ANALYSIS OF POWER CONTROL IN UNDERLAY COGNITIVE RADIO

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ANALYSIS OF POWER CONTROL IN UNDERLAY COGNITIVE RADIO NETWORK

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honours

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DECLARATION

I declare that this report entitled "Analysis of Power Control in Underlay Cognitive Radio Network" is the result of my own work except for quotes as cited in the references.

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Date : 15 JUNE 2021

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Bachelor of Electronic Engineering with Honours.

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Date	:	**25 JUNE 2021**

DEDICATION

I dedicate this thesis to the God Almighty my creator, gives opportunity and inspiration during this project assessment and to my all beloved family and friends stay support along the way. Thank you.

ABSTRACT

Frequency spectrum is important in the wireless communication industry due to the growth of the technology in the Internet of Things (IoT) and others. In maximizing the usage of vacant spectrum holes that are not used by the primary user (PU) the cognitive radio (CR) network is used by the secondary user (SU) to transmit data in the spectrum holes. In this paper, an investigation of power control which is a method to allocate the power transmission in the frequency spectrum is been done. This paper also, analysis the power control algorithm in the underlay CR network. The power control waterfilling model is implemented by following the underlay technique of the cognitive radio network. By using the energy detection in the frequency spectrum, the percentage of the spectrum hole is identified and the spectrum utilization after the power control method is implemented is also been identified. The simulation of the analysis is done in Matlab software. Lastly, in this paper analysis the comparison of spectrum utilization between overlay and underlay technique is obtained and able to conclude the underlay technique is more efficient than the overlay technique.

ABSTRAK

Spektrum frekuensi penting dalam industri komunikasi tanpa wayar kerana pertumbuhan teknologi di Internet of Things (IoT) dan lain-lain. Dalam memaksimumkan penggunaan lubang spektrum kosong yang tidak digunakan oleh pengguna utama (PU), rangkaian radio kognitif (CR) digunakan oleh pengguna sekunder (SU) untuk menghantar data dalam lubang spektrum. Dalam makalah ini, penyiasatan kawalan daya yang merupakan kaedah untuk mengalokasikan transmisi daya dalam spektrum frekuensi telah dilakukan. Kajian ini juga, menganalisis algoritma kawalan kuasa dalam rangkaian CR yang mendasari. Model pengisian air kawalan kuasa dilaksanakan dengan mengikuti teknik asas rangkaian radio kognitif. Dengan menggunakan pengesanan tenaga dalam spektrum frekuensi, peratusan lubang spektrum dikenal pasti dan penggunaan spektrum setelah kaedah kawalan daya dilaksanakan juga dikenal pasti. Simulasi analisis dilakukan dalam perisian Matlab. Terakhir, dalam analisis kajian ini perbandingan penggunaan spektrum antara teknik overlay dan underlay diperoleh dan dapat menyimpulkan teknik underlay lebih efisien daripada teknik overlay.

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my gratefulness to Allah S.W.T for his blessings, allowed this thesis completed with ease. Here also, I would like to express my deepest appreciation to Pn. Siti Rosmaniza Ab Rashid and Dr. Mas Haslinda bt Mohamad for the guidance in both theoretical and practicality of this thesis by giving feedback on the task given weekly and comment on this thesis writing. I am truly thankful to them for allocating their time and energy to listen attentively regarding my problems and provide insightful advice and also knowledge on this project.

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LIST OF ABBREVIATIONS

AWGN	:	Additive white noise Gaussian noise
BER	:	Bit error rate
CR	:	Cognitive Radio
D2D	:	Device-to-device
DVB	:	Digital broadcasting
IoT	:	Internet of Things
LSA	:	Licensed shared access
MGF	:	Moment generating function
MMSE	:	Minimum mean square error
PU	:	Primary user
PPP	:	Poison point processes
QoS	:	Quality of service
SNR	:	Signal-to-noise ratio
SINR	:	Signal-to-interference-plus-noise ratio
SU	:	Secondary user
UTEM	:	Universiti Teknikal Malaysia Melaka
WRAN	:	Wireless Regional Area Network

LIST OF APPENDICES

CHAPTER 1:

INTRODUCTION

This thesis proposes the analysis of power control in underlay cognitive radio based on the waterfilling model. This chapter will discuss the background of the project, the problem statement, the objectives, the project scopes, and the importance of the study.

1.1 Background of Project

In surging demand of wireless connectivity in communication technology, as widely used in mobile telephony, digital broadcasting (DVB), and Internet of Things (IoT). The frequency spectrum has become in high demand as it is a vital part of wireless connectivity systems. In January 2018, more than one million people connect to the internet for the first time each day [1]. Thus, Cognitive Radio (CR) network is introduced by Joseph Minolta III in 1998 to encounter constraint usage of the frequency spectrum.

In the CR network a term of licensed spectrum user is called as primary user (PU) and the unlicensed user is called as secondary user (SU). The SU is the user opportunistically access the spectrum holes while keeping the interference on the PU receivers at either zero or below Interference Threshold [2].

The CR network is capable to improve the overall spectral efficiency and allow unlicensed users (SU) to access spectrum holes to the licensed user (PU) [2]. The CR helps the transceiver to identify spectrum holes in the channel of the frequency spectrum of the PU system. In utilizing the spectrum hole, the SU able to move instantly to spectrum holes in the channel. These characteristics of the CR network are important in minimizing the interference to the PU system and decrease the congestion data transmission at the channel.

For the spectrum holes to be utilized, the CR networks have been standardized in IEEE 802.22 WRAN (Wireless Regional Area Network) and its amendments, IEEE 802.11af for wireless LANs, IEEE 1990.x series and it also has a motivating factor for licensed shared access (LSA) for LTE mobile operators [2].

CR network ensures the spectrum sharing without causing harmful interference to exist traffics, the SU needs to possess a minimum of information about the PU. Depending on the knowledge that gains from the PU system CR able to approach three classes of techniques. There is three technique of spectrum sharing [3]. The description of techniques is explained in the table below.

Characteristic	Overlay	Interweave	Underlay
Condition during transmission	The SU knows the channel gains and messages of the PU	When the PU is not using spectrum, the SU knows spectrum holes in space, time, or frequency	The SU knows the channel strength of the PU
SU power level	Transmit at any power level	Limit at the range of its spectrum hole sensing	Limit by interference constraint
Interference	Interference effect to the PU, offset by using part of the SU power to relay the PU message	When there is the loss of the PU activity	Below Interference Threshold

Table 1.1 : The types of the CR techniques

1.2 Problem statement

The increasing demand for wireless connectivity leads to an increasing number of devices connected to the spectrum because of the rapid development in IoT and mobile connectivity. The capability of IoT in creating a bridge between devices has created a whole range of new services. With the huge number of devices is connected to the spectrum, the frequency spectrum experienced a bottleneck situation and it will influence the quality of service (QoS) [4].

Increasing the spectral efficiency, the overlay technique becomes slightly disadvantage compare to the underlay technique. In the overlay technique, the PU has a higher priority to use the spectrum. Hence, the SU transmission able to access spectrum is not used by the PU, then will be cut-off when the PU is reappearing.

Thus, the underlay technique proposes to encounter the problems. The underlay technique can use the PU capability to tolerate the interference and enable the transmission of the SU to continue in the presence of the PU transmission [5].

1.3 Objectives

i. To investigate the energy detection in the underlay CR network
ii. To implement the power control algorithm in the underlay CR network
iii. To analyze the utilization of frequency spectrum in using power control method in the underlay CR network.

1.4 Scope of Work

In this project, the scope of work in this project is to study the spectrum access of underlay method and an energy detection method based on spectrum sensing is used to detect the spectrum hole with probability of false alarm (P_f) [6] and then waterfilling model technique is used. These models are implemented in MATLAB. By using MATLAB software, the C language is used to write commands and equations. Thus, student obtains the output of waveform and data through MATLAB. The dataset for the simulation is gain from the USRP N210, that range in the frequency band of 2.4 – 2.5 GHz.

1.5 Importance of Study

The growth in the innovation of technology in Malaysia especially the increasing number of IoT devices usage and other digital tools has helped to stimulate the study in improving wireless communication. The competition for using the spectrum frequency to send data became intense as the secondary user is looking for the opportunity to access the spectrum full of the PU. Thus, through this project student studies in creating the opportunistic conditions for the SU to be able to share the spectrum with the PU.

Besides that, in the economy sector, this project encourages the development of the industry through the advantages of wireless communication based on the analysis of the project. This project also able to study minimizing the possibility of interference to the PU while the secondary user sharing the spectrum. Lastly, the project helps to analyze the method in utilizing the spectrum hole to be used more effectively to accommodate the increasing number of the SU.

CHAPTER 2:

LITERATURE REVIEW

This chapter contains the literature review of the underlay technique, including the power control method through previous researches and selecting the appropriate power control method.

2.1 Overview of Cognitive Radio Network Techniques

As the student introduces the significance of the cognitive radio network in chapter 1, the CR network helps the SU with low priority compare to the PU to transmit data by using three distinct methods of sharing spectrum across the frequency [7]. There are recognize as underlay, interweave and overlay techniques which are also briefly explained in Table 1.1. In the underlay technique, the transmission data is allowed if the interference generated by the SU on the PU receiver is below a predefined threshold. Besides that, in interweave technique the SU able to transmit data when there are no ongoing transmission data by the PU on the channel. Lastly, in the overlay technique, the SU completely cooperates with PU to transmit data but to accomplished this, permission from the PU must be granted [7]. The figure showed the relationship between the CR network and the PU to allow the SU in sharing the spectrum at each technique.

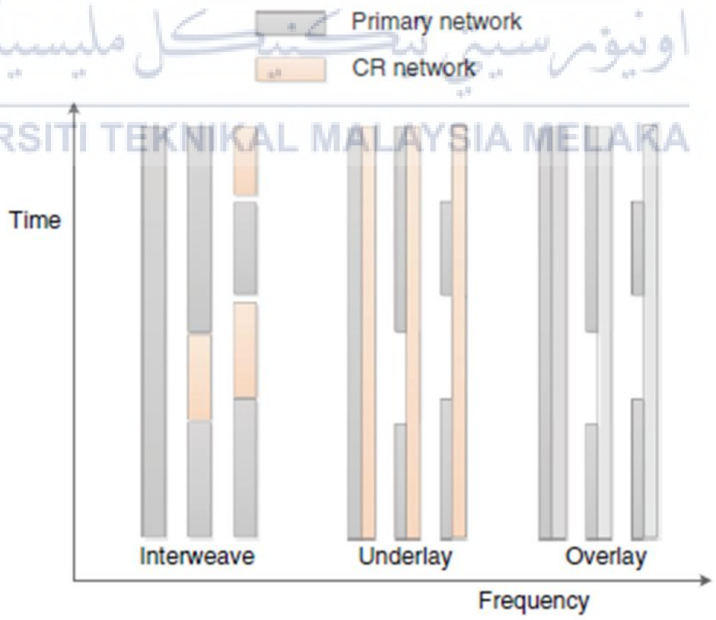

Figure 2.1 : Interweave, underlay, and overlay techniques [2]

For this project, the student selects the underlay technique based on the problem statement of disadvantages in using the overlay technique in chapter 1. The underlay technique is a technique that uses the PU system capability of interference tolerance to allows the SU to transmit even the PU is present in the spectrum. There are four key functions in CR networks to enable opportunistic spectrum access conditions [2]. Firstly, spectrum sensing to detect spectrum holes correctly. Secondly, spectrum management and the decision to select the best spectrum holes across a wide frequency range. Thirdly, spectrum sharing provides a fair division of spectrum holes among different CR devices. Lastly, spectrum mobility is for the ability of the CR nodes to hop among different spectrum holes seamlessly.

2.2 Cognitive Radio Network Functionality

In enabling the opportunistic surrounding for the SU spectrum access, there four key functions of the CR network must be satisfied [2]. These functions are briefly explained next.

2.2.1 Spectrum Sensing

Spectrum sensing is specializing in determine the spectrum state which in detecting spectrum holes accurately [2]. This process must be ongoing as to when the PU is using the spectrum, this process responsible to tell the SU to cease the transmission immediately or accommodate depend on what type of technique of spectrum sharing is used. It also helps to adjust the power levels to limit unwanted interference.

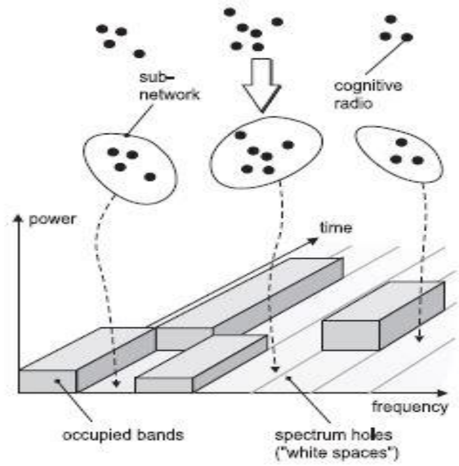

Figure 2.2 : Energy detection technique in underlay cognitive radio network [8]

2.2.2 Spectrum Management and Decision

In the process of detection of spectrum holes, multiple spectrum holes are determined across the channel. Thus, spectrum management and decision process help to select the best possible spectrum hole to be used depend to transmit power, bandwidth, and coding schemes [2].

2.2.3 Spectrum Sharing

Spectrum sharing is the process of the CR network to allocate the SU across the spectrum by using the selected method of underlay, interweave and overlay techniques. These techniques had been explained in chapter 1.1, the background of the project, and chapter 2.1, an overview of cognitive radio network techniques.

2.2.4 Spectrum Mobility

This process is referring the ability of the CR network to hop among different spectrum holes seamlessly depending on the condition [2] which is also referred to as a handoff. This ability enables the users of CR to adjust their operating frequency. The CR network is helping maximize the usage of the spectrum to operate at suitable frequency range availability without interfering with other users.

2.3 Power Control Method

In applying the underlay technique, power control is used to maintain the interference at the PU receiver within Interference Threshold [9]. The transmit power of the SU needs to control finely as to limit the interference to PU. Thus, power control vital in the underlay technique [10].

To perform the power control method, the channel state information (CSI) needs to be obtained which contained data of interference of SU transmitter to PU receiver. By assuming the data CSI has perfectly obtained [10] the student selects water filling model power control. In choosing the power control method, the student investigates several types of power control methods under different power constraints. These methods are explained next.

2.3.1 Aggregate *I* Transmit Power Control

In the study of previous paper on the power control method [11], student able to learn that this method power control principle derived the moment generating function (MGF) and mean Aggregate *I*. MGF is a tool to derive various statistics as it immediately providing moment and evaluate bit error rate (BER) and the outage. The method also uses stochastic-geometry tools for mapping and marking theorem as the number and the location of the cognitive transmitter and receiver are placed randomly. The Rayleigh model use for small-scale fading in experiencing path loss in the system. For this method, the authors able to derive the following equation for transmitting power (Pi) [11]:

$$Pi = \begin{cases} P_s r^{\propto}(|h|^2)^{\mu} & , P_s r^{\propto}(|h|^2)^{\mu} < P_c \\ 0 & , otherwise \end{cases} . \tag{2.1}$$

In this equation, $|h|^2$ and r is the channel gain due to small-scale fading and distance between the cognitive transmitter. P_s is the required average received power at cognitive receiver, while P_c is the cut-off power level, and $\mu \in \{0, -1\}$.

The limitation of the method is as the channel state information (CSI) provides better performance on the PU system, the performance in respect to cognitive transmitter cut-off probability became slightly poorer [11].

2.3.2 Imperfect CSI Power Control Method

Based on the previous study [12], the student investigates the power control method used homogenous Poison Point Processes (PPP) as it is assuming the location of the device-to-device (D2D) transmitter is distributed randomly. Each antenna has a maximum transmit power constraint and the minimum mean square error (MMSE) estimation to evaluate the interference value. As the locations are distributed randomly, the transmission power and SINRs at the receiver are also random.

This paper suggested two distributed algorithms which are On-off power control and Truncated channel inversion. The student selects the first algorithm to be used in comparing suitable power control methods as the equation parameters are closely similar with others compared to power control methods. The equation of transmit power (Ps) [12]:

$$P_s = \mathbb{P}\left[(1-\alpha)\left|\hat{h}_{k,k}\right|^2 d_{k,k}^{-\delta} \geq \mathrm{g}_{min}\right]. \qquad (2.2)$$

In the equation, P_s is the average transmit power equal to link-activated of direct channel condition at receiver ($p_k = P_{md}$). The $\mathrm{g}_{min}(P_s)$ are vital as in this equation as the determined overall performance of the users.

The limitation of the method is the method fails to guarantee the reliability of cellular communication as the coverage distance is decreased [12].

2.3.3 Waterfilling Algorithm Power Control Method

In article journal [13], the student learns the theory of the power control method is formed on the condition of the users is selfishly aimed to maximize their own normalize the effectiveness of the capacity. The optimization of the system capacity is done by considering the BER target and the outage probability. The minimization BER is achieved by using the iterative method as it is fixing the water level parameter until the power and group constraint is satisfied in terms of QoS. Lastly, the Lagrange multipliers are used to gain the power level of the user in the base station.

In this journal [13], the power level and group assignment of the individual user are obtained by initializing the power level (water level) which is P_A^u according the QoS requirement of demands and varying it resiliently until the it reached satisfied demands [13].

$$P_{A^*}^{u^*} = \left[\frac{1}{U}\left(P_{Total} - \sum_{n-1}^{U}\sum_{n=1}^{N_c}\frac{\sigma^2}{\left|H_n^U\right|^2}\right) - \frac{\sigma^2}{\left|H_{n^*}^{U^*}\right|^2}\right]^+ \qquad (2.3)$$

$$[x]^+ = \max\{x, 0\}$$

The limitation of the method is the performance experienced degradation due to bad channels having a low value of SNR as the equal power allocation [13].

2.4 Decision Making in Selecting Power Control Method

Based on the earlier research on the power control method, the waterfilling algorithm is selected. The decision is made based on the investigation that the method able to improve the transmission process without having to trade-off the performance of the PU system to achieve better performance of the cognitive system. Lastly, the method able to avoid excess power and allocate diverse powers to users according to their effective channel response [9].

CHAPTER 3:

METHODOLOGY

This chapter describes methodologies and the power control method. Firstly, the flowchart is described for the flow of the project. Then, the method shows the spectrum holes by using MATLAB software. Lastly, the description of waterfilling model flowchart.

3.1 Overall of Project

The project is conducted in several stages of methodology that complement the flowchart shown in Figure 3.1. Each stage is important for this project able to run smoothly following the flowchart. By completing each stage, the objectives of the project are simultaneously achieved. The project started with the research stage, then the implementation stage, and continued with the analysis stage. The research stage is completed in a part of chapter 2 that focuses on studying about underlay technique and doing analysis between several power control methods. The implementation stage starts from identifies the information of the PU and the SU until waterfilling model development that will be explained further in this chapter and this stage is implemented in MATLAB software. Lastly, the analysis stage is done in chapter 4 for the result and analysis of the project.

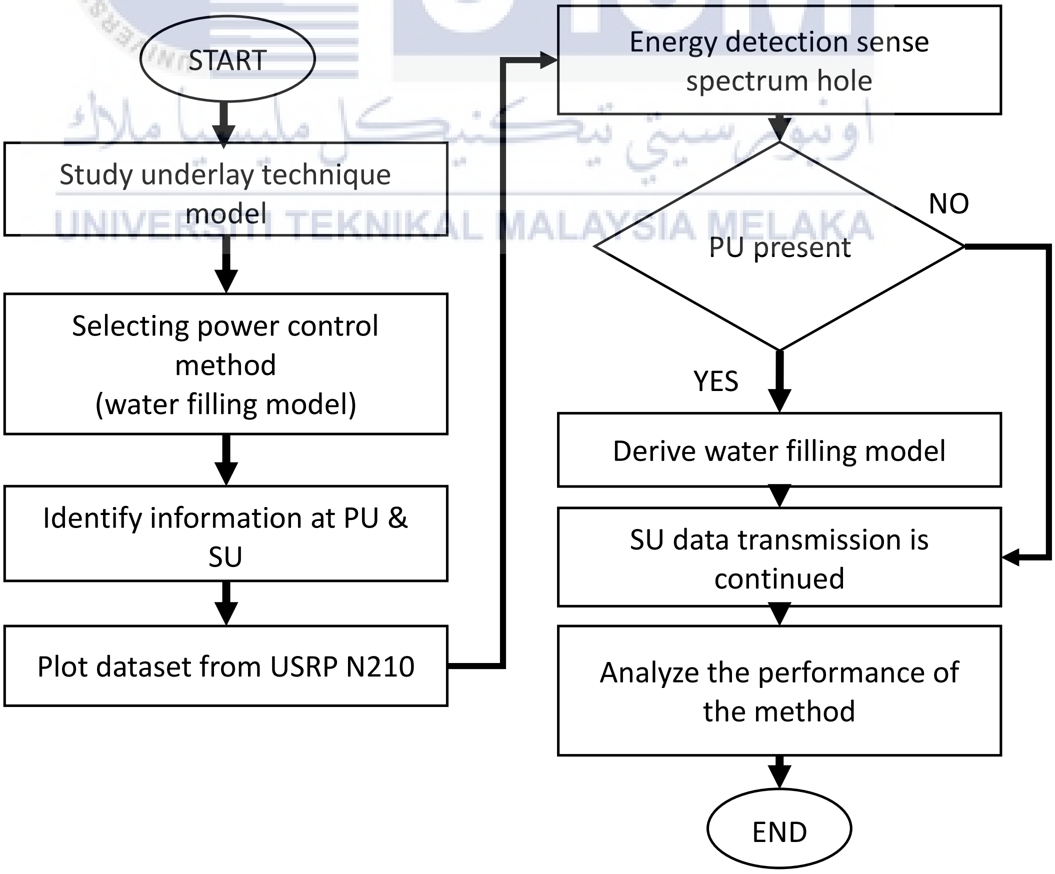

Figure 3.1: Flowchart of project diagram

3.2 System Model of Underlay Technique.

Based on research in chapter 2, the student recognizes two scenarios during the operation of this technique [5]. The first scenario is the SU transmits the data when PU is absent. Lastly, the second scenario when the SU transmits data when the PU is present in the system. Both scenario is follow the energy detection spectrum sensing scenario as the technique shows the signal condition across the frequency spectrum. These scenarios are defined in the condition of signal detection time that described as [6]:

$$x(t) = \begin{cases} (P_{SU} * G_{SU}) + C_{AWGN} & , H0 \\ (P_{SU} * G_{SU}) + (P_{PU} * G_{PU}) + C_{AWGN} & , H1 \end{cases} \quad (3.1)$$

3.2.1 Channel Gain

In the system model, the channel gain will be appearing at each user's receiver based on the scenario that happens. The channel is assumed to consist of path loss and independent flat Rayleigh fading slowly varying in the system model at each scenario. Let $G_A^B = |h_A^B|^2$ as the channel gain [14], $G_A^B = X_A^B d_A^{B^{-\propto}}$ with the fading coefficient, X which is a complex Gaussian random variable, d is the distance, and α is path loss exponent. The channel gain is a random variable distributed exponentially with the variance $1/_{\lambda_A^B}$ and average power channel is defined as $1/_{\lambda_A^B} = E[G_A^B] = d_A^{B^{-\propto}}$ where E[ ] represents the expectation. Which is shown below, $f_{G_A^B}(x)$ generally represents the channel gain as the probability density function (pdf). In the equation, A and B notation, represent the parameter between A and B, or from A to B, and vice versa. Thus, the channel gain equation is defined in (3.1).

$$G_A^B = |h_A^B|^2 \quad , \quad f_{G_A^B}(x) = \lambda_A^B e^{-\lambda_A^B x} \quad (3.2)$$

3.2.2 PU absent, H0

Based on Figure 3.2, the SU is transmitting data during the PU absence. Thus, data transmitted at the maximum power level. When the PU transmitter (PU-Tx) is not active, the SU transmitter (SU-Tx) will access the spectrum and transmit the data to the SU receiver (SU-Rx) while continuing to sense the presence of the PU. During this situation, PU-Rx will not be receiving any interference from SU-Tx.

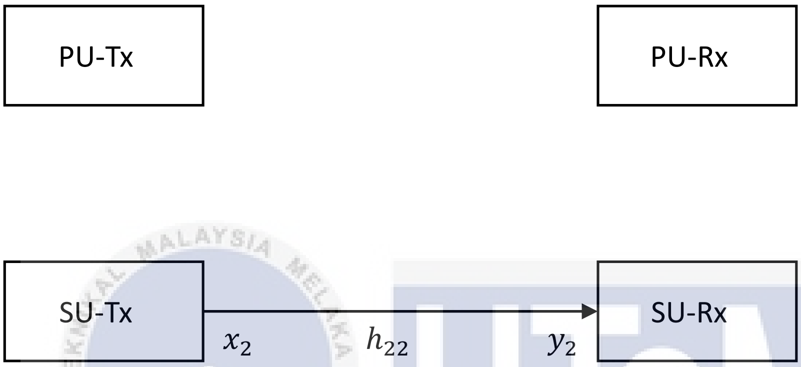

Figure 3.2: Underlay system model in scenario 1

The channel gain present in this scenario is in Figure 3.2 is h_{22} which is gain transmit from the SU to the SU receiver. The gain is recognized as signal-to-noise ratio (SNR). The received SNR at SU-Rx is obtained based on equation (3.1) the equation of SNR given by [15]:

$$SNR_{SU} = \frac{G_{SU}}{n} \tag{3.3}$$

where n is the variance of additive white noise Gaussian noise (AWGN).

3.2.3 PU present, H1

Based on Figure 3.3, the PU reappears in the system model while the SU-Tx is transmitting data, the SU-Rx will be receiving interference from the PU-Tx. Thus, it will alert the SU-Tx to change its power level to define the level in accommodating the condition in continuing transmitting the data while the PU is present in the spectrum. In this condition, both users receiving low interference at the receiver.

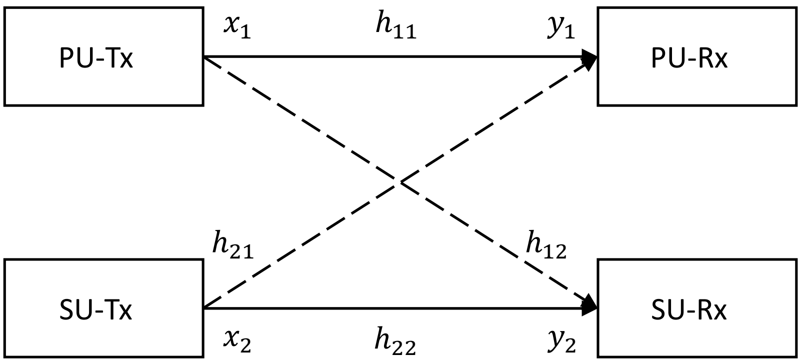

Figure 3.3 : Underlay system model in scenario 2

Based on equation (3.2), the channel gain is obtained as shown as below,

$$G^{SU-Rx}_{SU-Tx} = \left|h_{22}\right|^2 \quad , \quad f_{G^{SU-Rx}_{SU-Tx}}(x) = \lambda^{SU-Rx}_{SU-Tx} e^{-\lambda^{SU-RX}_{SU-Tx} x} \tag{3.4}$$

$$G^{PU-Rx}_{PU-Tx} = \left|h_{11}\right|^2 \quad , \quad f_{G^{PU-Rx}_{PU-Tx}}(x) = \lambda^{PU-Rx}_{PU-Tx} e^{-\lambda^{PU-RX}_{PU-Tx} x} \tag{3.5}$$

Assume the value of parameter distance, n, and path loss exponent is the same within scenario *H0*, the value of the signal-to-interference-plus-noise ratio (SINR) of both transmit power user are given by [15]:

$$SINR_{SU} = \frac{P_{SU}G_{SU}}{n} + P_{PU}G_{PU} \tag{3.6}$$

$$SINR_{PU} = \frac{P_{PU}G_{PU}}{n} + P_{SU}G_{SU} \tag{3.7}$$

3.3 Energy Detection of PU USRP N210 Dataset

In detecting the spectrum hole the sensing algorithm is used. The energy detection algorithm is built around the principle that the transmitted signal will only be perceived by comparing with a defined threshold that depends on the signal and noise variance [6]. The indicator of the algorithms that control the detection performance is the probability of detection (P_d) and probability of false alarm (P_f). The P_d is the probability of event that CR detect the correct presence of the PU in the spectrum and the P_f is the probability of event that CR detect incorrect presence PU.

3.4 Waterfilling model

In the context of this power control, the water is representing as power and the container is the system across the frequency spectrum. The waterfilling model is a power control method that is derived based on equation (3.8) below as the method work like pouring water in a container and the water poured will occupy any available space within the limit of maximum water level [16]:

$$Capacity = \sum_{i=1}^{n} \log_2(1 + power\ allocated * H) \tag{3.8}$$

In waterfilling model, the sum total power, P_t, and the inverse of channel gain of H, which is the network matrix of the system framework will give the complete area power distribution in the waterfilling and inverse power gain. Thus, from the equation (3.9) the model able to decide the initial water level of the system by following equation of average power allocated equation (3.10), and both equations are shown below [16]:

$$P_t + \sum_{i=1}^{n} \frac{1}{Hi} \tag{3.9}$$

$$Avearage\ power\ allocation = \frac{P_t + \sum_{i=1}^{n} \frac{1}{H_i}}{\sum channels} \tag{3.10}$$

For equation (3.8), the *n* is the maximum water level that able to pour into the system. The power allocated in each channel is obtained from the equation (3.11) below [16]:

$$Power\ allocated = \frac{P_t + \sum_{i=1}^{n} \frac{1}{H_i}}{\sum channels} - \frac{1}{H_i} \tag{3.11}$$

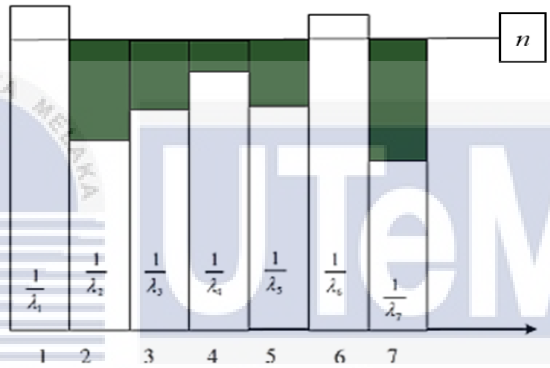

Figure 3.4 : Illustration of waterfilling model [16]

Figure 3.4 illustrates how the shaded part is representing the power allocated, assigned to occupy the channel within the limit of *n* while the unshaded part shows the inverse addition of *H* of the system [16]. Thus, based on the concept explained above. The flowchart of Figure 3.5 is implemented in the Matlab software for the waterfilling model. For the waterfilling model method, the geometric waterfilling method is used as can solve the conventional waterfilling problem and its weighted form [17].

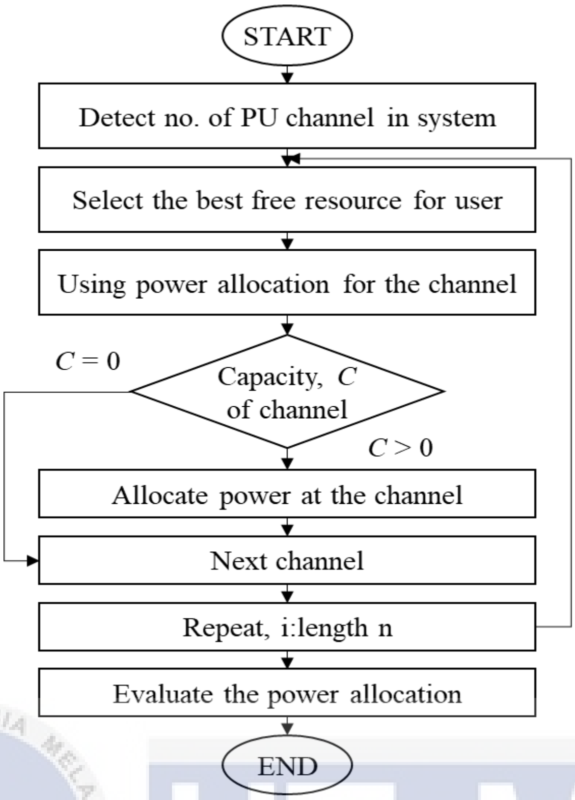

Figure 3.5 : Waterfilling model flowchart

This flowchart is proposed by referring to procedure work that proposed in the main reference of waterfilling model [16] where the authors implement the equation (3.8) and (3.9) in their waterfilling model. The algorithm model will start with detecting the number of the channel of the PU and will select the free resource in the channel within the power budget. Then, the power allocated in the channel within the maximum of the power level, *n* in the model as threshold without interfering with the PU power signal when the capacity of the channel is present.

3.5 Project Schedule

For this project to run smoothly, the schedule had been planned wisely to achieve the objectives for this project and finish the final thesis on the given time. Therefore, the scheduling of this project is shown in the Gantt chart in Appendix A.

CHAPTER 4:

RESULTS AND ANALYSIS

This chapter compiling the result of the project by following the methodology featured in chapter 3. The simulation of the project is obtained by using MATLAB software. Firstly, this chapter will include the result of the frequency spectrum which is analyzed by using the energy detection method, and then the result of generated power of the SU. Lastly, the result of waterfilling model is shown at the end of chapter 4.

4.1 Introduction

The first and second objectives of this project are to investigate the energy detection in the underlay CR network and to implement the power control algorithm in the underlay CR network the parameters in Table 4.1 are used. The design parameter of the model is followed according to three references [6], [14], and [18] where the authors work closely on CR network application.

The dataset of USRP N210 in the range of 2.4 – 2.5 GHz is upload in the Matlab workspace and rename as *Y_inp* which contains the PU power and channel gain amplitude in dBm unit. This data input will be used in the project to investigate energy detection and to implement the power control algorithm in the underlay CR network. The snippet of the data is can be referred at Appendix B.

Parameter	**Value**
Path loss exponent, ∝	4
Distance between PU-Tx and PU-Rx (d_{PU})	150 m
Distance between SU-Tx and SU-Rx (d_{SU})	150 m
Noise variance, *n*	10^(-13)
Frequency channel range, *f*	2.4 to 2.5 GHz
Energy detection threshold, *z*	0.99
Transmit power of PU, P_{PU}	1.9950 to 1.9959 W
Transmit power of SU, *Psu*	0.1990 to 0.1999 W
Probability of false alarm, P_f.	0.01:0.01:1
Number of PU channel, *N*	80250

Table 4.1 : Table of parameter

4.2 Analysis of Energy Detection in Frequency Spectrum

For the given set of parameter based on Table 4.1, the P_f is used to obtain the threshold, z by using the energy threshold equation, λ [6] .

$$\lambda = \left(\frac{Q^{-1}(P_f)}{\sqrt[2]{N}}\right) + 1 \quad (4.1)$$

Where, $Q^{-1}(P_f)$ is the inverse function of $Q(x)$. The Q function is related to the complementary error function [19] according to equation .

$$Q(x) = \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right) \quad (4.2)$$

Following the implementation of the energy threshold equation in Matlab, the student used the 'mean()' function by averaging the 100 iterations of energy threshold value to get the threshold, z = 0.99. Thus, this will reduce the randomness value as the number of simulations to calculate the energy threshold is increases.

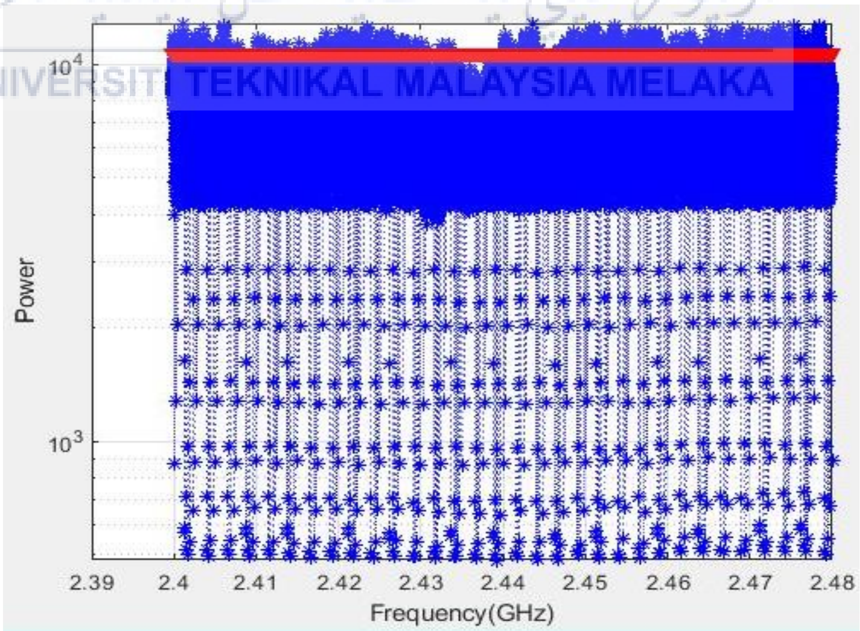

Figure 4.1 : Energy detection frequency spectrum with *z* threshold

In Figure 4.1, the *z* = 0.99 is used to compare with *Y_inp* to get the red line in the figure. The red line representing the threshold of the energy detector to identify the spectrum holes across the frequency band. Thus, Figure 4.2 is obtained to show the spectrum occupation of the PU.

Based on Figure 4.2, the graph is plotted with conditions if the PU is absent the power is equal to 0 else the PU is present the power is 1. Thus, the classification of the black spaces and blue spaces is done. The black spaces are examples of the spectrum hole and the blue spaces indicate the presence of the PU. This classification shows the black is spaces are free of power signals from the PU while the blue spaces are spaces highly occupied by the PU power signal. Based on the occupation of the PU in the spectrum band the spectrum utilization is obtained which is 99.9090%. Table 4.2 shows the detailed information of spectrum usage across the frequency band by using the energy detection technique.

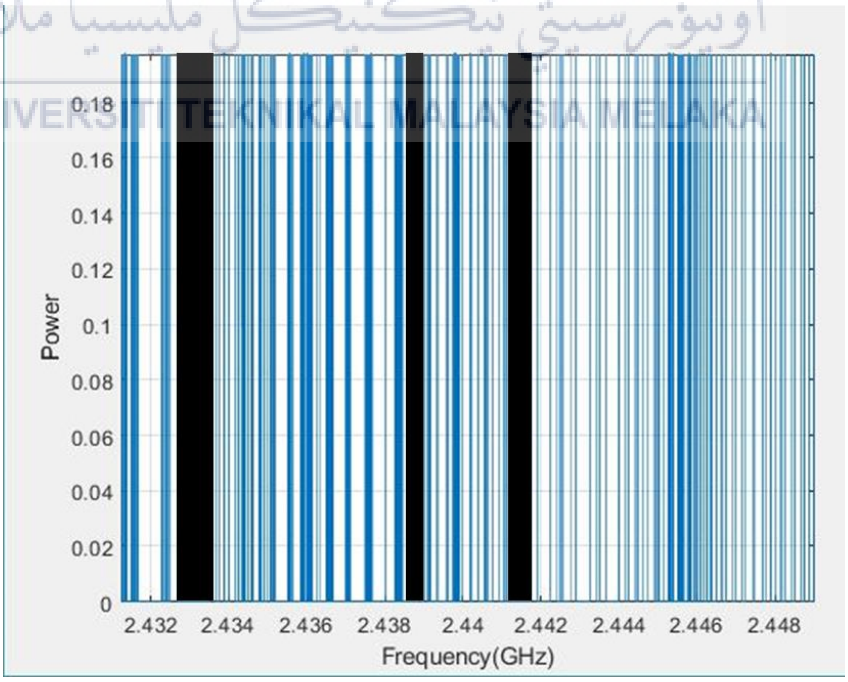

Figure 4.2 : Spectrum hole in the frequency band

Spectrum usage (*N* = 80250)	Percentage (%)
Spectrum occupied by PU	55.0916
spectrum holes	44.9084
spectrum utilization	99.9090

Table 4.2 : Spectrum usage in 80250 channels

4.3 Analysis of Power SU

In generating the power of the SU, the parameters in Table 4.1 are used and the graph is plotted. Figure 4.3 is a generated power randomly from the range of 0.1990 to 0.1999 W with 100 iterations.

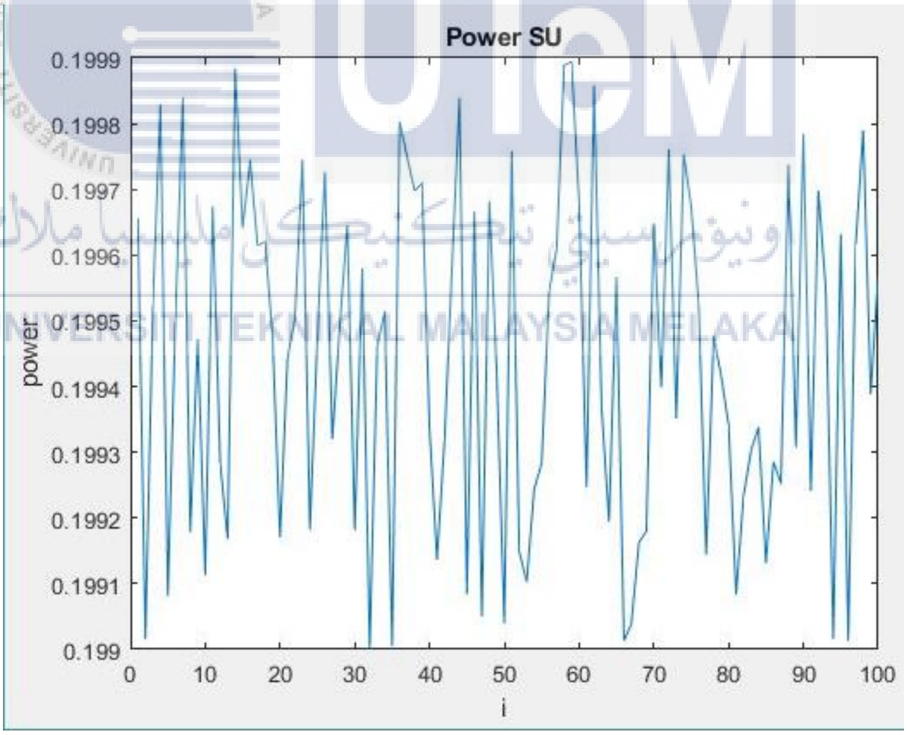

Figure 4.3 : Graph generated Psu using Table 4.1 parameters

In Figure 4.4, equation (3.3) is used with the parameters given in Table 4.1 (∝, d_{SU}, and *n*) to get SNRsu. This graph shown as the power transmission is increasing, the SNR value is increasing. This is representing the condition of the SU during the PU is absent, H_0 scenario (3.1), where the SU transmits freely using spectrum holes without the presence of the PU.

In Figures 4.5 and 4.6, the graph plot showing the relationship between the PU and the SU during the PU is absent, H_0 and the PU is present, H_1 scenario (3.1). Both figures using equations (3.3) and (3.6) to get the SNR and SINR of the SU value.

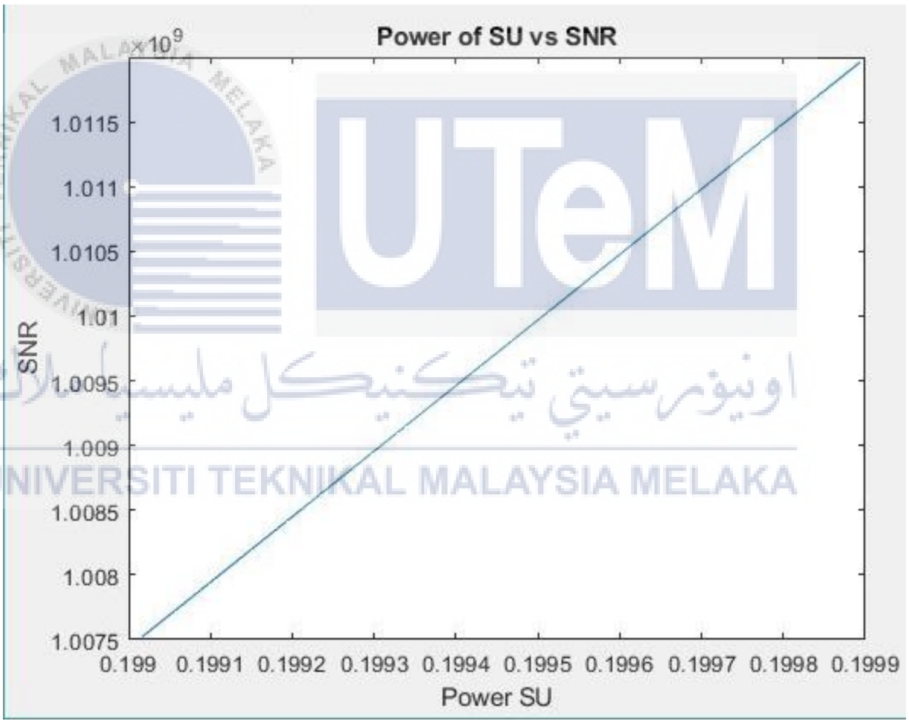

Figure 4.4 : Graph Power SU vs SNR SU

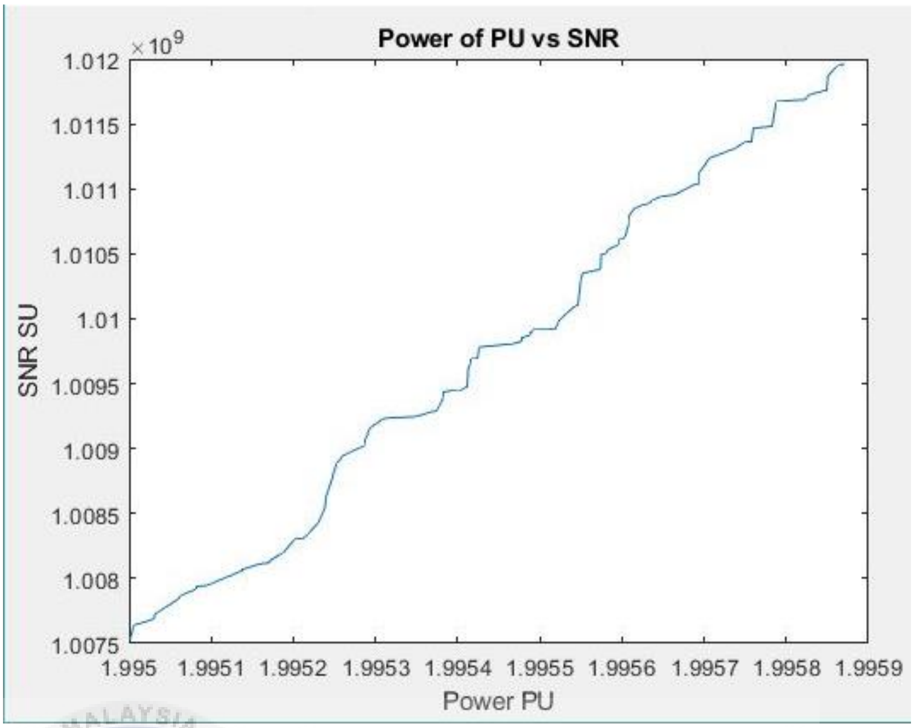

Figure 4.5 : Graph Power PU vs SNR SU

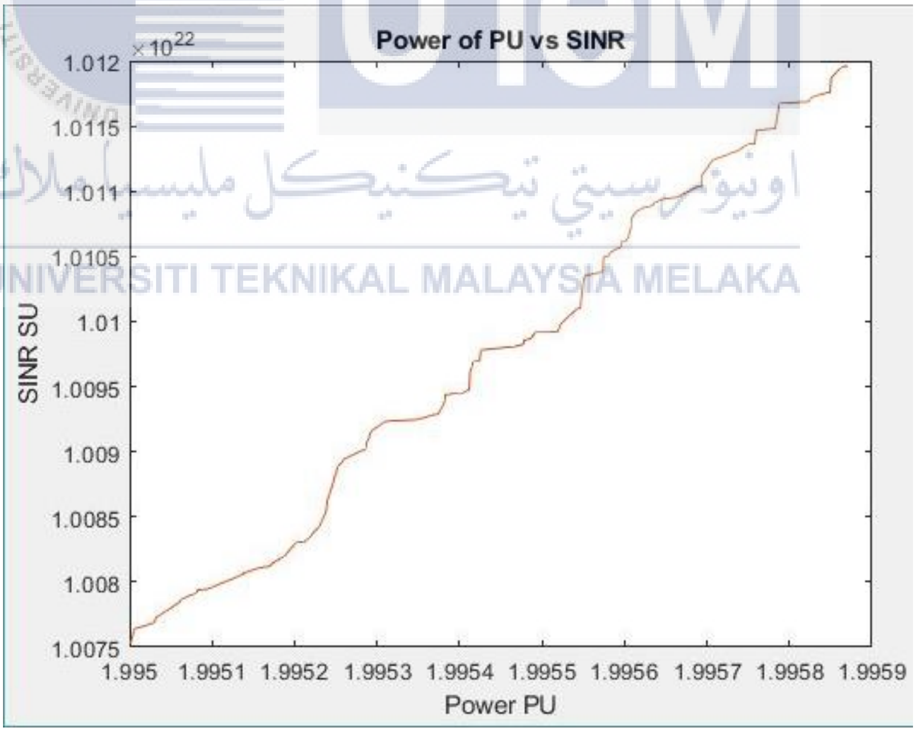

Figure 4.6 : Graph Power PU vs SINR SU

Figure 4.5 is shown the condition of the PU during the H_0 scenario while Figure 4.6 is shown the condition of the PU during the H_1 scenario. In both figures graph, shown as the power of the PU increase, the value of SNR and SINR is increases. The average $P_{PU}G_{PU}$ of the PU is -89.51 dBm which mostly is background noise [20]. Thus, during both scenarios, the SINR of the SU has been not affected by the PU while the average $P_{SU}G_{SU}$ of the SU is 10^{-4} and $P_{PU}G_{SU}$ is 10^{-3} which also a small value that gives no effect to the SINR of the PU.

4.4 Analysis of Waterfilling model

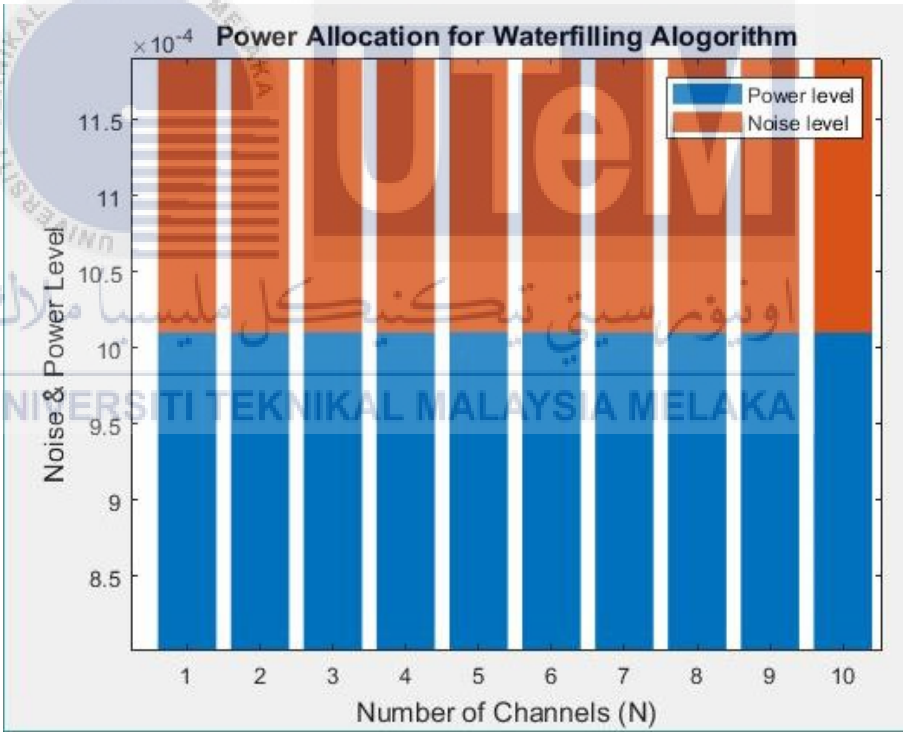

Figure 4.7 : Waterfilling algorithm model with peak constraint

In equation (3.1) based on Figure 4.2, the H_0 scenario allows the SU to transmit data using the black spaces. The SU will transmit normally during this scenario and by using the underlay technique the SU will continue to transmit into blue spaces with the regulation of a power control method, waterfilling model during the H_1 scenario.

In the waterfilling model, the 200 datasets in Appendix C are used. Thus, Figure 4.7 is obtained with the allocated power (red shaded part) in the channel at the PU power signal (blue shaded part) with the threshold of maximum water level, *n* in equation (3.8). The red shaded part contains the allocated power signal by using equation (3.9) pour in the channel. Table 4.2, shows the snippet data of 10 channels of occupied spectrum by the PU. The allocated power is obtained based on the power total of the system while the capacity of the channel (3.8) is obtained based on the allocated power. The allocated power of the channel is 0.01 W. In Figure 4.8, the SNR of the SU is a plot against the capacity of the channel with $P_t = P_{PU}$. The increasing value of the SNR of the SU, the capacity of the channel is increasing [21].

Channel, N	Frequency, GHz	Capacity
1	2.40021	688.61
2	2.40022	688.61
3	2.40022	688.60
4	2.40022	688.61
5	2.40022	688.60
6	2.40022	688.60
7	2.40022	688.61
8	2.40022	688.61
9	2.40022	688.62
10	2.40022	688.61

Table 4.3 : The waterfilling model result data in the occupied spectrum

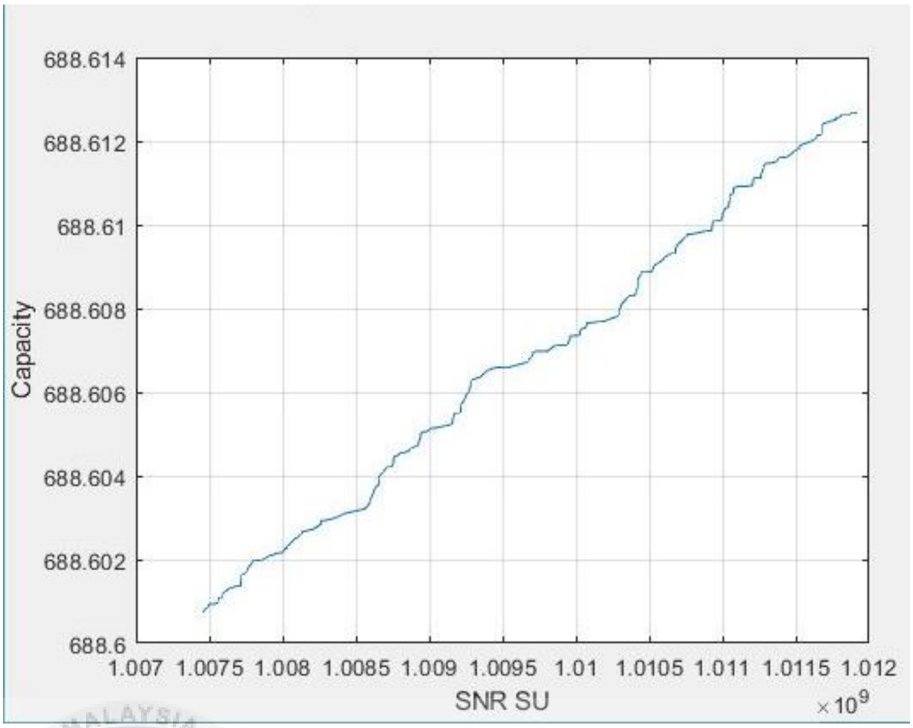

Figure 4.8 : Graph SNR SU vs Capacity

4.5 Discussion

Referring to the problem statement in Chapter 1.2, the implementation of the underlay technique with the power control waterfilling method replacing the overlay technique is to allow the SU to continue to transmit when the PU is reappearing without being cut off. Using the underlay technique with a power control method enables to allocated power to the channels occupied by the PU in Figure 4.7. Thus, the SU able to transmit using the channels within the capacity range. The range of the SU power within 0.1990 to 0.1999 W smaller than the capacity value in the channel, 14.0828. Hence, the SU able to transmit data without interfering and receiving interference from the PU power signal.

Table 4.4 is tabulated the data spectrum usage using the overlay technique. Based on equation (3.1), in H_0 scenario both system model allows the SU to use 41% of the frequency spectrum as the spectrum hole present and unable to use the spectrum occupied by the PU which is 59% as contain a total of 118 channels from 200 channels. By the following flowchart in Figure 3.1 when the PU is present the waterfilling model is activated. Table 4.3 is the snippet data of 10 channels in the spectrum used (59%) by the PU that is used in the waterfilling model.

Spectrum utilization (*N* = 200)	**Percentage (%)**	**USER**
Spectrum used	59	PU
Spectrum holes	41	SU
Total Spectrum Utilization = 100%		

Table 4.4 : Spectrum usage by users in 200 channels

Thus, the underlay system model with help of the power control method increases the spectrum usage of the SU by allowing the SU to transmit data in the spectrum used (59%) by the PU from 0% to 100% during the H_1 scenario. The SU can use 100% of the spectrum during the PU present because the value of the SNR and SINR of the SU is small and does not exceed the capacity of the channel in waterfilling model.

In Table 4.4, the data obtained by based on the data input of Appendix C. The data in Appendix C is a data channel of 200 channels from 80250. This selection is done because simulation on 80250 channel on the Matlab is unable to run with an error 'array exceeds maximum array size preference' as the data requested using large memory. Thus, using a small number of channels can solve this problem. Furthermore, the spectrum usage across frequency band in Table 4.2 shows the utilization of spectrum is 99.9090% so the result data in Table 4.4 do not accurately represent the whole spectrum across the frequency band of 80250 channels as the total spectrum utilization in Table 4.4 achieved 100%. This situation happens because the selected dataset from frequency range 2.40018 to 2.40035 GHz has no unutilized frequency spectrum data.

CHAPTER 5:

CONCLUSION AND FUTURE WORKS

This chapter concludes the project that contains the knowledge gain through the project assessment and suggestions for future works that are related to this topic.

5.1 Conclusion of Project

A cognitive radio network is a vital tool in breaking the limitation of the radio spectrum. The cognitive radio focuses on exploiting the unused licensed spectrum so the secondary user can use the unoccupied licensed spectrum part instead of accessing the free frequency that will constraint the spectrum as congested with other unlicensed users which is one of the existing problems in wireless communication networks.

By using the energy detection spectrum sensing, two scenarios are considered is the first scenario is when the PU is not present, the SU freely accesses the spectrum and transmits at maximum power level. Then, the second scenario is when the PU is reappearing in the spectrum, the SU keeps transmitting the data within the defined power level. The energy detection method can detect spectrum holes across the PU channels of 44.9084% while the spectrum occupied by the PU is 55.0916% with a total spectrum utilization of 99.9090%. Furthermore, when the dataset of 80250 channels is reduced to the dataset of 200 channels the energy detection method can detect spectrum holes across the PU channels of 41% while the spectrum occupied by the PU is 59% with a total spectrum utilization of 100%. This situation happens because the selected dataset of 200 channels from frequency range 2.40018 to 2.40035 GHz has no unutilized frequency spectrum data.

By referring to the various journal of the previous study, the algorithm of the waterfilling model is run in Matlab with the appropriate equation and parameters to suit with input dataset. The waterfilling model is implemented when the PU is detected in the channel during H_1 following the flowchart in Figure 3.1. By using the underlay technique, the SU keeps transmitting the data by adapting its power level by using the waterfilling model to keep interference to the PU at a minimum rate. During this process, tabulating data of Table 4.3 is done to show the capacity of the channel during the PU is present and Figure 4.8 is obtained to show the relationship between the SNR of the SU and the capacity of the channel. The data collected in waterfilling model shows the power allocation of 0.01 W is allocated at each channel.

At the end of the project, the utilization of the frequency spectrum by using the power control method in the underlay technique is obtained. Based on the data in Table 4.4, showing 59% of the occupied spectrum which contains 118 channels from the 200 channels can be used 100% by the SU. Thus, the SU from only using spectrum holes, 41% to transmit data using the overlay CR network but now spectrum usage of the SU able to increase to 100% as the SU can use all 118 channels that occupied by the PU using the underlay CR network. Hence, the analysis based on data obtained and discussion in this project has shown, by using the waterfilling model in the underlay technique able to encounter the problems that discuss in the problem statement in Chapter 1 which is the disadvantages of the overlay technique that's PU has higher priority to use spectrum while the SU only able to transmit data when the spectrum holes are present.

5.2 Future Works

In conclusion, cognitive radio was proposed as an effective way to maximize the usage of wireless spectrum resources. In this project, the student assumed the primary user is absent and reappearing in the channel, and the student using MATLAB software to code the situation. The advancement of IoT devices may become hinder in keeping continue to used MATLAB software. So, the study case for power level in the future needs to be run in LabView software.

The LabView software is a system of engineering platform for applications that require easier access to hardware and data information, monitoring, measurement, and control. This software offers a graphical programming framework that helps visualize any part of the application such as hardware configuration, measurement data, and debugging. This function enables the integration of measurement equipment for any manufacturer, which reflects abstract logic on the diagram, creates algorithms for data analysis, and designs custom user interface design.

REFERENCES

[1] S. Kemp, “DIGITAL 2019: GLOBAL DIGITAL OVERVIEW,” *DataReportal.com,* 2019. [Online]. Available: https://datareportal.com/reports/digital-2019-global-digital-overview.

[2] J. G. Webster, S. Kusaladharma, and C. Tellambura, “An Overview of Cognitive Radio Networks,” *Wiley Encycl. Electr. Electron. Eng.*, no. March 2017, pp. 1–17, 2017, doi: 10.1002/047134608x.w8355.

[3] S. M. Baby and M. James, “A Comparative Study on Various Spectrum Sharing Techniques,” *Procedia Technol.*, vol. 25, no. Raerest, pp. 613–620, 2016, doi: 10.1016/j.protcy.2016.08.152.

[4] I. E. Etim and J. Lota, “automation,” *Power Control Cogn. radios, Internet-of Things factories Ind. Autom.*, pp. 4701–4705, 2016.

[5] A. Kaushik, S. K. Sharma, S. Chatzinotas, B. Ottersten, and F. K. Jondral, “On the Performance Analysis of Underlay Cognitive Radio Systems: A Deployment Perspective,” *IEEE Trans. Cogn. Commun. Netw.*, vol. 2, no. 3, pp. 273–287, 2016, doi: 10.1109/tccn.2016.2606625.

[6] U. Salama, P. L. Sarker, and A. Chakrabarty, “Enhanced energy detection using matched filter for spectrum sensing in cognitive radio networks,” *2018 Jt. 7th Int. Conf. Informatics, Electron. Vis. 2nd Int. Conf. Imaging, Vis. Pattern Recognition, ICIEV-IVPR 2018*, pp. 185–190, 2019, doi: 10.1109/ICIEV.2018.8641079.

[7] K. A. Mehr, J. M. Niya, and N. Akar, “Queue management for two-user cognitive radio with delay-constrained primary user,” *Comput. Networks*, vol. 142, no. May, pp. 1–12, 2018, doi: 10.1016/j.comnet.2018.05.028.

[8] T. Renk, C. Kloeck, and F. K. Jondral, “A cognitive approach to the detection of spectrum holes in wireless networks,” *2007 4th Annu. IEEE Consum. Commun. Netw. Conf. CCNC 2007*, pp. 1118–1120, 2007, doi: 10.1109/CCNC.2007.225.

[9] C. Xing, Y. Jing, S. Wang, S. Ma, and H. V. Poor, “New viewpoint and algorithms for water-filling solutions in wireless communications,” *IEEE Trans. Signal Process.*, vol. 68, pp. 1618–1634, 2020, doi: 10.1109/TSP.2020.2973488.

[10] Z. Yan, X. Zhang, H. L. Liu, and Y. C. Liang, “An efficient transmit power control strategy for underlay spectrum sharing networks with spatially random primary users,” *IEEE Trans. Wirel. Commun.*, vol. 17, no. 7, pp. 4341–4351, 2018, doi: 10.1109/TWC.2018.2822817.

[11] S. Kusaladharma, P. Herath, and C. Tellambura, “Underlay interference analysis of power control and receiver association schemes,” *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 8978–8991, 2016, doi:

10.1109/TVT.2016.2518988.

[12] A. Memmi, Z. Rezki, and M. S. Alouini, “Power Control for D2D Underlay Cellular Networks with Channel Uncertainty,” *IEEE Trans. Wirel. Commun.*, vol. 16, no. 2, pp. 1330–1343, 2017, doi: 10.1109/TWC.2016.2645210.

[13] S. Arumugam and D. Perumal, “Power control through water filling game theory in adaptive modulation based MCCDMA-MIMO system,” *Int. Conf. Commun. Signal Process. ICCSP 2016*, no. April 2016, pp. 1415–1419, 2016, doi: 10.1109/ICCSP.2016.7754388.

[14] J. Zou, H. Xiong, D. Wang, and C. W. Chen, “Optimal power allocation for hybrid overlay/underlay spectrum sharing in multiband cognitive radio networks,” *IEEE Trans. Veh. Technol.*, vol. 62, no. 4, pp. 1827–1837, 2013, doi: 10.1109/TVT.2012.2235152.

[15] D. Tse and P. Viswanath, “Capacity of wireless channels,” *Fundam. Wirel. Commun.*, pp. 166–227, 2012, doi: 10.1017/cbo9780511807213.006.

[16] N. Kaur and S. Kaur, “A Novel Technique to Decrease BER using Waterfill Algorithm in OFDM-MIMO,” vol. 7, no. 2, pp. 124–130, 2018.

[17] S. Agrawal, “POWER ALLOCATION USING GEOMETRIC WATER FILLING AND DYNAMIC CHANNEL SENSING ALGORITHM IN COGNITIVE RADIO,” vol. 2, no. 3, pp. 27–31, 2017.

[18] A.-A. A. Boulogeorgos, P. D. Diamantoulakis, and G. K. Karagiannidis, “Low Power Wide Area Networks (LPWANs) for Internet of Things (IoT) Applications: Research Challenges and Future Trends,” no. November, pp. 1–

15, 2016.

[19] “Inverse Q function - MATLAB qfuncinv.” [Online]. Available: https://www.mathworks.com/help/comm/ref/qfuncinv.html#mw_827657ee-1939-4036-bf18-91c39c34ce54.

[20] E. Moyers, “Why is almost everything negative in Wi... - Cisco Community,” 2015. [Online]. Available: https://community.cisco.com/t5/small-business-support-documents/why-is-almost-everything-negative-in-wireless/ta-p/3159743.

[21] K. Kumar and M. Singh, “Proposed Water filling Model in a MIMO system,” *Int. J. Emerg. Technol. Adv. Eng. Website www.ijetae.com*, vol. 1, no. 2, pp. 127–132, 2250.

APPENDICES

APPENDIX A

PERA
PROJECT PL

Senaraikan aktiviti-aktiviti yang berkaitan bagi projek yang dica
List all the relevant activities of the proposed project and

Aktiviti Projek Project Activities	SEM I																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Consultation with the supervisor	X	X	X	X	X	X	X	X	X	X	X	X	SEMINAR PSM I	X	X	X	X
Deciding FYP title	X	X															
Writing and editing proposal		X	X	X													
Literature research		X	X	X	X	X	X	X	X	X	X	X					
Collecting the data variable						X	X	X	X	X	X	X					
Identify the underlay technique						X	X	X	X								
Identify information at PU & SU								X	X	X	X						
Analyze the algorithm of the system model in MATLAB								X	X	X	X						
Writing and editing report FYP 1								X	X	X	X	X					
Derive water filling algorithm																	
Implementation of coding in MATLAB																	
Observation of the data																	
Analyze the performance of the water filling model																	
Writing and editing report FYP 2																	

ukan bagi setiap aktiviti.
. of the activities.

SEM II

Aktiviti Projek Project Activities	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Consultation with the supervisor	X	X	X	X	X	X	X	X	X	X	X	X	SEMINAR PSM II		
Deciding FYP title															
Writing and editing proposal															
Literature research															
Collecting the data variable	X	X	X	X	X	X	X	X	X	X	X	X			
Identify the underlay technique															
Identify information at PU & SU															
Analyze the algorithm of the system model in MATLAB															
Writing and editing report FYP 1															
Derive water filling algorithm	X	X	X	X	X	X	X	X							
Implementation of coding in MATLAB	X	X	X	X	X	X	X	X	X	X	X	X			
Observation of the data	X	X	X	X	X	X	X	X	X						
Analyze the performance of the water filling model								X	X	X	X	X			
Writing and editing report FYP 2						X	X	X	X	X	X	X			

APPENDIX B

FREQUENCY (Hz)	AMPLITUDE (dBm)
2.4G	-85.6111
2.4G	-84.9071
2.4G	-85.3915
2.4G	-79.2225
2.4G	-29.5539
2.4G	-63.0495
2.4G	-69.6793
2.4G	-93.9841
2.4G	-94.2948
2.4G	-95.5704
2.40001G	-96.5163
2.40001G	-97.602
2.40001G	-97.7787
2.40001G	-98.6642
2.40001G	-98.1035
2.40001G	-98.1984
2.40001G	-99.2057
2.40001G	-98.5496
2.40001G	-98.6476
2.40001G	-98.2993
2.40002G	-97.2288
2.40002G	-97.3378
2.40002G	-95.8156
2.40002G	-97.1864
2.40002G	-96.6017
2.40002G	-97.6214
2.40002G	-98.8078
2.40002G	-99.1063
2.40002G	-99.4563
2.40002G	-100.215

APPENDIX C

FREQUENCY (Hz)	AMPLITUDE (dBm)	PUon = 1
2.40018	-89.9131	0
2.40019	-89.8219	0
2.40019	-89.967	0
2.40019	-89.2957	0
2.40019	-89.4873	0
2.40019	-89.1914	0
2.40019	-89.2878	0
2.40019	-88.68	0
2.40019	-88.4799	0
2.40019	-88.5273	0
2.40019	-88.3921	0
2.4002	-88.1392	0
2.4002	-87.7359	0
2.4002	-88.1191	0
2.4002	-87.3406	0
2.4002	-87.3986	0
2.4002	-87.2858	0
2.4002	-86.9885	0
2.4002	-86.7497	0
2.4002	-86.6791	0
2.4002	-86.2479	0
2.40021	-86.3969	0
2.40021	-85.8739	0
2.40021	-85.7209	0
2.40021	-85.5722	0
2.40021	-85.2274	0
2.40021	-85.0721	0
2.40021	-85.1091	0
2.40021	-84.4089	0
2.40021	-84.3026	0
2.40021	-84.0711	0
2.40022	-83.6523	0
2.40022	-83.5368	0
2.40022	-83.0862	0
2.40022	-82.9473	0
2.40022	-82.4556	0
2.40022	-82.0204	0
2.40022	-81.9996	0
2.40022	-81.3669	0
2.40022	-81.209	0
2.40022	-80.7249	0
2.40023	-80.3247	0
2.40023	-79.9455	0
2.40023	-79.608	0
2.40023	-78.9707	0
2.40023	-78.7217	0
2.40023	-78.179	0
2.40023	-77.6078	0
2.40023	-77.0422	0
2.40023	-76.7311	0
2.40023	-75.9537	0
2.40024	-75.5326	0
2.40024	-74.8399	0
2.40024	-74.0591	0
2.40024	-73.4762	0
2.40024	-72.7525	0
2.40024	-71.9597	0
2.40024	-71.0367	0
2.40024	-70.1538	0
2.40024	-69.3223	0
2.40024	-68.2632	0
2.40025	-35.7067	0
2.40025	-67.412	0
2.40025	-66.8983	0
2.40025	-68.3064	0
2.40025	-65.8436	0
2.40015	-100.587	1
2.40015	-99.4727	1
2.40015	-99.9878	1
2.40015	-98.7208	1
2.40015	-98.7706	1
2.40015	-97.9961	1
2.40015	-97.9662	1
2.40016	-97.5386	1
2.40016	-96.6599	1
2.40016	-96.3051	1
2.40016	-96.7058	1
2.40016	-95.7249	1
2.40016	-95.3146	1
2.40016	-94.9701	1
2.40016	-95.3161	1
2.40016	-94.5488	1
2.40016	-94.1944	1
2.40017	-93.7672	1
2.40017	-94.0049	1
2.40017	-93.5539	1
2.40017	-92.8538	1
2.40017	-93.6916	1
2.40017	-93.1129	1
2.40017	-91.8221	1
2.40017	-92.8527	1
2.40017	-91.9781	1
2.40017	-91.8931	1
2.40018	-91.8168	1
2.40018	-91.6386	1
2.40018	-90.971	1
2.40018	-91.2444	1
2.40018	-90.9245	1
2.40018	-90.6134	1
2.40018	-90.6106	1
2.40018	-90.3321	1
2.40018	-90.284	1
2.40025	-105.249	1

2.40025	-103.913	1
2.40025	-104.044	1
2.40025	-106.881	1
2.40025	-105.883	1
2.40026	-104.561	1
2.40026	-105.568	1
2.40026	-105.531	1
2.40026	-105.092	1
2.40026	-103.97	1
2.40026	-105.958	1
2.40026	-105.312	1
2.40026	-104.745	1
2.40026	-106.521	1
2.40026	-105.424	1
2.40027	-105.024	1
2.40027	-107.323	1
2.40027	-105.858	1
2.40027	-106.112	1
2.40027	-105.369	1
2.40027	-107.218	1
2.40027	-104.087	1
2.40027	-106.039	1
2.40027	-102.863	1
2.40027	-105.925	1
2.40028	-103.873	1
2.40028	-106.039	1
2.40028	-103.761	1
2.40028	-104.53	1
2.40028	-103.186	1
2.40028	-105.332	1
2.40028	-102.799	1
2.40028	-105.036	1
2.40028	-103.074	1
2.40028	-102.326	1
2.40029	-104.235	1
2.40029	-102.383	1
2.40029	-103.097	1
2.40029	-102.223	1
2.40029	-101.66	1
2.40029	-102.149	1
2.40029	-101.621	1
2.40029	-101.92	1
2.40029	-101.556	1
2.40029	-101.24	1
2.4003	-100.827	1
2.4003	-101.299	1
2.4003	-99.9925	1
2.4003	-100.688	1
2.4003	-101.036	1
2.4003	-100.074	1
2.4003	-99.3446	1
2.4003	-100.492	1
2.4003	-99.7736	1
2.4003	-99.8487	1

2.40031	-99.3607	1
2.40031	-98.8917	1
2.40031	-99.4794	1
2.40031	-98.6133	1
2.40031	-98.4288	1
2.40031	-98.5331	1
2.40031	-98.6232	1
2.40031	-98.3359	1
2.40031	-98.1747	1
2.40031	-97.3021	1
2.40032	-97.7768	1
2.40032	-97.8402	1
2.40032	-97.5644	1
2.40032	-97.8205	1
2.40032	-97.2446	1
2.40032	-97.2125	1
2.40032	-96.9797	1
2.40032	-98.0731	1
2.40032	-96.1797	1
2.40032	-97.1388	1
2.40033	-96.5849	1
2.40033	-96.7399	1
2.40033	-96.9216	1
2.40033	-96.6165	1
2.40033	-96.324	1
2.40033	-96.4958	1
2.40033	-96.0967	1
2.40033	-96.4427	1
2.40033	-95.7984	1
2.40033	-96.6013	1
2.40034	-96.0057	1
2.40034	-96.5145	1
2.40034	-95.8092	1
2.40034	-95.8214	1
2.40034	-96.3822	1
2.40034	-95.727	1
2.40034	-95.952	1
2.40034	-95.798	1
2.40034	-95.6855	1
2.40034	-96.0502	1
2.40035	-95.7834	1
2.40035	-95.4444	1
2.40035	-95.586	1

APPENDIX D

```
%ENERGY DETECTION CODING

load('usrp.mat');
Pf = 0.01:0.01:1;
n=80250; %no. of sample

TH_POW = (qfuncinv(Pf)./sqrt(n))+ 1; %threshold equation
TH_POW(~isfinite(TH_POW))=0;
z = mean(TH_POW);    %=0.99

Y_amp = Y_inp .* conj(Y_inp);
Y_th = Y_amp > z;

base = max(Y_amp);
botom = mean(Y_amp);
mini = min(Y_amp);

botomx = mean(Y_inp);
figure
 semilogy (freq,Y_amp,':b*' );
 hold
 semilogy(freq, Y_th * base / (5) + botom ,'-rv'); %%% 1st analysis
 hold
 grid on
 xlabel('Frequency(GHz)');
 ylabel('Power');

 Y_pow = Y_th * base / (5) + botom;
 a = botom;
for i=1:length (Y_amp)
    if Y_amp(i)> a
        C(i)=1; %PU is present
        PUon(i) = C(i);
    else
        C(i)=0; %PU is absent
        PUoff(i) = C(i);
    end
end
% figure
% plot (freq, C);
% xlabel('Frequency(GHz)');
% ylabel('Power');
% grid on

%calculate utilization  = 99.9090
h=sum(C==0);
d=h;
f=length(freq);
utilization= (d/f)*100
```

```
%SNR/SINR PU & SU

load('energy.mat');
n = 10^(-13);
d = 0.15; %distance between Pt and Pr in Km
a = 4; %path loss exponent
G = (d)^a; %channel gain
Nf = G./(n);
L = 200;
% y_amp = snrPU

ymin=1.9950;
ymax=1.9959;
Ppu =ymin+rand(1,L)*(ymax-ymin);
A = sort (Ppu);

xmin=0.1990;
xmax=0.1999;
Psu = xmin+rand(1,L)*(xmax-xmin);
B = sort (Psu);

SNRsu = Nf.*B; % scene 1, pu not transmit

SINRsu = (B.*Nf)./n+(Y_amp); % scene 2

PsuGsu = Psu*G;
PpuGsu = Ppu*G;

%  figure
%   plot (Psu);
%   title ('Power SU');
%   ylabel ('power');
%   xlabel ('i');
%   hold on;
%  figure
%   plot (B,SNRsu)
%   title  ('Power of SU vs SNR');
%   ylabel ('SNR');
%   xlabel ('Power SU');
%   hold on;
%
%  figure
%   plot (A,SINRsu);
%   title  ('Power of PU vs SINR');
%   ylabel ('SINR SU');
%   xlabel ('Power PU');
%   hold on;
%
%  figure
%   plot (A,SNRsu);
%   title  ('Power of PU vs SNR');
%   ylabel ('SNR SU');
%   xlabel ('Power PU');
%   hold on;
%
```

```
% WATERFILLING MODEL CODING

load('varON.mat');
% load('var2water.mat');
% Y_pow = 10670.9930823715
% mean_y = 8.103886995171492e+03
% max_y = 1.283553043600000e+04

PpuGsu = PpuGsu.';
Trans_Power= Ppu; %average power
Noise_Power= PpuGsu;
Number_Channel= length(Noise_Power) ;
[S_Number dt]=sort(Noise_Power);
sum(Noise_Power)

for p=length(S_Number):-1:1
    T_P=(Trans_Power+sum(S_Number(1:p)))/p;
    Input_Power=T_P-S_Number;
    Pt=Input_Power(1:p);
    if(Pt(:)>=0),
        break
    end
end
Allocated_Power=zeros(1,Number_Channel);
Allocated_Power(dt(1:p))=Pt;
Capacity=sum(log2(1+Allocated_Power./Noise_Power));
for ii =1:length(Noise_Power)
    g(ii,:)=[Noise_Power(ii),Allocated_Power(ii)];
end

figure
bar(g,'stack');
legend ('Power level','Noise level','')
ylabel('Noise & Power Level','fontsize',12)
xlabel('Number of Channels (N)','fontsize',12)
title('Power Allocation for Waterfilling
Alogorithm','fontsize',12)
hold on

CAP = sort(Capacity);

figure
plot(SINRsu,CAP);
xlabel('SNR SU');
ylabel('Capacity');
grid on

% h=sum(C==1);
% f=length(freq);
% utilization= (h/f)*100
```