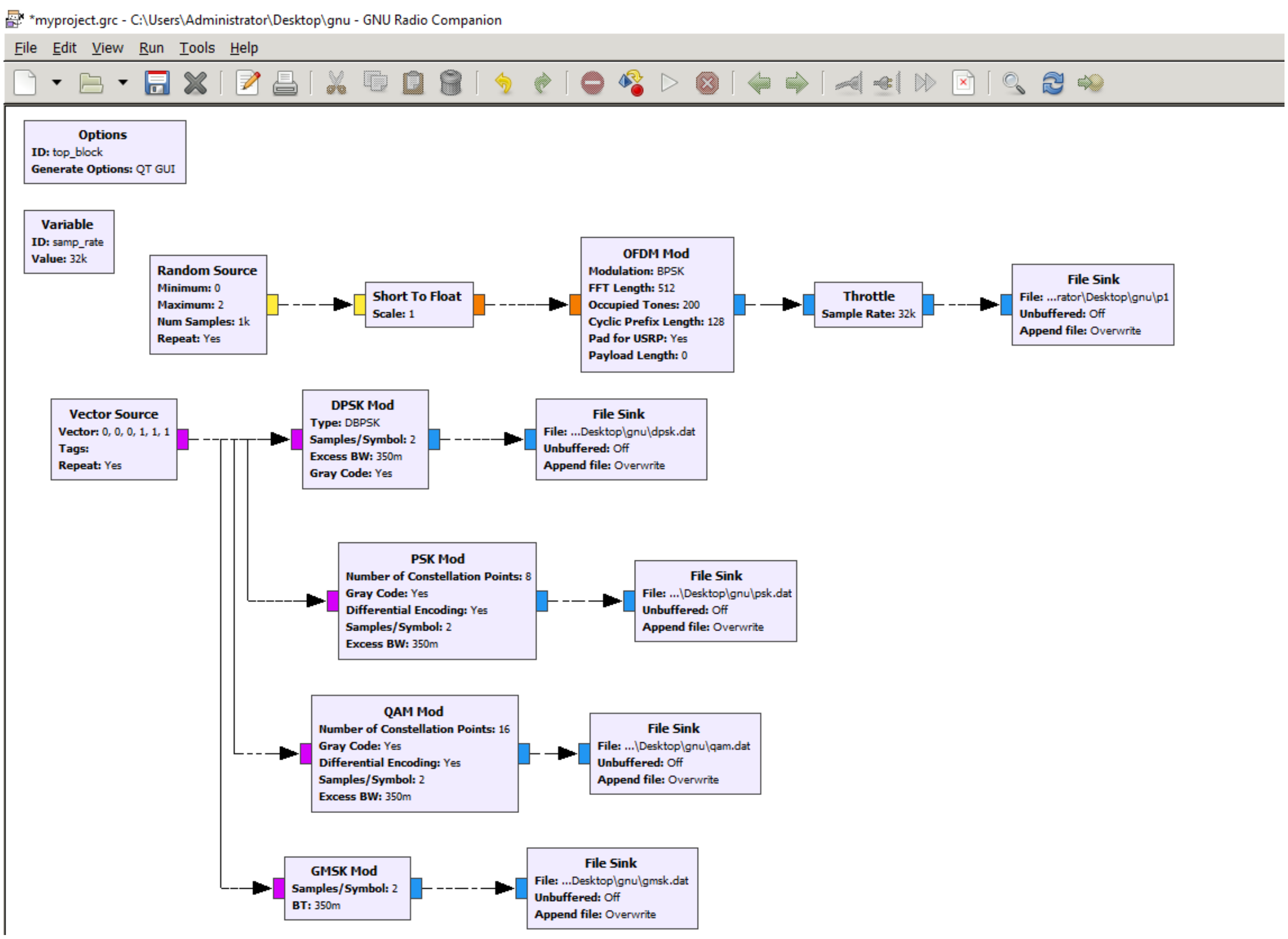


Figure 3.4: GNU Radio Program for data generation

3.4.2 Data Generation using MATLAB

Another set of data has been generated with the help of MATLAB. The generated signal is equivalent to the ATSC signal but the only advantage of generating this signal is that this user defined signal attributes are known and hence making it a reliable data set for implementing and testing spectrum sensing techniques.

Advanced Television Systems Committee TV Signal

Advanced Television Systems Committee (ATSC) defines the standards which are used in modern day digital Television (DTV) signal transmission. The highlighted aspects of ATSC standards are given below:

- It uses 8 Vestigial Side Band (VSB) modulation techniques for over-the-air local broadcast
- It works in VHF, UHF and Super High Frequency (SHF) bands
- ATSC Signals are designed to use the 6 MHz bandwidth
- A 19 kHz pilot signal is added at 0.31 MHz above the lower frequency edge of each ASTC TV channel band

3.5 Two-step Spectrum Sensing Approach

In Chapter 2, various spectrum detection techniques have been discussed. The matched filter algorithm is the technique with highest P_d and is considered the best technique for analyzing the presence of an incumbent user. To implement matched filter sensing algorithm, the system must have complete knowledge about the incoming signal as well as increased computational complexities makes this technique incompetent for our problem.

The proposed algorithm in the thesis introduces a combination of two spectrum sensing techniques to verify the presence of the licensed user in the spectrum. The first step is to detect the presence of a pilot-tone present in the signal. The next step is to estimate the energy of the received signal. If the first step of the scheme detects the presence of the PU then the system response will be "incumbent user detected." If a signal is not detected in the first step, the system will go to the next step and estimate the energy of the signal, if the estimated energy is above the threshold value then the presence of incumbent user is declared else, it will assume that there is no user present in the spectrum. The flowchart in Figure 3.5 explains the user detection in the spectrum.

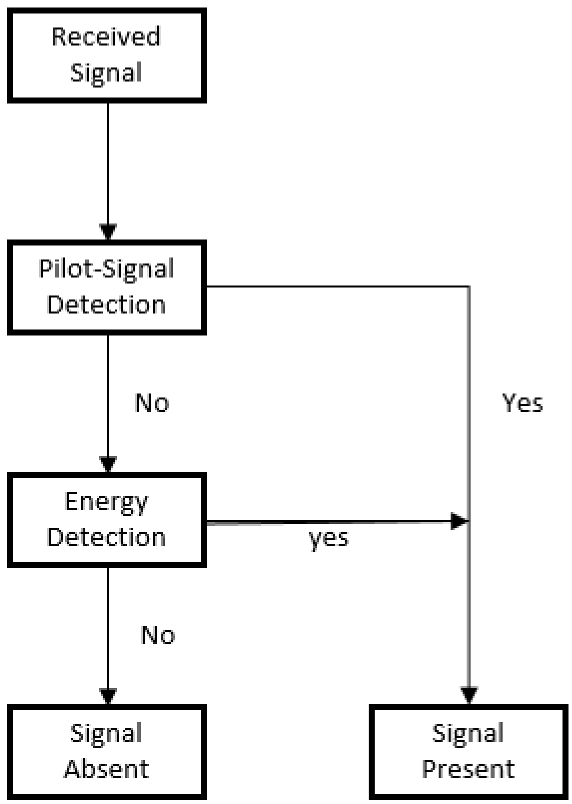


Figure 3.5: Block Diagram of Two step spectrum sensing Technique

3.5.1 Pilot-Signal Detection

According to the standards given by ATSC, each digital TV channel has an additional pilot signal present at the beginning of the channel whose magnitude is greater than the average of the combined signal strength [44]. The ATSC standards specify that each Digital TV (DTV) channel should have a pilot-tone at the beginning of the channel. In an analog system a channel is surrounded by a two pilot-tones, one at the beginning and one at the end of the channel. This thesis focuses on scanning the DTV channels only.

The filter used to detect the presence of a PU in this thesis is a band-pass filter (BPF).

Band pass filter designing

A BPF has been designed to detect the presence of a spectrum user. A BPF is the combination of a low-pass filter and a high-pass filter and allows a particular set of frequencies to pass while blocking the remaining set. A highly optimized band-pass filter has the capability to maximize the number of signals that can be transferred in a system while minimizing the interference among signals.

A signal is going to pass through a BPF and this filter will detect the presence of a pilot signal. A generic concept is shown in Figure 3.6. A channel ranging from one to n, stored in Buffer B has a starting point at "a" and an ending point at "b," a channel window containing n channels is entering at "a" and going to pass through "b" where there is BPF with a cut-off frequency lying at f_1 and f_2. The center frequency of the filter is at f_0. The n represents the sequence number of each channel. Each channel is examined individually and presence of signal is detected.

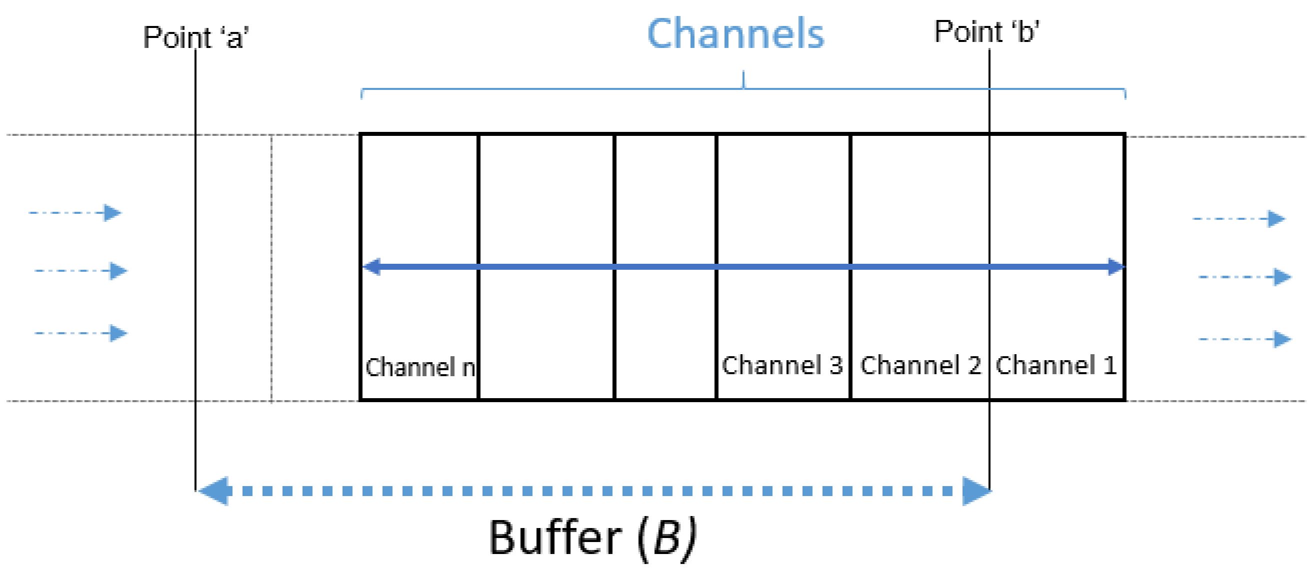


Figure 3.6: Pilot-tone detection using Filter

To design a BPF we first need to define:

- Upper cut-off frequency f_2: the frequency below which all the frequencies are passed
- Lower cut-off frequency f_1: all the frequencies above this frequency are passed

The critical frequency f_0 can be calculated by using Equation 3.1.

$$f_0 = \sqrt{f_1 f_2} \tag{3.1}$$

The bandwidth of the BPF is generated by using Equation 3.2.

$$BW = f_2 - f_1 \tag{3.2}$$

A FIR BPF has been designed in MATLAB signal processing toolbox to verify the proposed algorithm. The results will be demonstrated in Chapter 4. The design algorithm used to design this FIR filter is *Kaiser Window*. The Kaiser window is an approximation to the prolate-spheroidal window, for which the ratio of the main-lobe energy to the side-lobe energy is maximized. As described earlier, the pilot signal of ATSC signal lies at 0.31 MHz and is of 19 kHz bandwidth. The filter is stopping every frequency before 300 kHz and after 329 kHz. These frequencies have been selected based on the calculations of given pilot position and its bandwidth. A 10 kHz frequency is added before and after to avoid miss detection in case if there is any attenuation in the signal. The filter response can be seen in Figure 3.7.

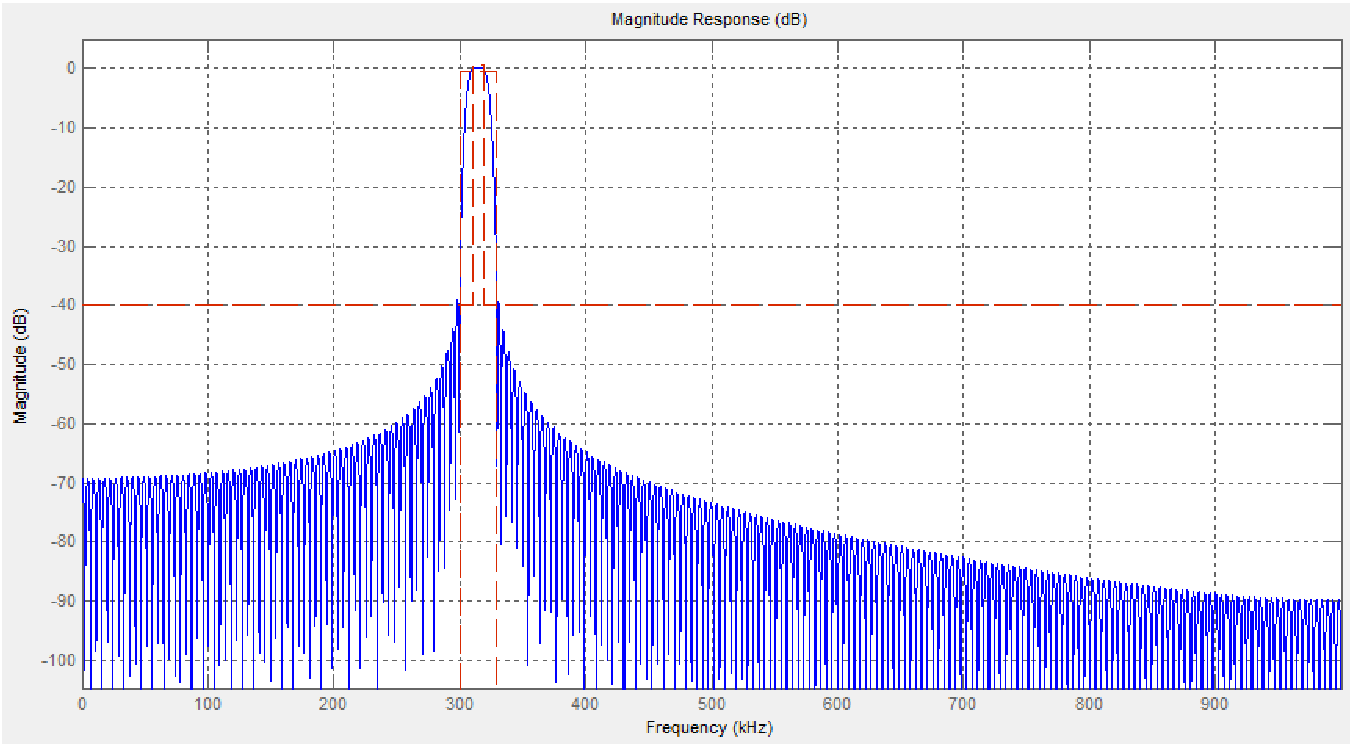


Figure 3.7: Magnitude Response of Band-pass filter

3.5.2 Energy Detection

Energy detection scheme is the simplest technique to implement as it has the lowest computational complexity. The primary objective of this scheme is to estimate the energy of the incoming signal. The binary detection hypotheses of the energy detector have been discussed in Chapter 2.

The detected signals are measured in the form of real-imaginary *(I/Q)* signals. Since the number of samples per second is enormous, these signals are first "decimated" at a particular rate. After finding the amplitude of each signal using Equation 3.3, they are converted in logarithmic (dB) scale using Equation 3.4 to estimate the signal strength of each channel. The signals are then stored in the form of a dataset.

$$Amplitude = \sqrt{I^2 + Q^2} \tag{3.3}$$

$$signal\ strength = 20\ log_{10}(Amplitude) \tag{3.4}$$

A run is defined as the dataset which contains all the channels ranging between 500 MHz to

698 MHz. The average of complete data set for each run is taken over n samples. This average is denoted by γ in Equation 3.5 and n_i represents the number of samples.

$$\gamma = \frac{\sum_{i=1}^{n} n_i}{n} \tag{3.5}$$

The set is further divided into subsets based on each particular channel data. x in Equation 3.6 represents the sum of Received Signal Strength (RSS) for a particular channel having n' number of samples. λ is the average energy of the channel.

$$\lambda = \frac{\sum_{i=1}^{n'} n'_i}{n'}, \tag{3.6}$$

where, n'_i represents the samples of the channel.

The threshold γ is then compared with λ to verify the test hypothesis. This concept has been shown in Figure 3.8.

$$signal\ detection = \begin{cases} 0, & \lambda < \gamma \\ 1, & \lambda \geq \gamma \end{cases} \tag{3.7}$$

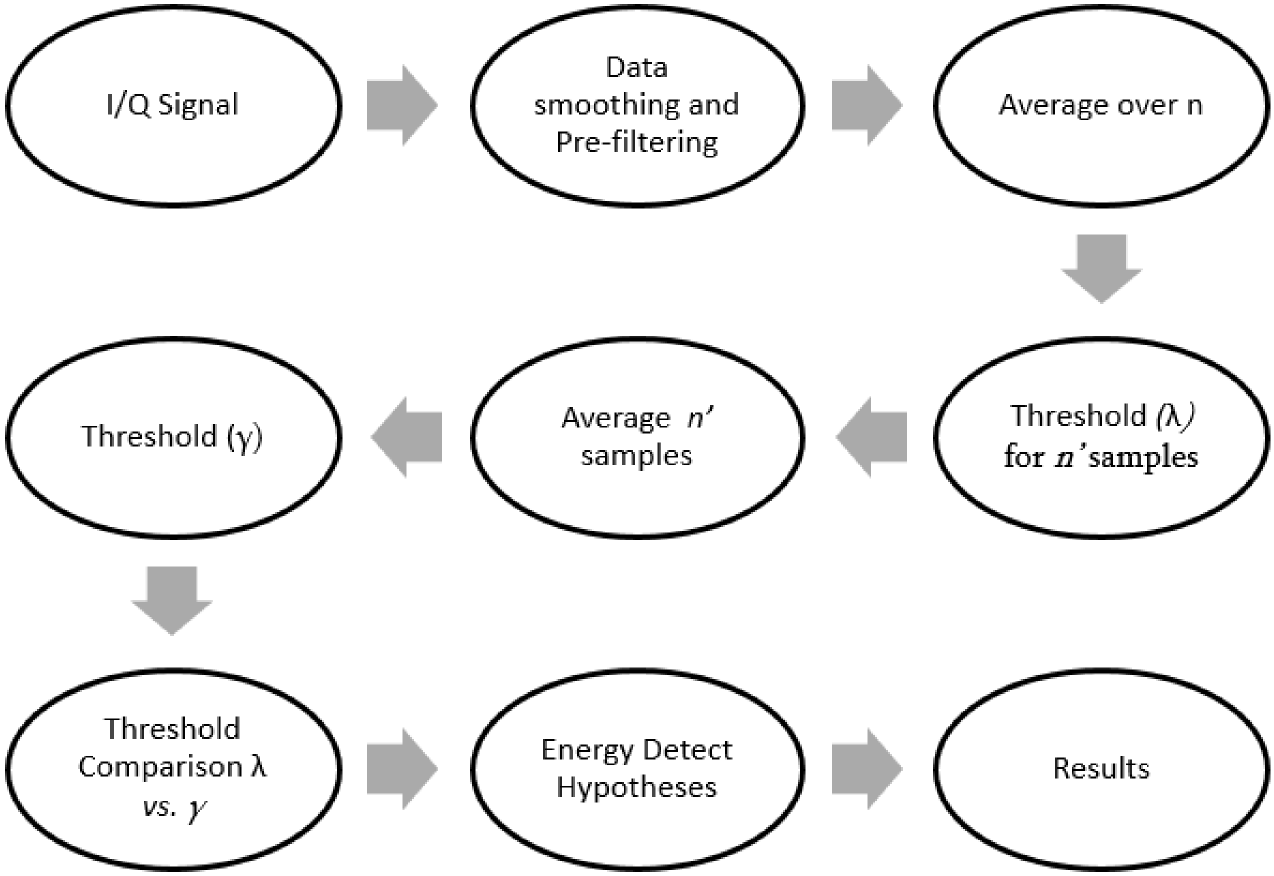


Figure 3.8: Block Diagram of Utilized Sensing Algorithm

3.6 Performance Analysis

The performance of any given sensing scheme is detected by estimating its P_d as well as its P_f. Another case is if a signal is not present but is detected then this is missed detection, which contributes to probability of missed detection (P_m).

Considering the hypothesis given in section 2.3.1, P_d, P_f, and P_m can be perceived as:

i) Declaring H_1 under H_1 hypothesis leads to P_d

ii) Declaring H_1 under H_0 hypothesis leads to P_f

iii) Declaring H_0 under H_1 hypothesis leads to P_m

The equations can be written as:

$$P_d = P(\hat{H}_1|H_1) \tag{3.8}$$

$$P_f = P(\hat{H}_1|H_0) \tag{3.9}$$

$$P_m = 1 - P_d = P(\hat{H}_0|H_1) \tag{3.10}$$

where $\hat{H}_1$ and $\hat{H}_0$ represent detected and undetected signals respectively.

The truth table of this is presented in Table 3.1.

Table 3.1: Performance Metrics Truth Table

Performance Metrics Truth Table			
Signal Present	Signal is Detected	Result	Outcome
True	True	True	P_d
True	False	False	P_m
False	True	False	P_f
False	False	True	P_d

The truth table presents the analogy according to which if a signal is present and detected, also, if a signal is not present and is not detected then it is P_d. If the signal is present and not detected, then it is P_m, and if a signal is not present and is detected then it is P_f. The ideal case is where we have highest P_d and lowest P_f and P_m.

3.7 Summary

The techniques and algorithms used to conduct the research have been discussed in this chapter. At first, the chapter gave an overview of research steps. The equipment along with prototype design and implementation has been presented. Two different software platforms were employed to generate various simulated ideal signals, the simulated signals and their applications were also discussed and shown. Two separate spectrum sensing approaches were considered in designing the proposed prototype to improve the detection performance. Moreover, the detection performance metrics have been discussed.

Chapter 4

Testing and Implementation

4.1 Introduction

This chapter presents the effectiveness of the spectrum sensing techniques. At first, the data captured using prototype along with the simulated data can be visualized. Prototype data figures were obtained using *Python* scripts and GNU Radio blocks whereas, to observe the simulated data MATLAB functions were used.

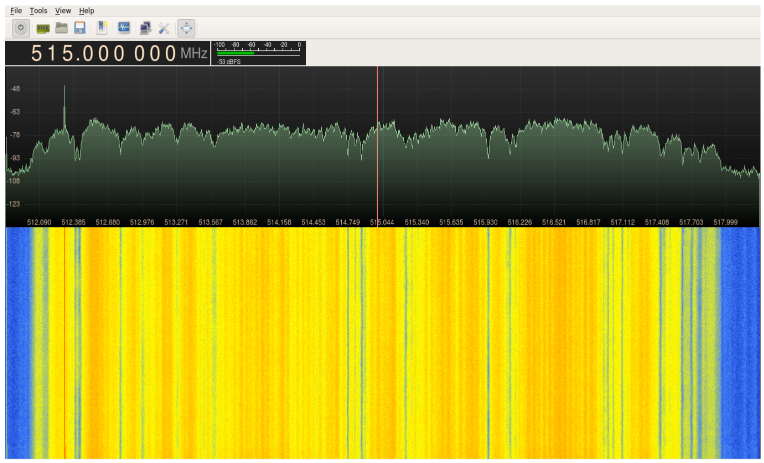
The results obtained from pilot-detection method has also been illustrated and discussed in this chapter. The real-time data and ideally generated data both have been used to obtain the results of the proposed algorithm. This filter was implemented in MATLAB. The data used for pilot-detection has been stored in SQL as shown in Figure 3.3.

Energy detection algorithm results have also been presented. These results have been prepared using MATLAB's signal processing toolbox. Different cases have been discussed. Each channel (i.e., from channel 19 to channel 51 except channel 37) can be visualized in this chapter. Analysis of obtained results has been given in the end.

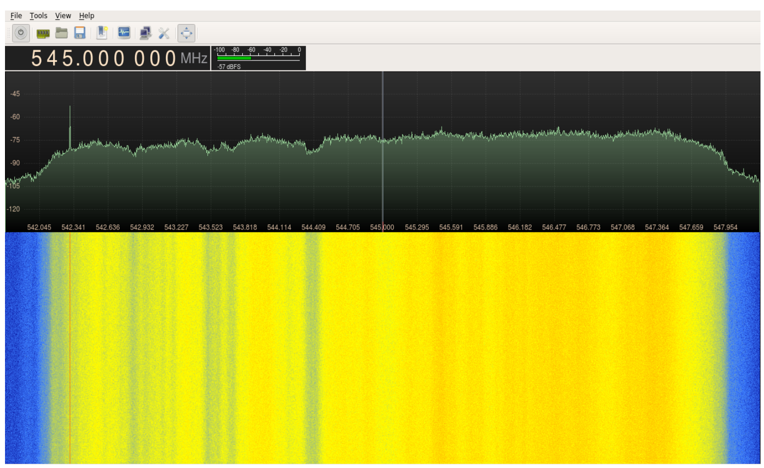
4.2 Data Visualization

4.2.1 Prototype Data Visualization

The data captured using prototype can be observed using the GNU Radio blocks. In Figure 4.1, two different set of data having different center frequencies have been shown. Figure 4.1a shows a center frequency of channel 21 at 515 MHz and Figure 4.1b represents channel 25 having a center frequency at 545 MHz. These channels have been chosen for giving examples only. Spectral waterfall or Spectrograms of both the frequencies are demonstrated in Figure 4.1. Spectral waterfalls illustrate the behavior of all available frequencies in the TV channel band. The density of spectrogram is also used to predict the presence of frequency user. Intense falls at a certain time represents that the user is highly active whereas weak signals or empty spaces presents the vacancy of the spectrum.



(a) Center Frequency at 515MHz



(b) Center Frequency at 545MHz

Figure 4.1: Frequency Observation at Data Collection Program

The program shown in Figure 4.2 was used to visualize the ATSC pilot-tone. It shows the high-resolution channel sweep of channel 41 ranging between 632-638 MHz, with the center frequency of 635 MHz. The power gain of this pilot is -90 dB. This pilot-tone has been observed by designing a BPF in GNU Radio. BPF designing has been explained in Chapter 3.

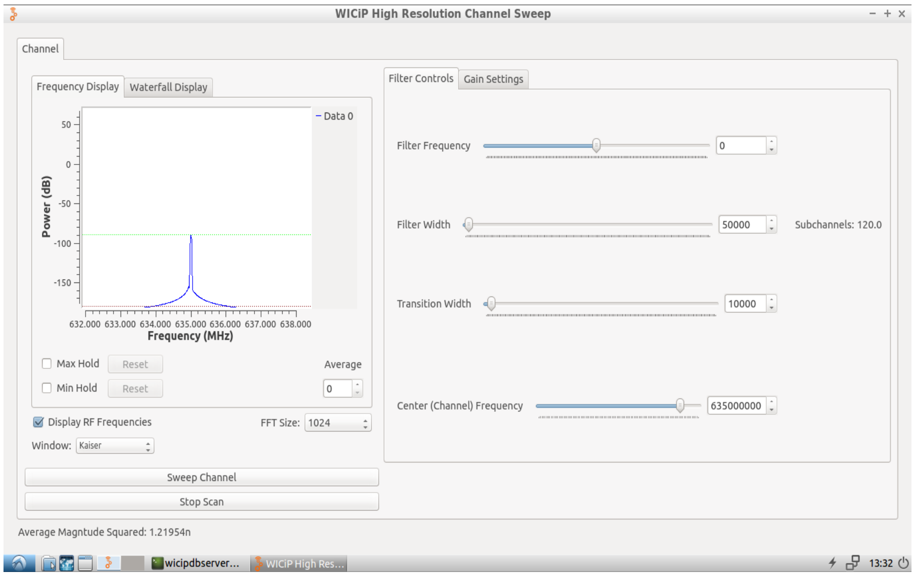


Figure 4.2: High Resolution Channel Sweep

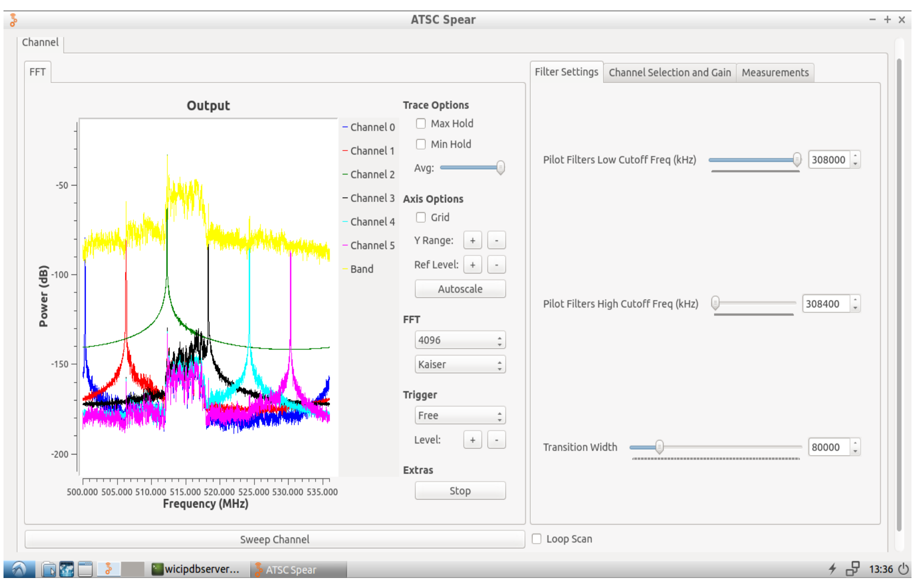


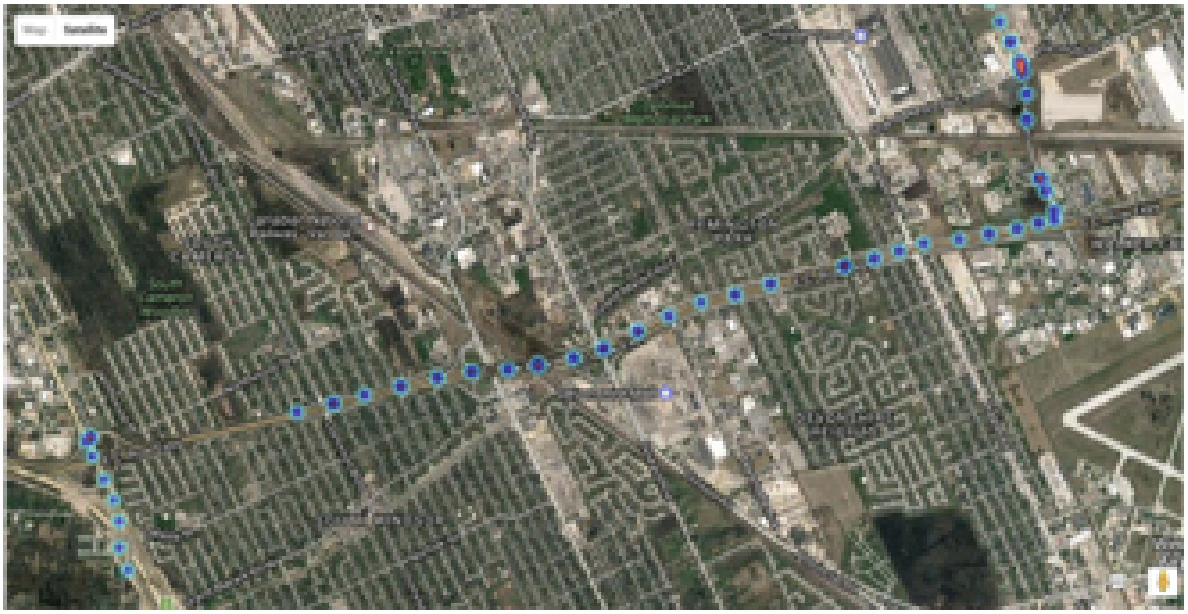
Figure 4.3: ATSC Pilot-tones

In Figure 4.3, six different channels ranging between 500-535 MHz has been presented. As mentioned previously, each DTV channel is of 6 MHz, and each channel has a pilot-tone present at approximately 0.31 MHz of frequency from the start of the channel. The presence of pilot-tone in each channel can be observed in the figure.

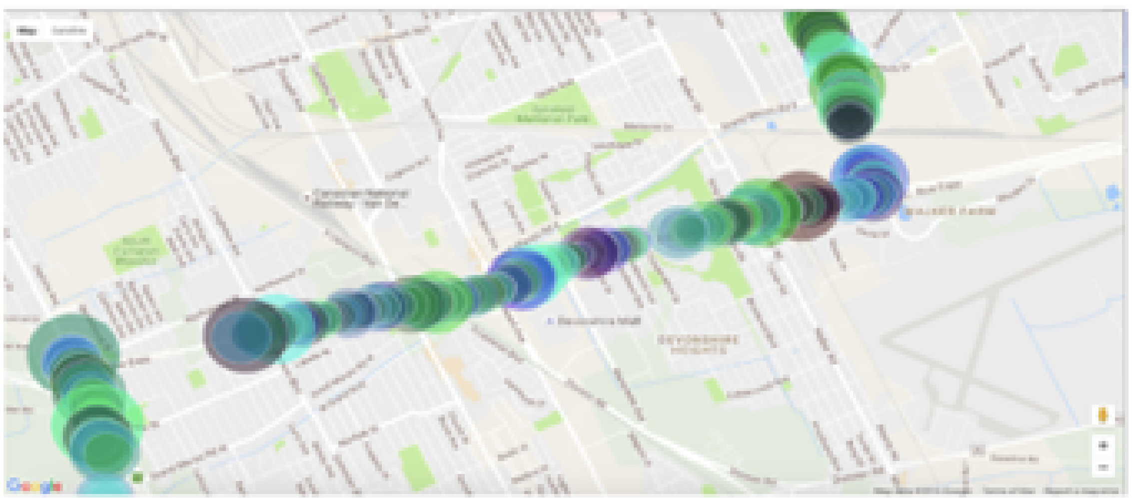
Another Python script generates the code necessary for a graphical representation of the collected information. The script queries the DB for a list of available readings based on date and time appropriately formats the data and generates an HTML file containing the heat-map which visualizes a single reading as a circle, with the color of circle based on the channel number and the radius based on the relative signal strength.

Figure 4.4a represents the detected energy of channel 19 along the E.C. Row (E.C. Row is the name of road present in the city of Windsor, Ontario, Canada). Figure 4.4b illustrates the collected data in the city of Windsor over Google Map during the frequency scan.

The mobile scan option executes the channel hop continuously regardless of the motion of the vehicle; therefore, the value displayed on the heat-map represents the value from the last reading taken at a particular point. For instance, if the scanning vehicle is stopped at a traffic signal, the same channel will be scanned twice at this particular coordinates. Due to idiosyncrasies in Google Maps Heat-Map API and the way it weights the data points, the radius of the marker circle is an aggregate of that channels signal strength; thus, skewing the display in favor of points where the car was stopped. To avoid this, a function was written to request readings which are distinct on their latitude and longitude [40].



(a) Heat map of Channel 19

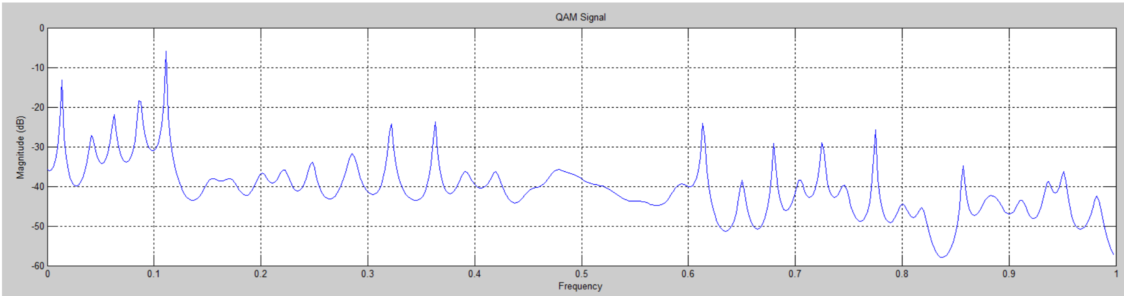


(b) Heat map of all channels present in scanned area

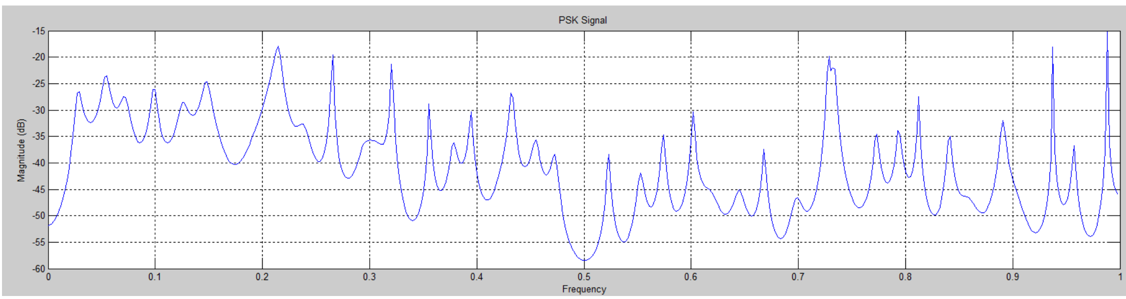
Figure 4.4: Heat Map visualization of channels

4.2.2 GNU Radio Generated Data Visualization

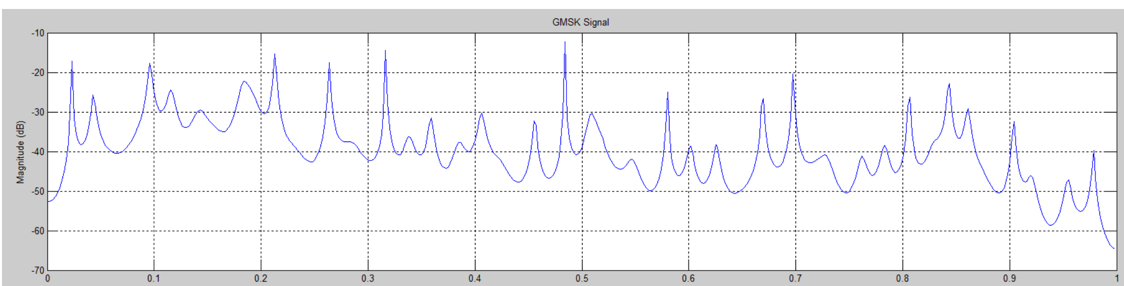
Various signals have been generated in GNU Radio to verify the effectiveness of proposed techniques. The signal samples generated for each modulated scheme have already been explained in Chapter 3. Figure 4.5 illustrates the signals obtained from the generated data. Each signal has been plotted over the frequency range of 1 MHz along with the magnitude gain in dB.



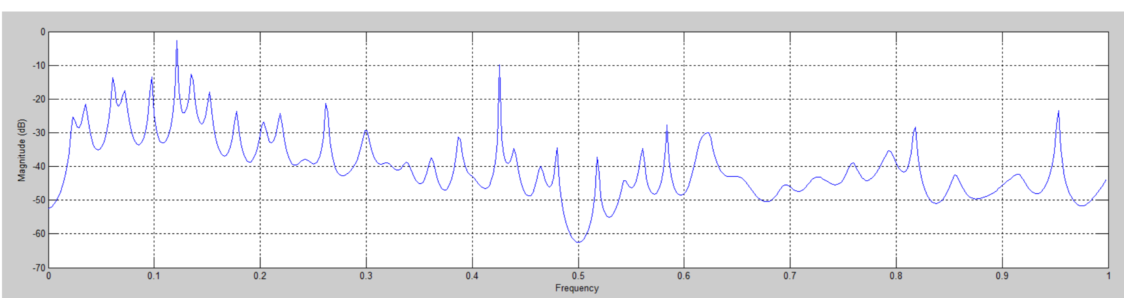
(a) Quadrature Amplitude Modulated Signal



(b) Phase Shift Keying Modulated Signal



(c) Gaussian Minimum Shift Keying Modulated Signal



(d) Quadrature Phase Shift Keying Modulated Signal

Figure 4.5: Signal Data generated by GNU Radio

The modulation schemes presented in Figure 4.5 are utilized by FCC and ECC while designing TV channels for the USA, North America, and the UK. The peaks observed in Figure 4.5a were considered while designing BPF for pilot-tone detection. The data then was utilized to estimate the energy of the signal. The threshold λ considered in this case was -30 dB. The Figures represented in 4.5b, 4.5c and 4.5d, were also analyzed while considering threshold λ at -30 dB.

4.2.3 MATLAB Generated Data Visualization

ATSC Signal Generated in MATLAB

An ATSC signal has been generated in MATLAB. The signal shown in Figure 4.6 is an example of the signal generated by the software. This channel is plotted over the 6 MHz frequency band with respect to its magnitude in dBW. The generated channel is an idle channel as no pilot-tone has been introduced while designing the achieved signal.

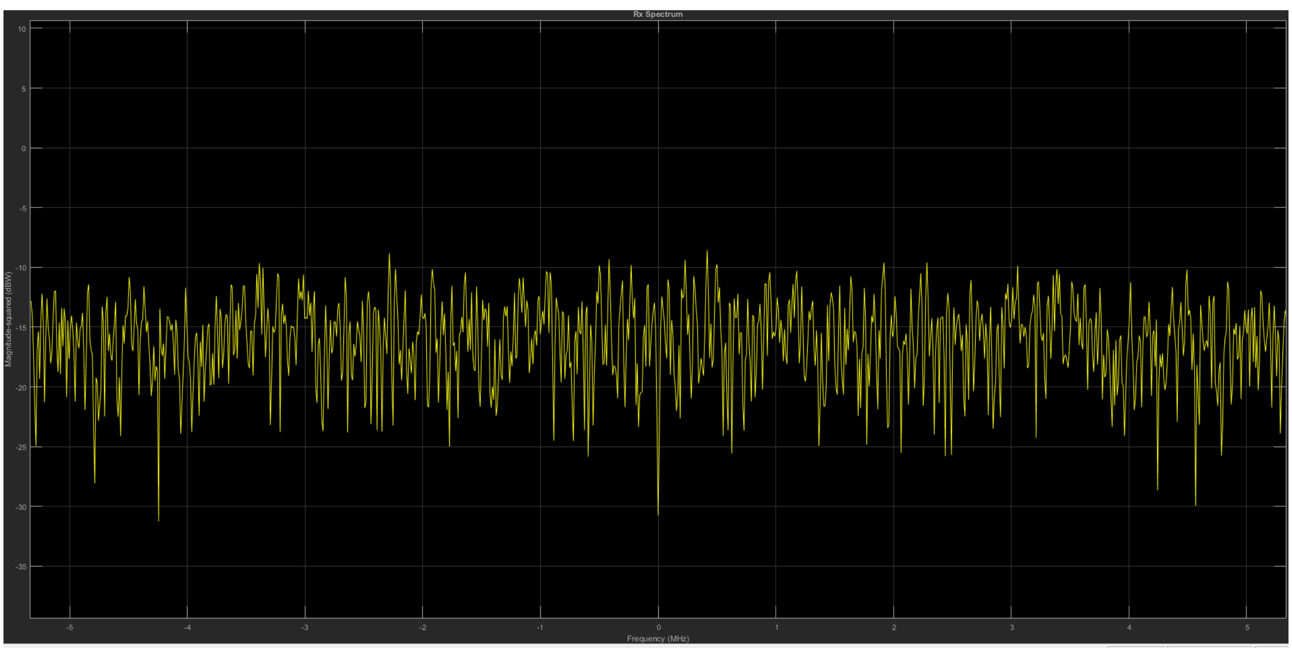


Figure 4.6: Generated TV signal by MATLAB

Pilot-tone in DTV Signal

A non-zero DC value is added to baseband signal before modulation to enable carrier extraction at the receiver end. The resultant signal is what we call a pilot signal. According to ATSC standards, this signal is of 19 kHz wide and lies at 310 kHz from the lower edge of the TV channel band [45].

Initially, the peak finder was used to detect the presence of peaks in the signal as shown in Figure 4.7. The peaks observed represents the pilot-tone present in the signal which represents the presence of licensed TV channel in the spectrum. The generated pilot signal lies at 0.31 MHz from the lower edge of the signal. The magnitude of pilot signal lies at -7 dBW.

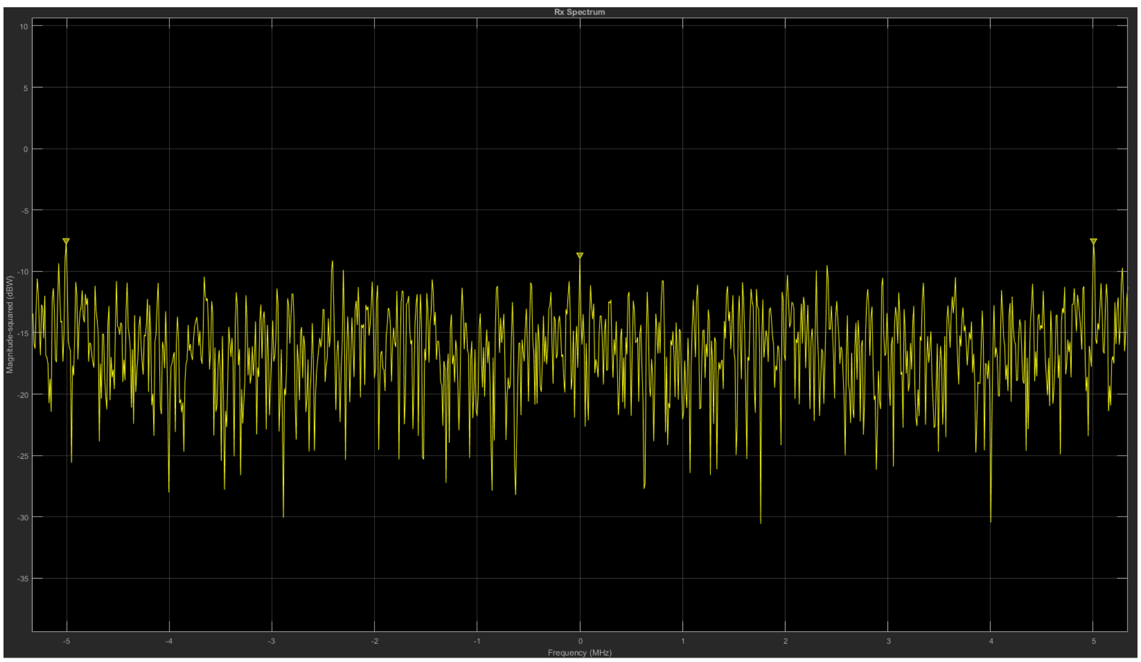


Figure 4.7: Peak detection in ATSC Signal

The pilot signal generated in MATLAB can be observed in Figure 4.8. The magnitude of generated pilot-signal lies at 8 dBW.

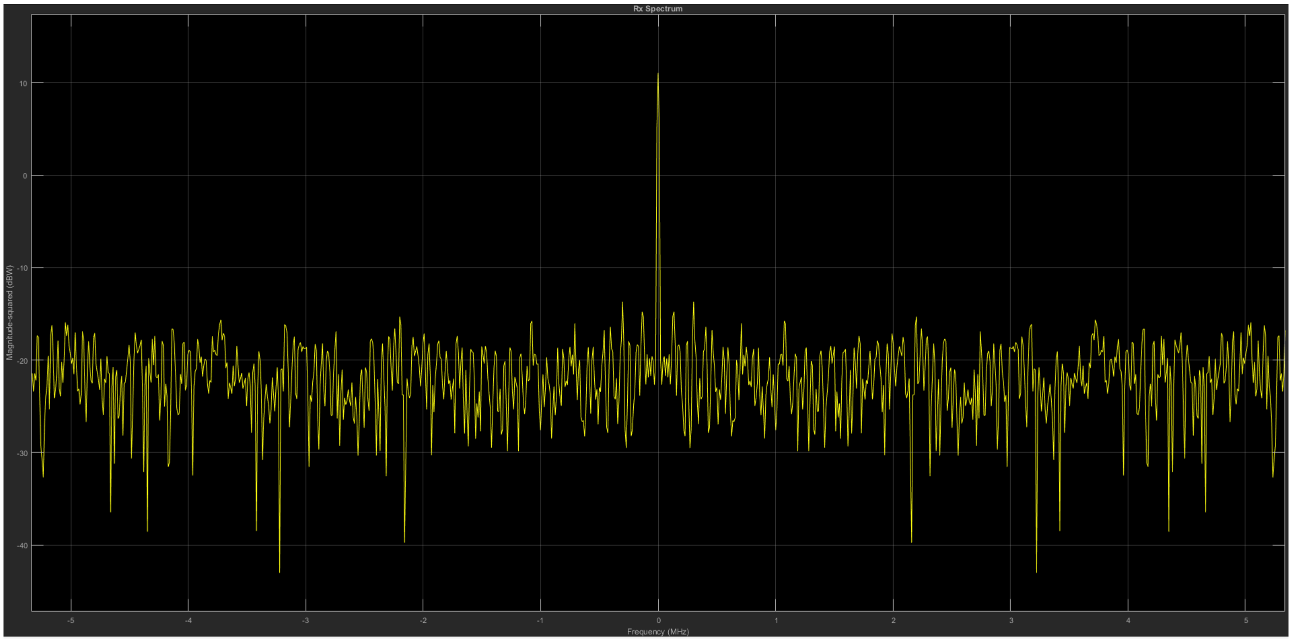


Figure 4.8: Pilot Signal generated in MATLAB

4.3 Pilot-tone Detection

The magnitude response of the filter is given in Figure 3.7. The signal spectrum was passed through a bandpass filter, and the detected pilot signal is seen in Figure 4.9 for a MATLAB generated channel. As mentioned previously, the BPF uses a Kaiser window technique which maximizes the main lobe energy while simultaneously minimizes the side lobes energy. Here in this figure, we can observe that pilot-tone signal has been detected while enhancing the overall signal strength of the pilot signal. In Figure 4.10, an idle TV channel has been shown. There is no ATSC pilot detected in the band which represents the absence of incumbent TV spectrum user. The observed data, in this case, is the noise power present in the spectrum.

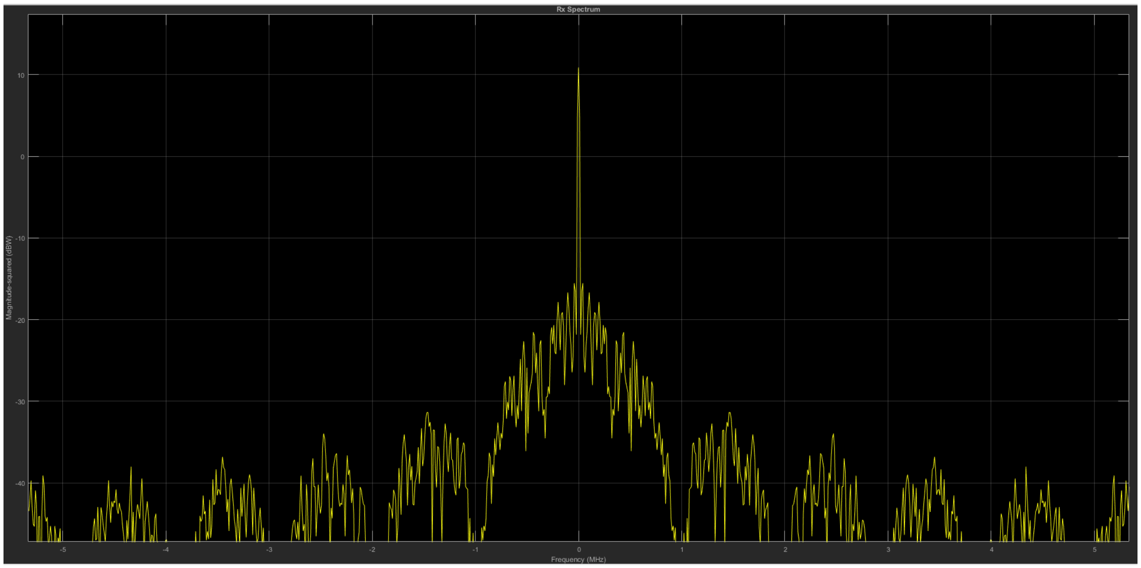


Figure 4.9: Observed pilot-tone for in a channel

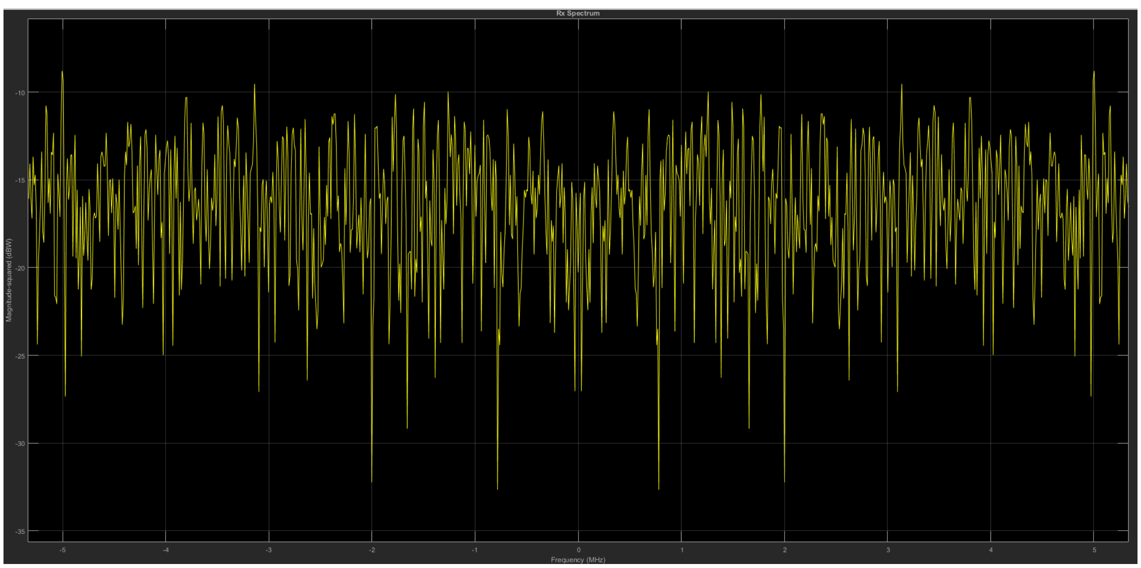


Figure 4.10: Idle TV channel

Spectrum characteristics of real-time captured channel 19 is illustrated in Figure 4.11. The spectrum frequency of channel ranges between 500 - 506 MHz. RSS of the channel was passed through the pilot detector to detect the presence of a pilot-tone but no pilot signal was observed at an output except the additive noise. Channel 19 is the idle channel as mentioned on Industry Canada website, and hence been proved here as well. Same channel was observed for energy detection as well, which was the second step in two-step detection scheme as mentioned in Chapter 3. ATSC defines that pilot signal as well as the overall energy of the signal should lie above the threshold λ of -114 dBm. Energy detection step also verified that no signal is detected and hence, channel 19 is an unoccupied channel.

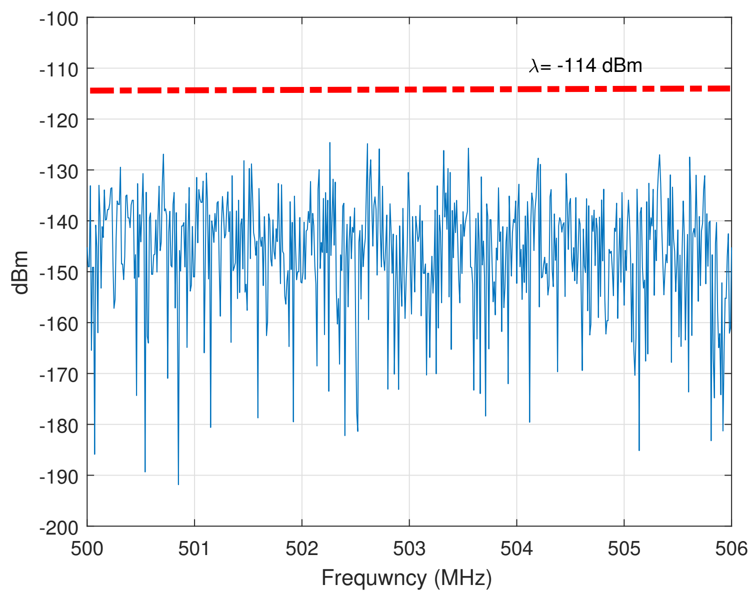


Figure 4.11: Observed channel 19

Channel 22 is observed in Figure 4.12. The pilot signal was detected in the signal while passing the channel data through a pilot detector. To further verify the signal presence, overall channel energy was also estimated while keeping λ= -114 dBm. Analysis as shown in the figure verified the presence of incumbent channel. Energy of the channel lies above the threshold value.

The comparison of results obtained in Figure 4.11 and 4.12 also verifies the lemma we made while designing the energy detector which stated that channel with incumbent user will have average magnitude energy much higher than overall noise present in an idle channel.

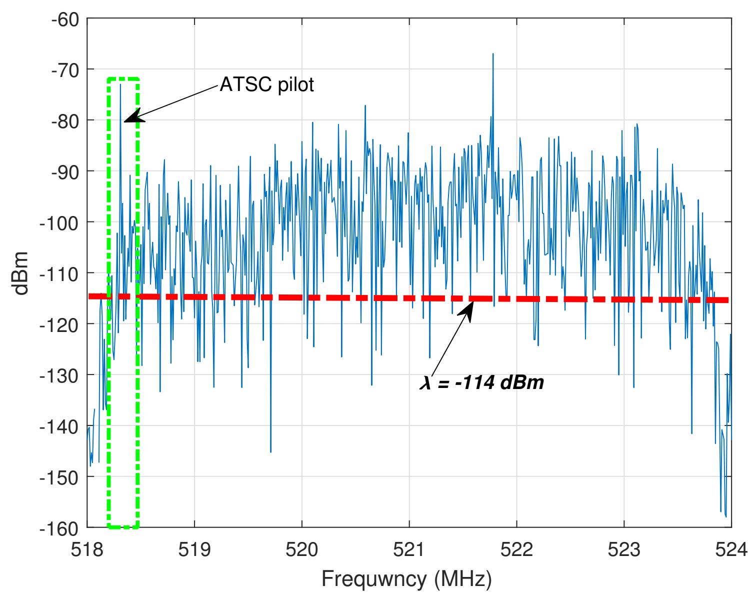


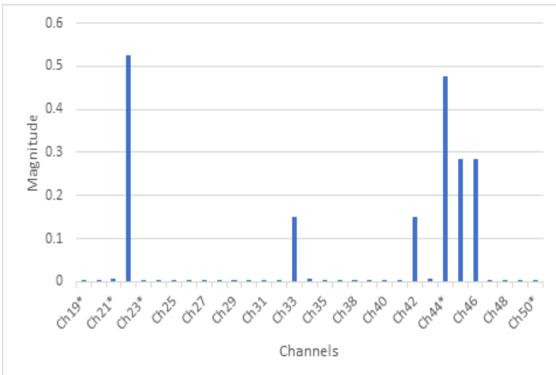
Figure 4.12: Observed pilot-tone for channel 22

4.4 Received Signal Strength Analysis

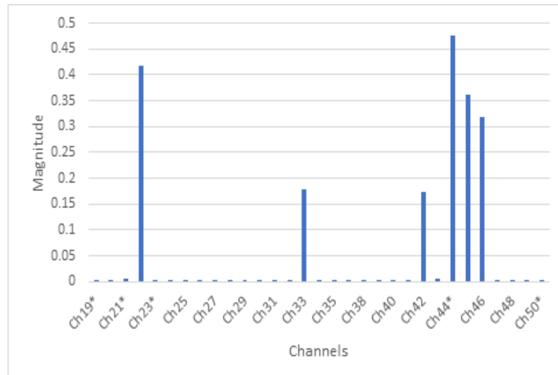
4.4.1 Magnitude Analysis

The experiment was done for several runs to collect data. The run, as mentioned previously, is the time required to detect all TV channels from 19 to 51 one time. After receiving the data using prototype, the magnitude of each channel was plotted to analyze the channel behavior. Figure 4.13 shows the graphs of receive magnitude for six different runs. Figure 4.13a represents the magnitude of each channel received for the first run. The analysis shows that channels who are present in the spectrum have higher magnitudes than the channel which is not present in the spectrum. The deviations observed in some cases can be detected due to variety of reasons. One of the reasons could be as these readings were taken in Windsor, ON, Canada which shares a border with Detroit, MI, USA. The observed behavior could be deviations of the captured signals from Detroit area. Another reason of deviations could be because of the prototype. The huge deviation are mainly observed for channel 19 which is the first observed channel of the spectrum. For initial few readings the system captures the false-positive results some times due to unpredicted radio conditions such as noise and multipath fading.

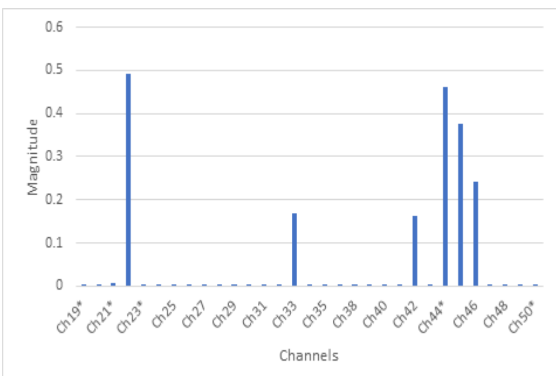
The overall comparison between six runs detected the presence of Channel 22, Channel 33, Channel 42, Channel 44, Channel 45 and Channel 46.



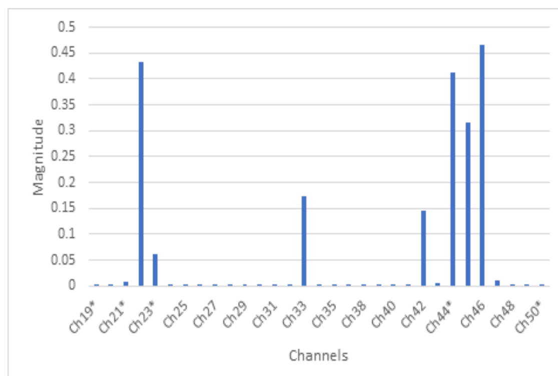
(a) Received Signal Strength for 1^{st} run



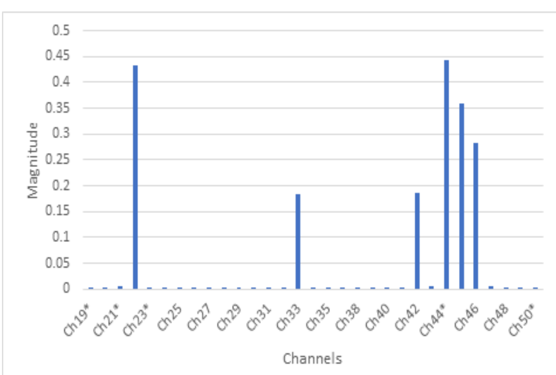
(b) Received Signal Strength for 2^{nd} run



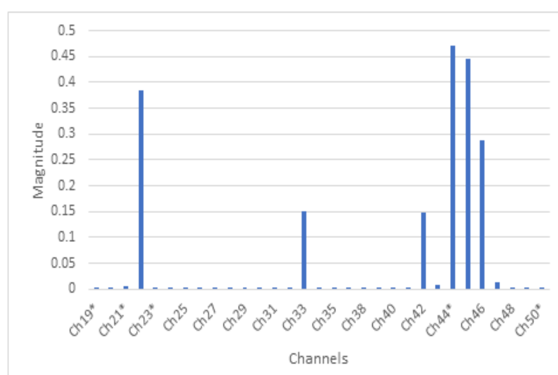
(c) Received Signal Strength for 3^{rd} run



(d) Received Signal Strength for 4^{th} run



(e) Received Signal Strength for 5^{th} run



(f) Received Signal Strength for 6^{th} run

Figure 4.13: Received Signal Strength for different data sets

4.4.2 Threshold Measurement Analysis

Three different data sets, each comprising of channel response for seven runs were selected from the prototype database. These signals were in I/Q for, so at first the received signal strengths of the signal magnitudes while applying Equation 3.3 and 3.4 was found respectively. After finding the RSS in dB for each dataset, the threshold λ for each set is calculated separately. The method of calculating λ has been explained in Chapter 3. Analysis showed that though these data sets were captured during different time and under different climatic conditions, the threshold λ for each set was found as λ= -40 dB. The RSS plots were generated using MATLAB. Channels above the threshold value is Channel 22, Channel 33, Channel 42, Channel 44, Channel 45 and Channel 46. The presence of these channels have further been verified from Industry Canada website. Observation of Channel 19 in Figure 4.14 shows a false detection, the suspected reasons for this could be multipath fading or prototype false-positive detection.

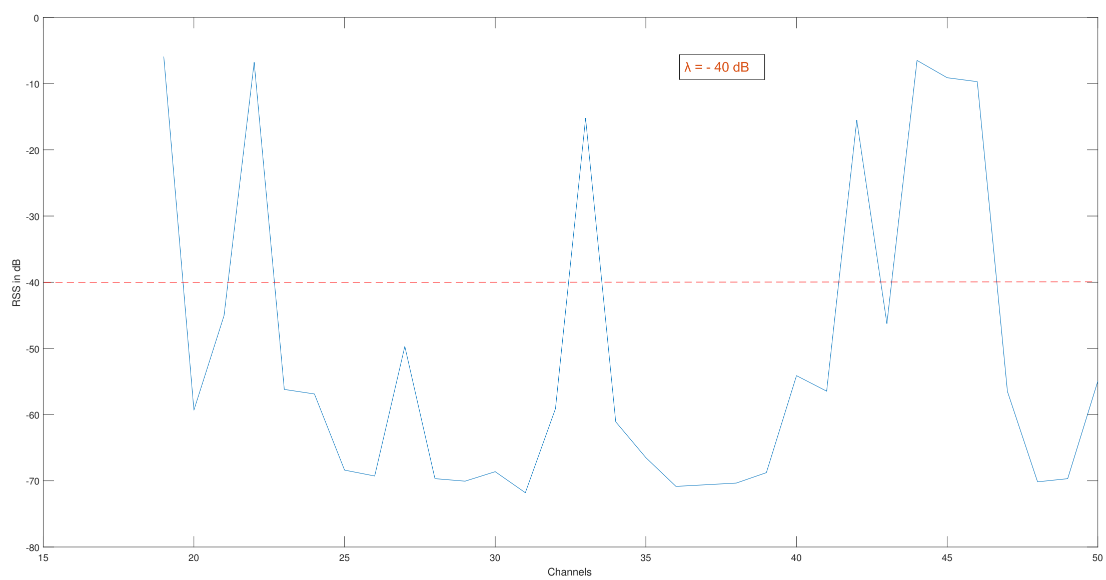


Figure 4.14: Channel 19 to 51 response for 7 runs (Data set 1)

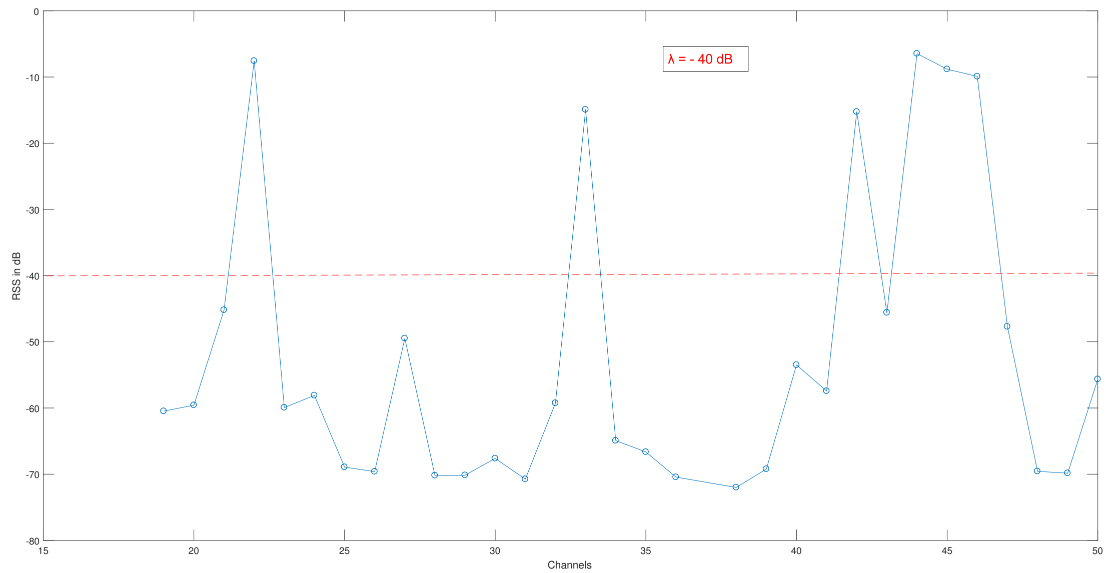


Figure 4.15: Channel 19 to 51 response for 7 runs (Data set 2)

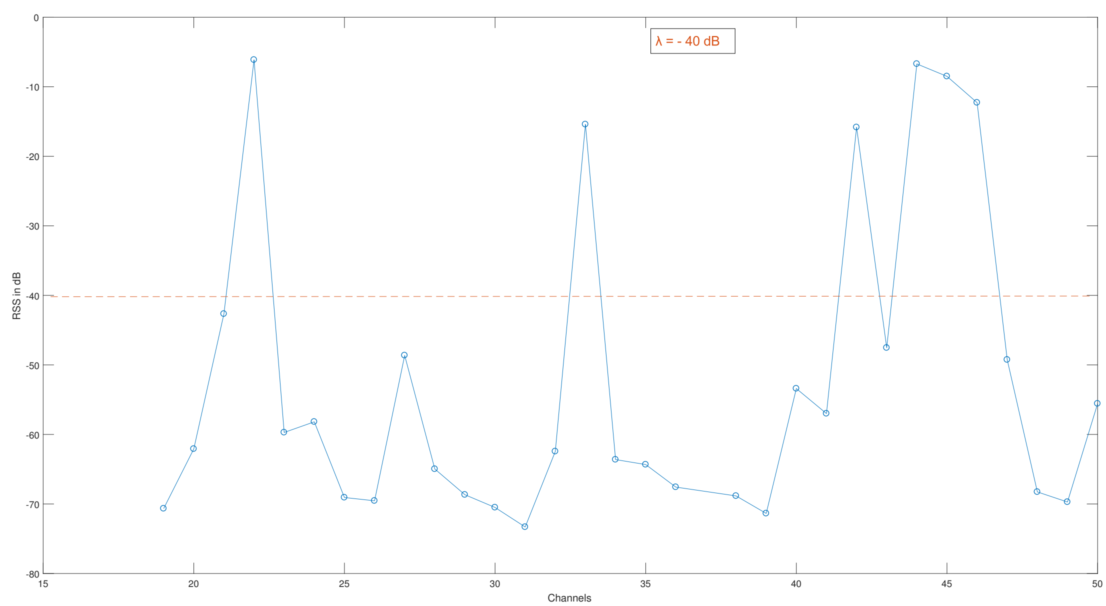


Figure 4.16: Channel 19 to 51 response for 7 runs (Data set 3)

4.4.3 Energy Measurement Analysis

The estimated energy for a data set containing readings of each channel for 20 runs has been presented in Figure 4.17. The signals present in each channel were captured under different climatic conditions and during different day time. This graph is illustrated to verify that the signals which are always present can be detected under any condition using the prototype implemented in this thesis. We have calculated the duty cycle of each channel while considering different threshold to prove the same concept.

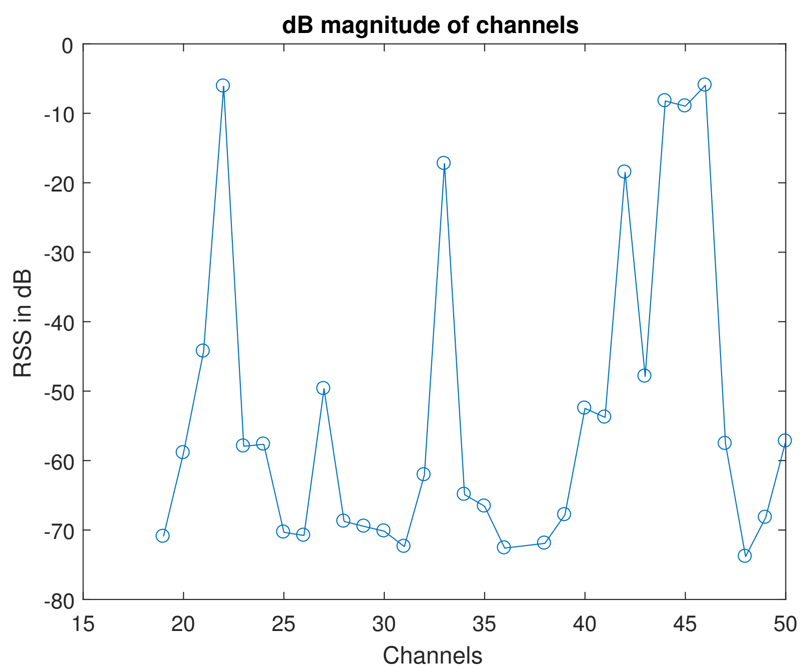


Figure 4.17: Received Signal Strength of Channel 19 to 50

Duty cycle Analysis

Duty cycle can be defined as the number of power readings taken on the threshold q_i while observing the number of readings exceeding the threshold p_i [38].

$$duty\ cycle = \frac{p_i}{q_i}. \tag{4.1}$$

Figure 4.18 represents the duty cycle of channel 19-51. Duty cycle, as mentioned above, was calculated while considering different threshold values. The blue bar here represents the threshold value of (λ = -114 dB) whereas, yellow bars represents the threshold value (λ = -120 dB). From this result we inferred that even if we change the value of λ, the signals which are always present will still be detected.

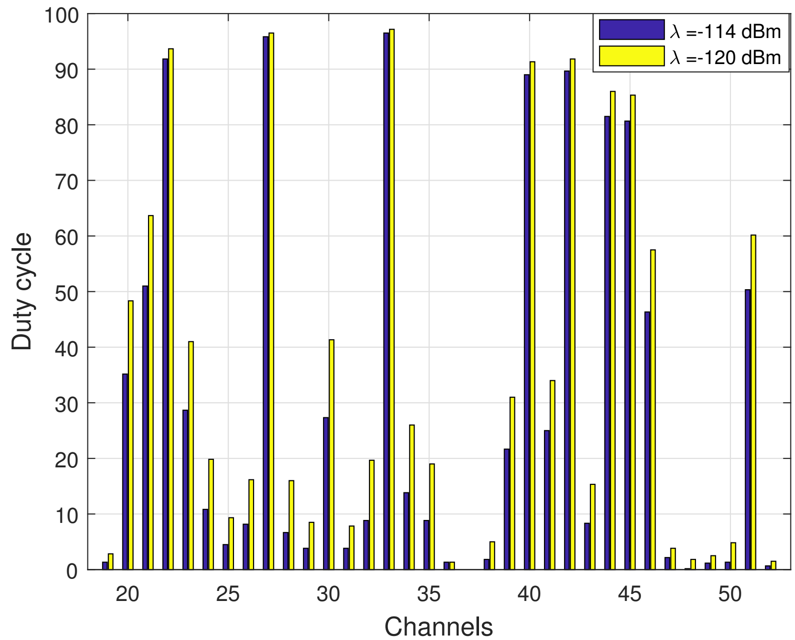
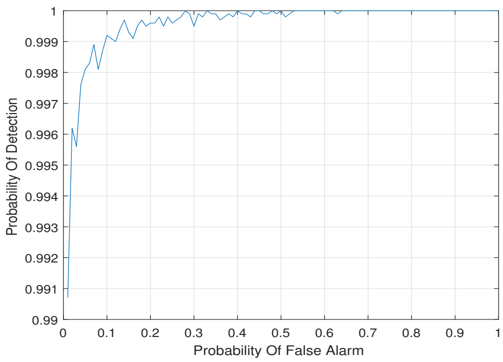


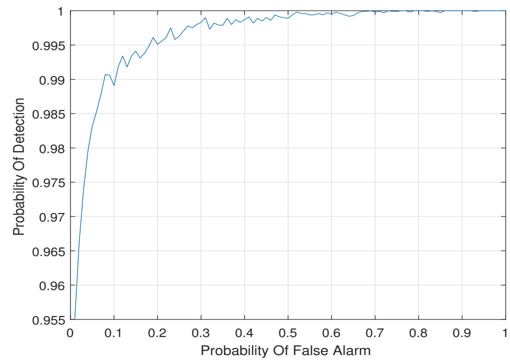
Figure 4.18: Duty cycle of each channel

4.5 Performance Analysis

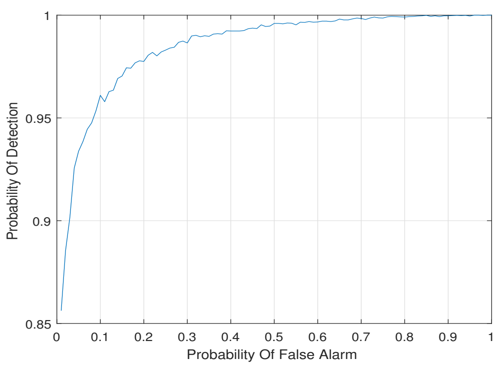
The Receiver Operating Characteristic (ROC) curve is created by plotting P_d against P_f under different SNR settings. The P_m can be calculated as $1 - P_d$. The objective of plotting ROC in this thesis was to calculate the performance of our system. IEEE 802.22 limits both P_m and P_f to 10%. This 10% requirement should be met even under very low conditions such as -20 dB SNR. The signal threshold was fixed at -114 dBm in our case. Figure 4.19 shows the Receiver Operating Characteristics (ROC) graph for P_d vs. P_f for different SNR values. These ROC curves were plotted under different SNR conditions. Figure 4.19a represents the ROC curve for -10 dB. It can be inferred from Figure 4.19 that probability of false alarm and probability of detection constraints can be satisfied in all different SNR values. Figures 4.19b, 4.19c and 4.19d were calculated with SNR values -12 dB, -14 dB and -17 dB respectively. From this we inferred that P_d decreases with the increase in SNR.



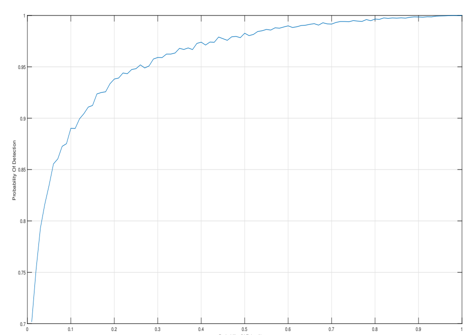
(a) ROC curve for SNR = -10 dB



(b) ROC curve for SNR = -12 dB



(c) ROC curve for -14 dB



(d) ROC curve for -17 dB

Figure 4.19: ROC plot for probability of detection and probability of false alarm

4.6 Summary

In this chapter, the detection performance of the proposed prototype in terms of RSS and ROC have been demonstrated and discussed. The attained experimental results of RSS have illustrated the behavior TVWS over UHF frequency band which is ranges from 500 MHz to 698 MHz (i.e., TV channels from 19 to 51 except channel which reserved from radio astronomy). The TVWS behavior showed a static behavior in the selected vicinity. Moreover, ROC curves corroborate that our proposed prototype satisfies the IEEE 802.22 detection requirements. Additionally, the impact of varying sensing threshold is considered.

Chapter 5

Conclusion and Future Scope

5.1 Conclusions

The CR is considered as the best solution to overcome the limited spectrum problem. The CR technology is used to take advantages from underutilized spectrum. Spectrum sensing technique is used to detect the TVWS available in the particular spectrum band. The main goal of the thesis was to adopt an algorithm which can detect the underutilized spectrum bands while ensuring the minimum computational complexity. The detected TVWS will be utilized to setup a communication system in disastrous situations.

A prototype using USRP 2901 and GNU Radio was practically implemented. The purpose of establishing this prototype is to detect the white spaces present in the TV band. The frequencies observed were between 500-698 MHz of TV band.

Pilot-tone detection and energy detection schemes were adopted to detect the presence of incumbent user. The validity of these sensing algorithms were tested using the simulated ATSC, QAM, PSK, GMSK, and QPSK signals. These signals were generated in MATLAB and GNU Radio. After initial testing, the proposed algorithm was tested on real-time signals captured using USRP.

The results obtained verified that the ATSC pilot tone with magnitude higher than the combined average magnitude of the channel is always present at 0.31 MHz from lower bound of the channel in the case if incumbent user is present. The result also verified that the received signal strength of channels which are always present can be detected even if the threshold values are changed.

The proposed prototype is being used to detect the presence of TVWS in the spectrum. As a future work, this prototype will be used to setup a communication system which can efficiently transmit and receive SU data.

5.2 Future Scope

The proposed implementation can further be extended to various uses other than disaster management. The potential examples can include the amalgamation of 5G technology with CR technology, use of CR for Smart Grid communications etc.

- **Implementation of CR in 5G communications**

  Wireless communication needs are expanding drastically. The CR can be considered as the potential candidate to overcome the problem of congested RF spectrum. If the concept of CR is applied to 5G communications, it can increase the energy efficiency, cost efficiency, and resource efficiency of spectrum.

- **Implementation of CR in Smart Grid communications**

  Cognitive radio sensor network (CRSN) can be integrated in a smart grid to meet challenges such as bandwidth sharing and efficient and reliable data transfer. The CR concept can be implemented in various SG communication applications for example, the use of CR to setup a broadband communication in rural areas. Smart meters of SG can be able to decide data transmission on either an original unlicensed channel or an additional licensed channel, so as to reduce the communication outage.

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