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Performance Monitoring of Spectrum Sharing in Cognitive Radio

OMAR ABBOOSH HUSSEIN GWASSI

Master Thesis

Supervisor

Assoc. Prof. Dr. Oguz Bayat

Co-Supervisor

Dr. Volkan Sevindik

PERFORMANCE MONITORING OF SPECTRUM SHARING IN COGNITIVE RADIO

by

Omar Abboosh Hussein GWASSI

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This is to certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Dr. Volkan SEVINDIK	Assoc. Prof. Dr. Oguz BAYAT
Co-Supervisor	Supervisor

Examining Committee Members (first name belongs to the chairperson of the jury and the second name belongs to supervisor)

Assoc. Prof. Dr. Oguz BAYAT	School of Engineering and Natural Sciences, Altinbaş University	___________________
Dr. Volkan SEVINDIK	Faculty of Engineering and Architecture, Beykoz University	___________________
Asst. Prof. Dr. Cagatay AYDIN	School of Engineering and Natural Sciences, Altinbaş University	___________________
Asst. Prof. Dr. Cagdas ATILLA	School of Engineering and Natural Sciences, Altinbaş University	___________________
Asst. Prof. Dr. Adil Deniz DURU	Faculty of Sport Science, Marmara University	___________________

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Asst. Prof. Dr. Çağatay AYDIN

Head of Department

Assoc. Prof. Oğuz BAYAT

Approval Date of Graduate School of
Science and Engineering: ____/____/____

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Omar Abboosh Hussein GWASSI

DEDICATION

To my parents.

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ABSTRACT

Performance Monitoring of Spectrum Sharing in Cognitive Radio

Omar Abboosh Hussein GWASSI,

M.Sc., Electrical and Computer Engineering, Altınbaş University

Supervisor: Assoc. Prof. Dr. Oguz Bayat
Co-Supervisor: Dr.Volkan Sevindik

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Due to the phenomenon of fixed spectrum allocation (FSA), the spectrum management failed to satisfy the demands of new, technologies that are always evolving. However, cognitive radio (CR) is employed for utilization improvement in the spectrum and resource deficiency completion. Day by day, the number of radio spectrum users is increasing, as new technologies are being introduced in all sectors of human life. Therefore, even the users of licensed bands are demanding a larger radio spectrum. In order to balance radio spectrum congestion, users can get assigned to other bands. In this thesis, radio spectrum is sensed for hole detection and secondary (or "unlicensed") user (SU) assignment. SUs are participating in the white band either by transmitting alongside primary (or "licensed") users (PUs) or by waiting to transmit until the hole becomes vacant. The behavior of PUs during the period of transmission is studied in order to determine the spectrum occupancy status. The activity of PUs is simulated in the form of random variables due to the occurrence of uncertain behaviors. Issues such as channel noise and fading effects interrupt spectrum sensing, thereby making spectrum holes appear busy. The CR network is modelled in Matlab software such that both PUs and SUs can sense the spectrum through the Energy Detection Method and share the spectrum effectively by employing the approach to estimate waiting time, which highlights behaviors and activity matrices. Candidates have to share the spectrum, thereafter which transmission delay and throughput are examined for the instances where underlay and interweave spectrum sharing techniques are in use. A time-estimator algorithm is used to reduce the computing budget and latency in order to obtain a trade-off between throughput and transmission delay.

Keywords: Wireless Communication**,** Spectrum Sensing, Spectrum Sharing, Power Spectrum Density, Behavior Matrix.

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LIST OF ABBREVIATIONS

PU	: Primary User
SU	: Secondary User
ADC	: Analog to Digital Converter
AWGN	: Additive White Gaussian Noise
CDF	: Cumulative Distribution Function
CR	: Cognitive Radio
DAA	: Detect and Avoid
DFT	: Discrete Fourier Transform
DVB-T	: Digital Video Broadcasting – Terrestrial
ECC	: European Community Commission
FCC	: Federal Communications Commission
FFT	: Fast Fourier Transform
GPS	: Global Positioning System
I.I.D.	: Independent, Identically distributed

IFFT : Inverse Fast Fourier Transform

MB : Multi Band

MC : Multi Carrier

MF : Matched Filter

MI : Mutual Information

MIMO : Multiple-Input Multiple-Output

MRC : Maximal Ratio Combiner

MMSE : Minimum Mean-Square Error

OFDM : Orthogonal Frequency Division Multiplexing

P.D.F. : Probability Distribution Function

PAM : Pulse Amplitude Modulation

PSD : Power Spectral Density

PSK : Phase Shift Keying

QAM : Quadrature Amplitude Modulation

QPSK : Quadrature Phase Shift Keying

R.V. : Random Variable

R.V : Random Vector

SNR : Signal-to-Noise Ratio

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1. INTRODUCTION

Like any other fortune, radio spectrum is presenting higher demand as today life tends to depend widely on communications to facilitate most life activities. Efficient spectrum utilization has become challenge for communication professionals. Cognitive radio (CR) is employed to ensure best utility of spectrum, it works in dynamic fashion to use spectrum with no interference. The electromagnetic spectrum consists of the range of frequencies from 3 kHz to 300 GHz. International Telecommunication Union (ITU) regulates the usage of this spectrum and organizes efforts to avoid interference between different players utilizing the wireless spectrum. Furthermore, local authorities in each country may have their regulations as well [1]. ITU sets around fifty services of communication channels as given in [2], sometimes, radio channels are leased to service providers such as mobile operator so that particular frequency will be used by those bodies only and last may be called as primary (or " licensed") users (PUs) Similarly, TV bands and broadcasting bands are also allotted to the working bands and called secondary (or " unlicensed") users (SUs). So, spectrum used by cellular applications may be called as cellular spectrum and the one used for television broadcasting is known as television band or spectrum.

Recently, radio spectrum is suffering of congestion as users are increasingly demanding radio resources [3].Techniques such as, frequency pooling, spectrum reuse, spread spectrum, and CR are on table for addressing the challenges of spectrum congestion.

In general, two main players are introduced. PU which is defined by ITU as such user that allotted to fixed band and can transmit freely within that band without interrupting of other bands transmission. The licensed band is the range of radio spectrum allotted to PUs. On the other hand, SU is new candidate of spectrum which not originally belongs to licensed band and willing to share the spectrum with PUs. CR is the technique in which allow such agreement of spectrum so that both users can transmit without harmful effects on each other.

1.1 PROBLEM FORMULATION

Depending on the results of surveys conducted to understand how spectrum bands are being utilized in last ten years, we can conclude that the spectrum utilized by PUs and such users are only twenty percent of the total available spectrum. The rest portion of spectrum is occupied by those users also and being used for some time instant and vacant for most of the time.

SUs are available and intended to utilize these spectrum holes, the challenges arisen when both PUs and SUs are willing to use the spectrum at the same time. Interference is considered as first drawback resulted from this simultaneous access. CR is proposed to ensure both PUs and SUs to transmit using the same band. PUs are utilizing the licensed band randomly and it is very challenging for SU to adopt with such environments.

1.2 RESEARCH OBJECTIVES

In order to study of cognitive radio (CR) network, we are going to cover the following tasks:

- To examine spectrum response to the random and uncontrolled behaviors of licensed candidates.
- To evaluate the vacant band by sensing the spectrum periodically for all simulation slots.
- To examine how the SUs will adapt at PUs' mobility.
- To develop waiting time estimator and provide the information to SU entities (towards interference minimization environments).
- To develop spectrum sensing approach that independent on channel disturbances irrespective to level of corruption in the channel.
- To study spectrum sharing approach and obtain delay and throughput information.

1.3 PROPOSED WORK

Problem statement may reveal about major challenges about assigning SUs to licensed band, such challenges may be simply when SU begins transmission and when it terminates the transmission. Asking this question implies that SU may receive time of transmission information from PU. In this thesis, we propose a method in which we can predict the behavior of PU during of particular period of time. Method consists of finding out the PU behavior in terms of band utilization. This information can be directed thereafter to spectrum sharing paradigms; in here we examined the transmission delay of SUs when underlay and interweave spectrum sharing techniques are proposed. Throughput in both techniques is tested as well, however, the findings were alike. SUs can develop queues so that each user may wait to get into band. For fixed interference level, most of SUs can participate the licensed band so that throughput in this case will be high. Otherwise, interweave technique is usable for applications demanding reasonable throughput and small delay. The same results are proved in here more likely, transmission delay is minimized with lesser throughput in case of interweave technique. Applications similar to live broadcasting may be fit with interweave technique as it is ensuring minimum possible transmission delay. Offline application can be suited with underlay technique especially those demanding higher throughput.

1.4 THESIS ORGANIZATION

This thesis is organized as shown in Figure 1.1. Chapter 1 summarizes the problem statement that motivated us to establish this research and objectives which we aimed to achieve during the incoming steps of research; proposed work is given in this chapter also. Chapter 2 in which we lists the similar problem statement and opinions of other researcher to overcome the same. Chapter 3 covers the methods which used in this research from building the CR paradigm until result achievement. Chapter 4 reviews the practical model and ways to demonstrate thesis findings. Finally, Chapter 5, we conclude our research and present the future directions.

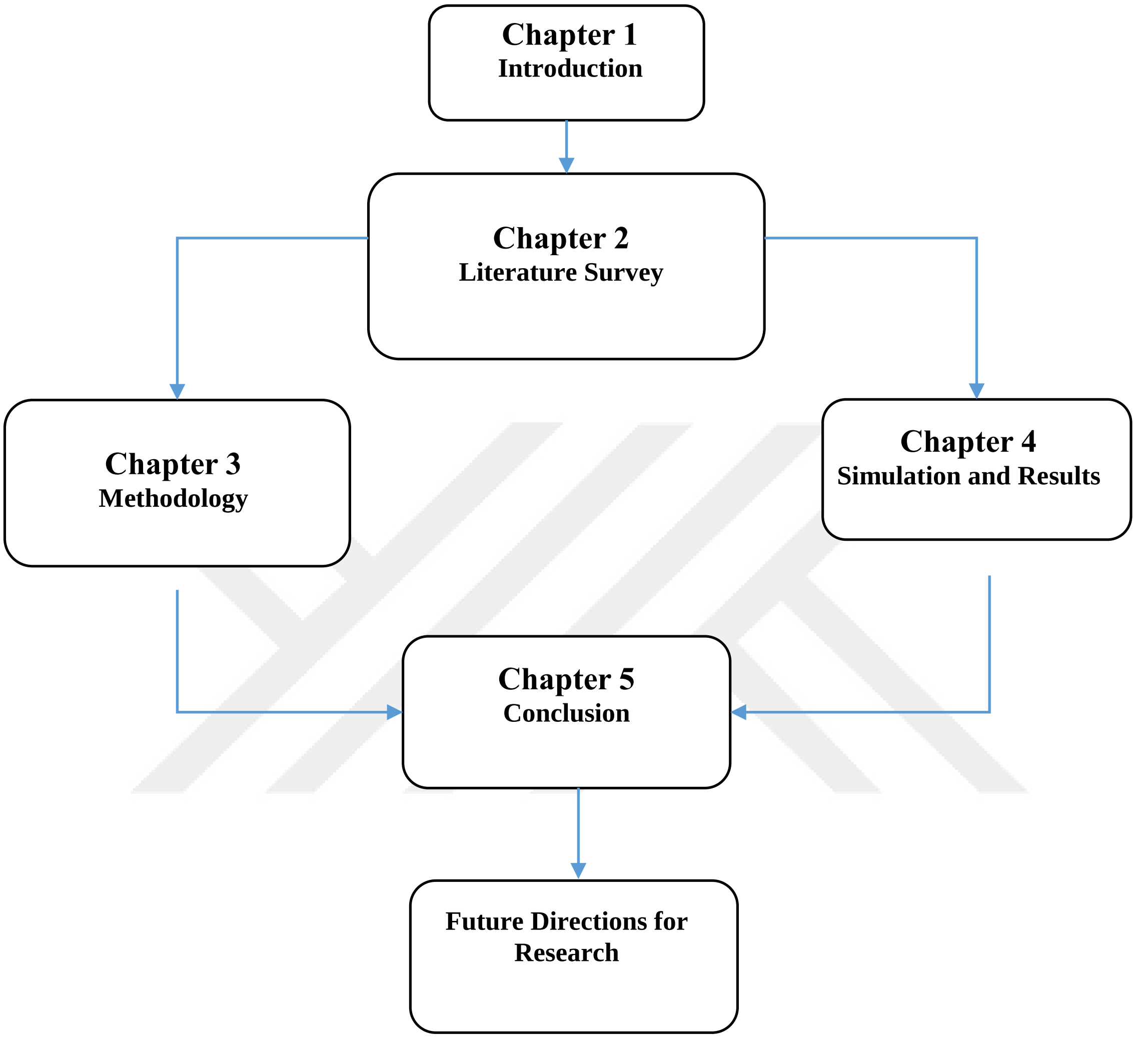


Figure 1.1: Thesis Organzation

2. LITERATURE REVIEW

2.1 TECHNOLOGY TIMELINE

Dynamic spectrum access is using cognitive radio (CR) as an enabling technology that deals with scarcity issue. Since radio spectrum is important resource in wireless systems, spectrum sensing approach needs to be treated with care as said by [4]. The concept of CR is forming what is so-called cognitive network that permits dynamic spectrum allocation instead of old static allocation of spectrum bands. Cognitive network involves intelligent infrastructures which are capable of sensing the surrounding environments and discovering the holes in the spectrum band dynamically. Moreover, CR is adaptable to real world conditions which make system parameters to be changed with spectrum fluctuation and radio status.

Author at [5] mentions that spectrum assignment of new wireless networks are considered as fixed policy of spectrum allocation since the limited spectrum resources are inefficiently utilized. So, new paradigm for spectrum management seems to be necessary for wisely utilizing the radio spectrum. CR approach is defined as a method in which either receiver or transmitter end users update their parameters in order to create the optimized spectrum usage. In other words, both PUs and SUs can transmit with minimal interference level if they sense and adopt each other in such way that SU detects the optimum suitable bands in spectrum and begins the communication over the same bands. Same author has proposed that SU can sense the available spectrum and transmits in the suitable band. Author stated that simulation gives satisfactory results in terms of spectrum allocation performance.

In [6], unlicensed bands are preferable by most organizations for testing their new technologies in terms of performance and its worthiness while they are deploying the same in remote and rural locations. World is in process of removing barriers from technology in order to deliver advantage to maximum possible number of beneficiaries, said by author. In order to make CR widespread, large number of research organizations and communities need to collaborate on the development of CR. However, signal processing, communication coding, radio frequency specialists, networking specialists, hardware designers, and software designers need to work side by side to establish fully cognitive network, such network is never an easy task to build.

Furthermore, system player’s behaviours need to be studied for ensuring perfect spectrum sharing and management in CR network within the frame of regulations made by geographical region spectrum organizations.

Followed: Future information technology applications will face serious challenges due to increasing need for data and therefore spectrum congestion problem will become a serious issue [7]. Since all slots of spectrum are allotted to various applications, studies shown that spectrum (white bands) is not a fully occupied in time by licensed users. CR concept is formed for justice spectrum distribution among variety of users. Author of [7] discriminates the wireless communications as a system consisting of cognitive channels and non-cognitive channels. If the transceiver detects a free channel (unutilized channels) then it is named as cognitive channel; otherwise, the term non-cognitive channel is used for the busy band. The available bands of the white spectrum can be utilized for other user‘s transmission in such way that minimal interference is guaranteed. Since the cognitive network is surrounded by variable conditioning environments, network should be self-upgradable. Dynamic spectrum access models are important to mitigate the scarcity of spectrum, and different techniques of spectrum management have reviewed in [7]. The recommended way as stated here is to let network to learn from the environment and scan the spectrum periodically for accurate channel assignment.

In [8], author discussed IEEE 802.22 standard of CR which will be used as 5th generation of wireless communication technology. Author states that both PUs and SUs are carried by CR network where no user can have harmful impact on others transmission such as interference. Three spectrum sensing techniques are widely used in CR research. This research involves a comparison survey among energy detector. The matching filter spectrum sensing techniques results are also compared with features based detection cycle-stationary technique. Results from this survey had revealed that each technique is attributed by its own benefits and drawbacks. PU status information is inquired to gain best detection in matching filter; in other word, the detection will be independent of SNR value. With energy detection method, no status information is necessary but signal to noise ratio is needed. Features detection has performed a better performance if PU information is provided.

In [9], it is mentioned that the density of traffic in radio spectrum is considerably increased after the massive technological revolution. Number of technology users has been increased and therefore, noticeable shortage in spectrum is expected. CR as mentioned by all studies offers a good opportunity to utilize the spectrum more efficiently. In this study, author called the holes in spectrum as those vacant rooms which is not occupied for a quick time instant by their resident user (licensed user). However, the detection of such holes is compulsory to begin the procedure in CR network; this followed by refilling the detected bands/holes of spectrum with another user who is not licensed to use such band under normal circumstances. The spectrum sensing method performance is considered as key performance criteria in CR network, in other words, CR performance can be judged based on sensing method. Different sensing methods are available in the literature. However, cognitive operations in CR network cannot be guaranteed by single sensing method as stated in [9], and therefore each method performance can be attributed by its capability to meet CR functions. In other words, CR network must be able to choose among the available sensing schemes depending on best performance prediction. This research is also involved in performance comparison of different sensing techniques after analysing each method individually. No method from the available spectrum sensing techniques is meeting the required detection parameters level more likely. The best achievable detection of PU in the spectrum bands as reported by this author, furthermore, spectrum sensing method is directly affecting the performance and quality of service (QoS) in CR network and effects is dependent on which method of sensing was in use. Performance in CR can be enhanced by enabling the last to accommodate various spectrum sensing methods, in this research two parameters are used to assist the sensing method: 1- Level that PU is protected from interference transmission and, 2- Demanded quality of service. Author stated that real time test may refer to choose among available sensing methods.

In [10], transmission quality can be improved by sensing the surrounding environments and upgrading the transmission parameters (usually the transceiver settings upgrading) of cognitive network. We noticed that physical layer needs to be established in such a way that it should be flexible with various spectrum requirements by using spread spectrum technique. Two methods of spread spectrum were tested: 1- Dynamic sequence spread spectrum and 2- Frequency hopping spread spectrum. Model was established in Matlab in order to compare the performance of legacy methods and that reveals frequency hopping spread spectrum is delivering better performance.

Three parameters were used in this comparison are; time delay of packet dropping, throughput and arrival time.

In [11], efforts paid to enhance the detection probability upon spectrum sensing, as other researchers, author here cleared that spectrum sensing in key performance to assist CR network. Covariance matrix with minimal eigenvalue is used in this research with semi-blind method for statistics calculations. Author said, no prior knowledge is needed in their proposed method to obtain eigenvalue, to detect the energy. Optimum results over other sensing techniques are obtained while digital TV signal is used.

In [12], CR network components such as sensing unit, haring unit, management, and mobility unit are discussed. This study has made important note about, why spectrum sensing is most important task in CR network. Good sensing method will impact CR quality of service (QoS) as mentioned by author. Particle swarm, genetic and colony algorithms have been used to compare results of spectrum sensing in here. Author said that Flower Pollination Algorithm (FPA) provides the best result among others.

In [13], it is noted that seventy percent of available white spectrum is not effectively used as per Federal Communication Commission (FCC). So secondary and primary users can share the spectrum in order to utilize this portion (that is achievable by cognitive radio network as declared earlier). In this article, secondary user (SU) has defined by FCC as unlicensed user and primary user (PU) is declared as licensed user. Different spectrum sharing techniques are discussed in this research where primary user permits some of its bands for the SU and SU may use the bands without degrading the PU performance.

Spectrum sharing techniques of underlay and overlay are examined in [14]. A new technique of both concepts combination has proved potential use in CR network. Hybrid method of spectrum sharing is merging both underlay and overlay principles so interference temperature and matching filter approached were recalled. IEEE 802.22 standard is CR concept that used by TV broadcasting which utilized here to implement practical model and examine of mentioned spectrum sharing varieties.

In [15] spectrum scarcity is practically solvable through CR, since spectrum sensing is essential part of cognitive network; this study involved a comparative approach of three sensing techniques: cycle-stationary, energy detection, and matching filter. The performance of every method ranked based on time, technique complexity and whether information need to be acquired about primary user's behaviours prior to performing the spectrum operations or not. Study found that each technique is attributed by its own advantages so each can play important role for different requirements.

Spectrum scarcity can be handled with dynamic recourse allocation in wireless system [16]. This remains the effective approach to challenge the spectrum congestion while users are increased. Authors define the performance of spectrum allocation in CR as how effectively the CR can detect the voids in spectrum space. Sensing of voids in spectrum plays critical role since SUs can relocate with minimum transmission errors. Noise is major constraint in wireless channel since we know the prediction can be made about noise level during transmission period. Author meant that noise level can be increased at any time of transmission where vacant voids can be seen busy in practical practice. So, power spectrum analysis of the channel may not always reveal the truth about PU availability. In this study, noise uncertainty was proved over traditional spectrum sensing algorithms and the need of another method that supports such situation is recommended.

Minimization of interference is another very important objective [17]. SU needs to be allowed to sense licensed spectrum periodically to find suitable voids which may tend to enhance the performance. Authors have reviewed the traditional methods of spectrum access and reached a decision that opportunistic spectrum access is achievable by CR as effective approach to achieve real time spectrum sensing. However, spectrum access by SU may degrade the transmission of nearby Pus. The article has taken three parameters to judge the access of spectrum which is the distance between PU and SU, the mobility of PU and number of SUs. Fuzzy logic is used here to establish robust access control of white spectrum, . The article clearly pointed out that CR approach is yet to be deployed and network design of next generation of wireless communication (fifth generation) will be dependent on CR standard in such a way that users from different network can be share unified frequencies. Coexistence of different users in one band can only achieved by CR network since it is the best possible solution for spectrum sharing.

This article is concerned about the cost factor in regular communication systems comparably with CR based wireless systems [18]. Licensed bands are limited for some applications and are not widely available for new applications, the article recommends using CR network since it is far less expensive approach than purchasing new spectrum. Further, the article has described the structure of cognitive cycle and applications utilized the CR network.

Spectrum handoff concept in CR network that used to perform dynamic spectrum access and efficient utilization of spectrum is discussed in [19]. CR is defined here as intelligent radio access technique that supports spectrum sensing, mobility and management. In order to make the network self-adaptable to the spectrum, network needs to learn the spectrum behaviours while it is occupied by PUs and SUs. The article is focused on addressing the spectrum status for different actions of PUs by employing fuzzy logic approach to predict channel condition. Now, spectrum mobility needs of proper handoff strategy to permit user of selecting the ideal band of spectrum in CR network. This study has implemented what so-called prediction of spectrum holes to be done prior to any spectrum sensing; therefor, fuzzy logic to be established to perform learning mechanism of fluctuation in radio environments. This practice will provide a scope of channel conditions; such information will help the cognitive network to decide which channel is suitable for each SU.

CR spectrum scarcity can be resolved in [20]. SUs are occupying the white band side by side with PUs or when PUs are not willing to transmit. However, proper and accurate spectrum sensing is essential to detect the band availability for secondary candidates for opportunistically utilizing the spectrum considering that no harmful effects on primary candidates by cognitive arrival. Interference avoidance is a crucial task of cognitive network; however. SU must avert transmission in the same primary user’s frequencies for amelioration of spectrum utilizing. The article presents a comparative approach aiming to highlight the strength of spectrum sensing techniques after applying the real life transmit conditions of CR. Practically, sensing accuracy is limited by several factors that affect directly the communication channel and these will be fading and shadowing effect that are caused due to signal reflection from surrounding object. Such obstacles are degrading the spectrum so sensing process may interrupt and then inappropriate decision may rise. Referenced article has summarized the spectrum sensing techniques in spatial conditions and encountered with the listed constrains.

In this article, spectrum scarcity has resulted naturally due to earlier plan of radio bands which were made fix (fixed spectrum allocation) and fully distributed among the working applications of that time, as a results organizations that looking after spectrum planning that alike federal communications commission (FCC) are facing spectrum congestion issues [21].

In [22], transmission opportunities to be decided with help of spectrum sensing intelligent that been provide the useful information to the transmitter about spectrum main player. When spectrum voids are detected properly, successful transmission from SUs may definitely will yielded unless channel disturbances are existing. The article involves the use of Boolean-Poisson hierarchy to estimate the real geometrical properties for cognitive radio spectrum sensing. So, by considering the region geometry, article reveals that symmetry in area design is critical for CR transmission i.e. circular symmetry will lead to communication interrupting in CR network. With bidirectional transmission link, SUs may freely transmit in only allowable region geometry; the study ends with that spectrum sensing is not only the major point to be considered while initiation of CR system.

2.2 SUMMARY

This section compares the recent approaches on cognitive radio (CR). First of all, cognitive radio (CR) is established to stand against spectrum scarcity which caused by Fixed Spectrum Allocation (FSA). FSA means that spectrum is segregated among some applications at early stage of spectrum management which lead to spectrum congestion after technology wide spreading [21]. CR is defined by IEEE 802.22 developed by IEEE to serve as backbone of wireless regional area network (WRAN) that is used for digital televisions broadcast. Furthermore, CR is used between base station and premises equipment attached device where the latter is searching the channel availability and preparing the header information which will be attached to super sensing frame header and propagate back to the base station which in turn take the necessary steps to relocate the user. CR has hugh potential to play an essential role in 5G communication systems which are targeting to provide fast and reliable technology with very high data rates as given in [18] where radio resources will be reused and idle channels will be reallocated [17]. Searching more in literature of CR technology may reveal other facts of operation challenges of this protocol. Spectrum sensing is major concept of CR and must be done accurately to avoid interference meaning that noise and fading within channels are uncertain characters that may degrade the performance of spectrum sensing. Thus, studying the channel behaviors is on demand.

In this thesis, we are intending to use proactive approach that predicts spectrum behavior and at the same time we aim to reduce computational budget of simulation to reach to targeted enhancement which tends to eliminate users interference by achieving accurate spectrum sensing and performing exact handoff. Furthermore, the proposed approach may minimize the risks of user mobility and channels of transient state.

3. METHODOLOGY

3.1 OVERVIEW

This chapter presents the key technologies of cognitive radio (CR) network by first reviewing the standard of Wireless Regional Area Network (WRAN) used as backbone of television broadcast. It developed by IEEE and was released in 2011. Two main components form the WRAN network: 1- Base station and 2- Premises equipment sweeping the channels to catch vacant bands and reporting the information back to base station by updating the headers of in-band frames. CR network is yet developed for high data rate applications and limited from small regional areas with low user's population. Technology is planned to form the future communication network of 5G onward which is supposed to provide high and low data rate services. However, establishing CR model requires collaboration of various communities; so digital signal processing (DSP) topologies are reviewed here to provide tools for deriving spectrum analysis in frequency domain. Later, spectrum sensing and spectrum sharing methods are analyzed.

3.2 IEEE 802.22

Wireless Regional Area Network (WRAN) is developed by IEEE 802.22 standard that supports digital television broadcasting. This protocol is established to serve small geographical regions and limited number of users that's why it is subjected as regional. CR first network is conducted with this protocol which applied network ability to reuse white spectrum in small geographical areas with minimum interference between network candidates. The technology of CR that was stated in details on chapter II is referred to wireless regional area networks that guarantee the spectrum sharing between licensed and unlicensed users with no harmful returns to licensed users; however, this standard supports small power applications like wireless microphone and TV broadcasting (analogue and digital television), this standard had published by IEEE on late 2011. IEEE 802.22.1 and IEEE 802.22 Working Group (WG) is consecutive standards developed for averting the interference of low power applications and to enhance the previous standard so that some applications of wireless local area networks (WLAN) are also involved to participate this technology. For first instant, IEEE 802.22 begins with point to multiple point communication (P2MP) that applied on digital television network that formed by installing premises attached equipment (PAE) with is connected directly to network base station (Base Station Subsystem BSS) by means of wires. The BSS is responsible to form the network traffic and initiate spectrum management. WRAN based digital television broadcasting with CR capabilities is working by make PAE to gather the information about channel status (which is so-called as spectrum sensing); with help of signalling capability, gathered information is directed to the base station sub system (BSS) which has the decision-making capabilities for channel allocations and user mobility. It is important to notice here that user assignment to new hole is cauterized and done by base station. However, user needs to be within network coverage in order to participate this facility. Users can only sense the channel and forward information to the higher layer Figure 3.1 depicts the architecture of WRAN network.

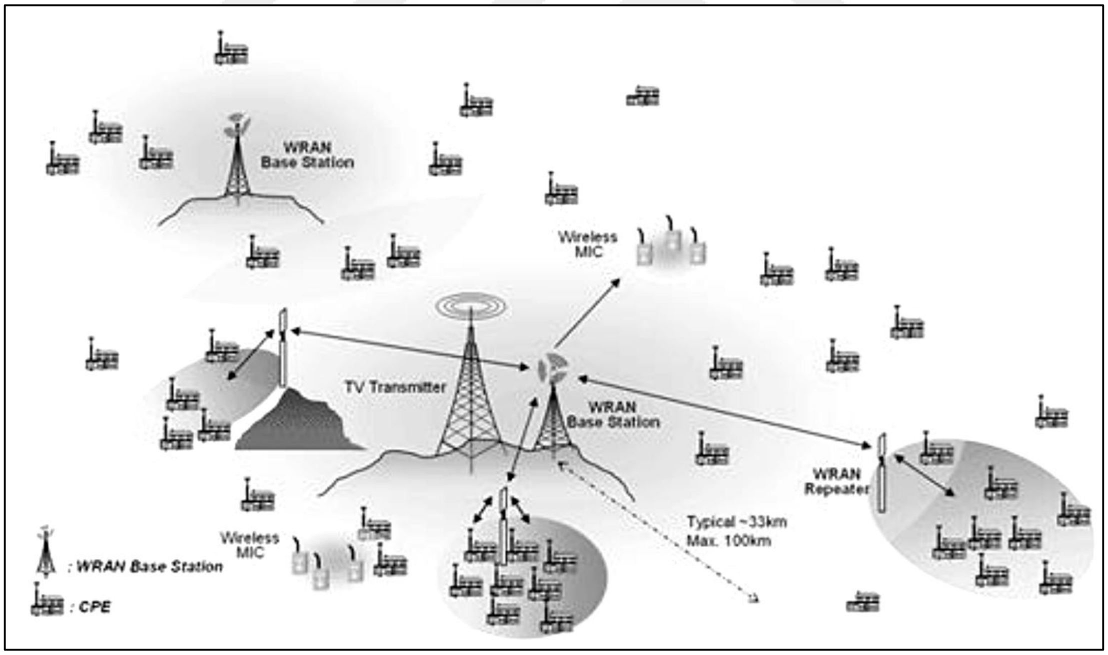


Figure 3.1: Wireless Regional Area Network Panning, Depicted As Base Station Tower Is Serving Multiple Nodes (PAE) [26].

3.2.1 IEEE 802.22 Physical Layer

Its last layer in the protocol stack which looks after physical medium interfaces, this layer need to adapt physical medium uncertainty like user mobility. So, it needs to be flexible with such episodes. However, modulation and coding schemes are conductible in this layer where signal is prepared prior of deploying it to physical channel. Studies noted that bandwidth is small for single channel and multiple channels are required to establish transmission with high data rate. Two links need to be established normally for such type of communication especially when base station and multiple users are presented, downlink which take care of transmitting data from base station to subscribers and uplink to transmit the data from subscriber (Premises Attached Equipment) to base station, Figure 3.2 depicts the links established between base station and user's entity.

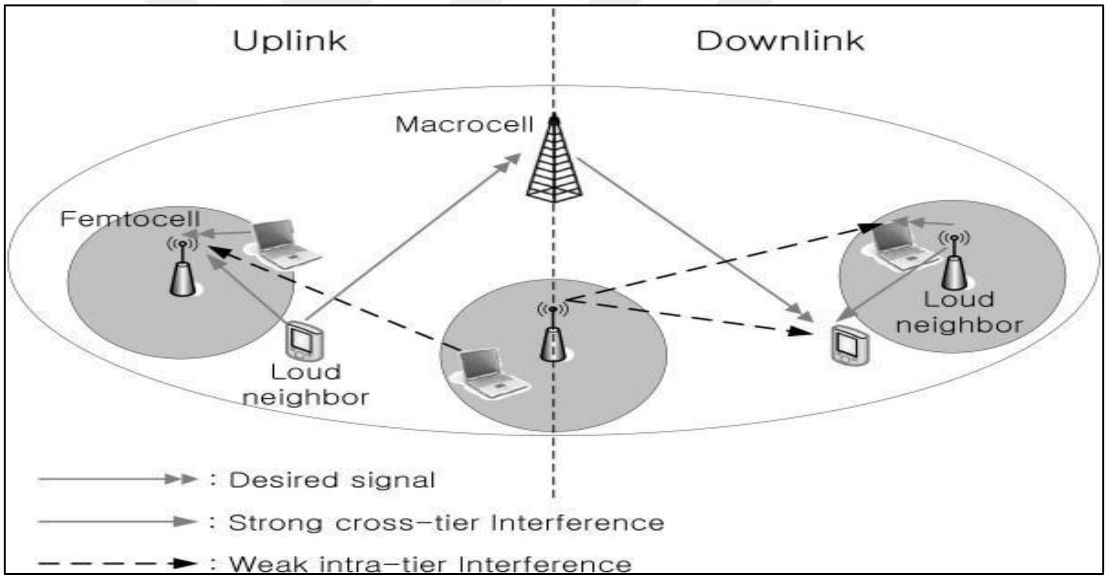


Figure 3.2: Depicts The Links Established between Base Station and User's Entity, Downlink and Uplink Are Shown [25].

3.2.2 IEEE 802.22 Medium Access Layer

Cognitive radio (CR) facility is integrated in this layer to play the role of spectrum access and sharing management. This layer has adaptive nature to handle with dynamically changing spectrum conditions. Two different frames are formed in this layer: frames and super-frames. The latter is created by sub-station and is forwarded to the suitable channel where interference level is within tolerance. In turn, the PAE may receive this super-frame as channel permits and declares availability. PAE may add sensing information to the header of this super-frame and transmit it back to the server (base station) which starts the required steps to update channel availability list.

Base station and user equipment are doing two types of spectrum management which used to identify the channel status. In band channel sensing to be done through selected single channel and used to provide information about that particular channel; form the other hand. Out-band sensing is performed by user equipment for all channels. In medium access layer, channel is sensed with two different methods: fast sensing which lasts for one mile second and fine sensing that takes longer time around 26 mile seconds and relies on fast sensing information. Both sensing techniques work to validate the fact that no collision will occur in any particular channel and they used in protocol stack to avoid the interference.

3.3 FREQUENCY MODULATION

Cognitive radio (CR) network protocol stack performs modulation and coding of information prior to sending in through the channel. In our approach, we let unlimited PUs to participate the predefined channel, each user data needed to be carried along the channel by higher frequency carrier signal, frequency modulation concept was used to multiplex number of user into one transmitted signal. Actually, this signal is group of subscribers who are willing to share spectrum bands. However, encoding all members of different frequencies into one signal is called as frequency modulation. If sinusoidal carrier can be transmitted as follow:

Let the transmitted single to be:

$$y(t) = \mathrm{A}\sin(2\pi\, f\, t) \tag{3.1}$$

$$y(t) = A\sin(2\pi\, f\, \sum_{ts=0}^{\frac{1}{fs}} t) \tag{3.2}$$

$$y(t) = \sum_{1}^{n} yn(t) \tag{3.3}$$

$$ts = \frac{1}{fs} \quad , \qquad t = 0:1*e^{-4}:ts \quad ,t = 0:1*e^{-4}:\frac{1}{fs}$$

$$y(t) = \sum_{1}^{n} A\sin(2\,\pi\, f * \sum_{ts=0}^{\frac{1}{fs}} t) \tag{3.4}$$

Where, Y (t) is referred to the transmitted signal after encoding all frequency subscribers, ‘f’ is carrier frequency of subscriber and‘t’ is time or signal length or sampling time. Frequency modulation involves two technologies; indirect modulation to be done by crystal oscillator and frequency multiplayer. Furthermore, direct modulation is done by using voltage control oscillator. Figure 3.3 demonstrates signals of frequency modulation and their differences from another modulation techniques.

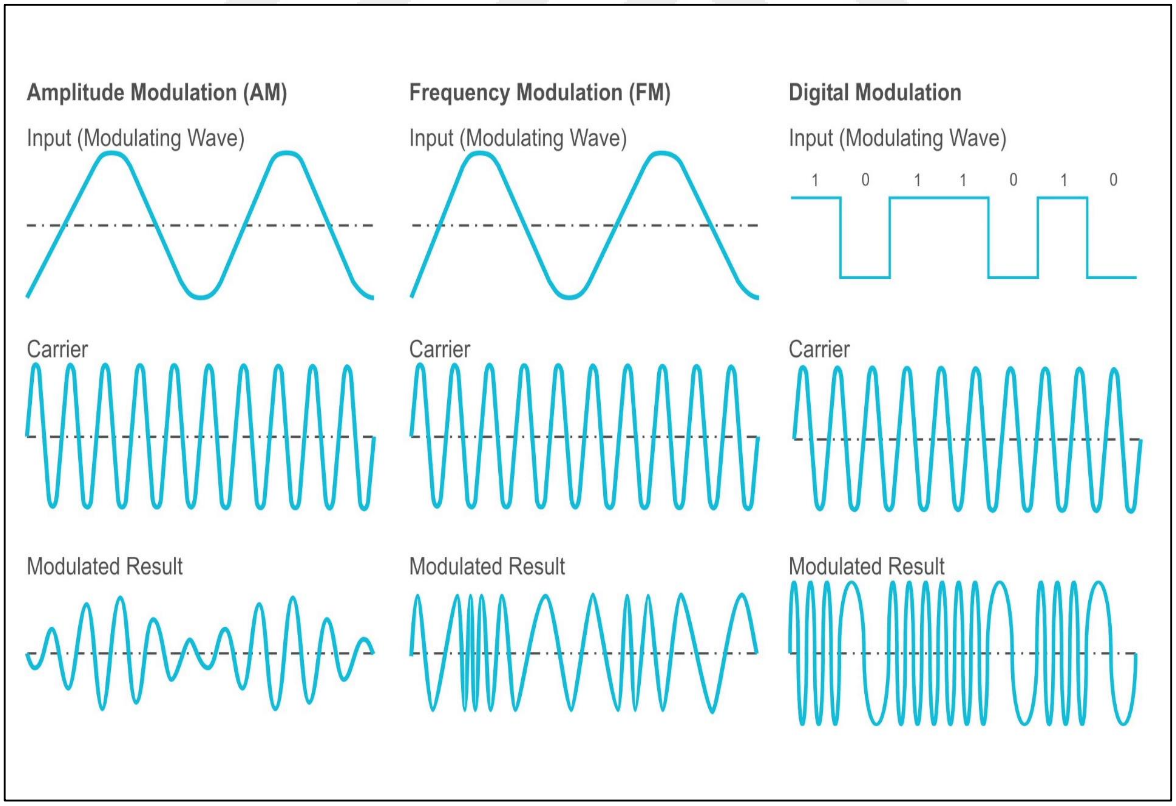


Figure 3.3: Signals of Frequency Modulation and Their Differences from the Other Modulation Techniques [24].

3.4 FREQUENCY DIVISION MULTIPLEXING

Frequency-Division Multiplexing (FDM) is the process of slotting the available spectrum into pieces of non-overlapping channels in the communication medium carrying independent signals. This technique enables taking advantage of single medium (cable, fiber optic, or wireless medium) and have many signals sharing this medium. Another possible scenario is dividing a high rate bit stream into segments transmitted in parallel.

Many examples of FDM are simply TV and Radio broadcasting, both have many signals of the same technology passing simultaneously in the air without interfering with each other. Telephone systems do use FDM in combining the voice calls of many users to be carried in high capacity trunk lines. Satellites are another example of communication systems that use FDM which channels for downlink and uplink transmit data, another is the broadband DSL modems which has high capacity of data transmission through twisted pair telephone lines. Other many uses are there

Wavelength Division Multiplexing (WDM) is the twin technique of FDM since it basically means the same but it’s more convenient in visible light communication to talk in terms of wavelength than frequency.

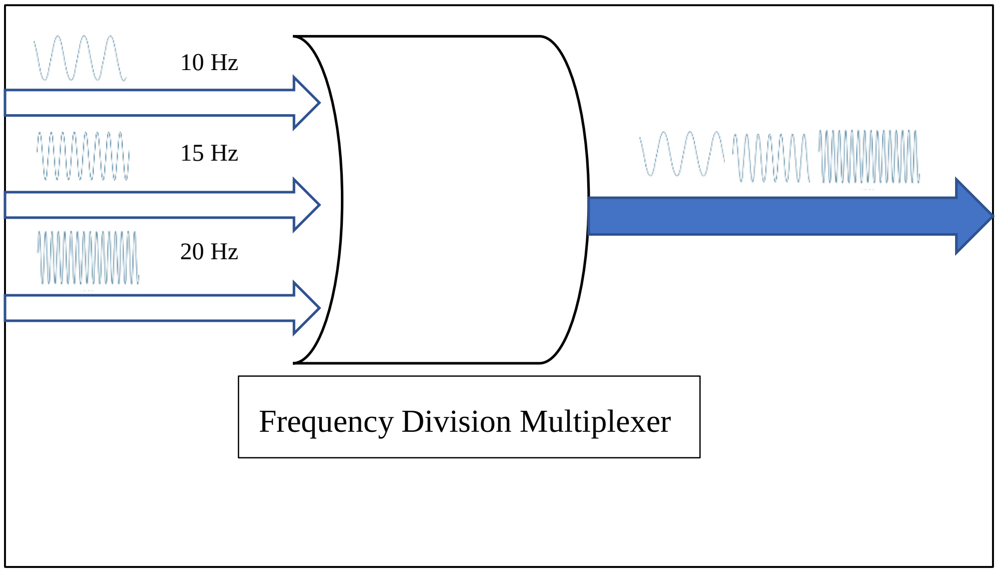


Figure 3.4: Frequency Division Multiplexing Procedure to Be Applied On Transmission Station

3.5 SPECTRUM ANALYSES

Spatial domain is used to describe the signals transmitted between the users to base station; forming the signal of multiple frequency participants may need to perform frequency analysis to understand nature of such signals. Signal processing approach is used widely during this process. So signals of time domain are sampled with suitable sampling rate ‘Fs’ and studied in frequency domain.

3.5.1 Discrete Time Analysis

Using of sampling approach for continues time signals may convert those signals into discrete time by reproducing of signal amplitudes for different time instants. Practically, signal can be sampled (converted into discrete time domain) by passing the signals through operation amplifier or (on-off) switch with known sampling time; Figure 3.5 gives the visual comparison of sampled single with continuous signal. The logical interpretation of sampling process can be understood form the figure 3.4 where the electronic or logical device is start operating with help of clock signal in which being feed into that device and accordingly all the operations (logic) will be produced; hence, sampler may be train of rectangular wave to be multiplied with continues time signal and resulting a discrete time signal of multiple sample. Each sample will have a bandwidth of fs/n where n is the total number of samples and fs is the sampler bandwidth.

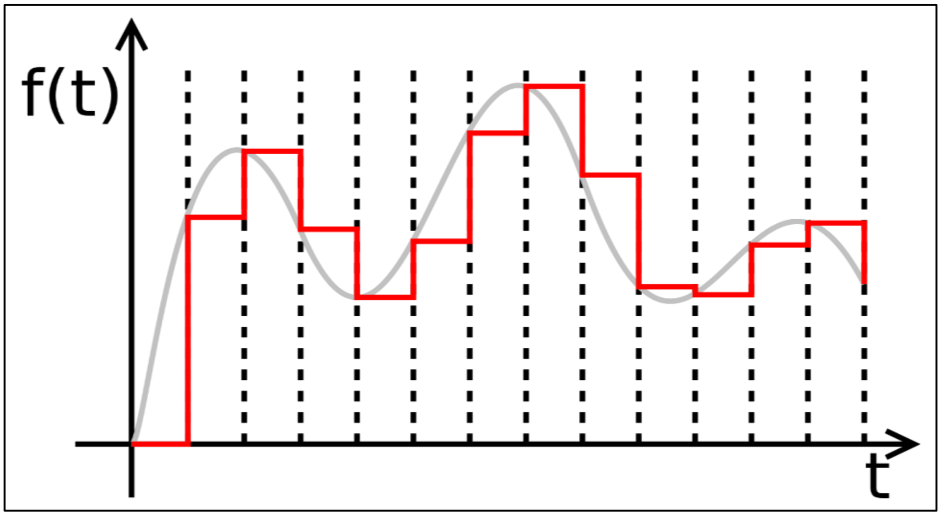


Figure 3.5: Visual Comparison of Sampled Single with Continuous Signal [23].

3.5.2 Fourier Analysis

After samples are obtained from continues time signals, the discrete time components may be useful to test the response of discrete system. Stability, linearity and causality of the system can be studied by monitoring the system response of discrete input. However, Fourier transform is another approach to determine the spectrum response of the system where all frequency components can be studied. Let’s see the mathematical derivation of Fourier transform.

$$Y[w] = \sum_{n=-\infty}^{+\infty} y[n].e^{-jwnt} \tag{3.5}$$

The equation is termed to discrete time Fourier transform where the y[n] is sampled sequence. Figure 3.6 depicts the discrete Fourier transform for sensorial signal.

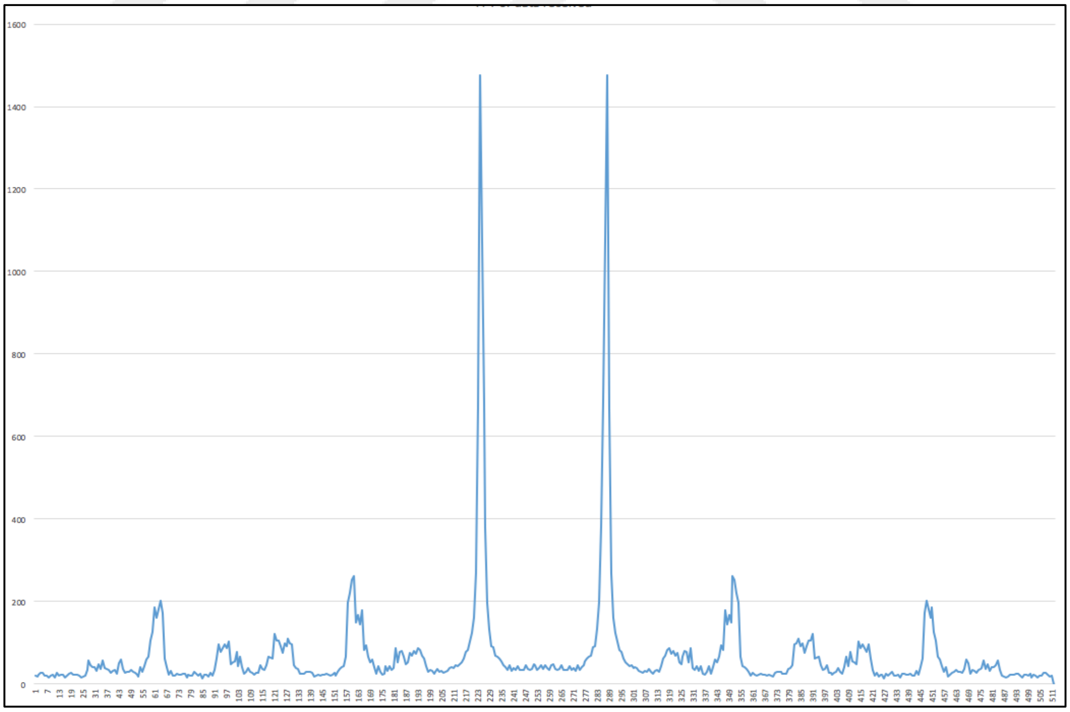


Figure 3 6: Discrete Fourier Transform For Sensorial Signal [26].

3.6 SPECTRUM SENSING

As defined earlier, cognitive radio (CR) network aims to share the spectrum between primary and secondary users where PU is not getting any harmful impact in return. However, previous studies revealed that spectrum sensing is essential operation in cognitive cycle. SUs need to sense the spectrum periodically to confirm the vacancy. Radio spectrum is divided into smaller bands which are used by different applications, and those applications are known as licenced users who are permitted to access those bands at any time and transmit freely but need to avert any harmful interference. Since CR network is assigning the same spectrum bands to SUs at the time PU is idle, CR network always needs to know about channel conditions to assign SU for vacant bands only and avoid interference with PUs. Sensing of spectrum is the process which is responsible for providing the channel information to the higher layer of CR stack. Channel status may be full with PUs or may be vacant, in other words, channel is practically experiencing noise such as Additive White Gaussian Noise (AWGN) and fading effects. Channel undesired participants can be listed as:

1. Noise components alike AWGN;
2. Fading effects alike Rayleigh fading;
3. Shadowing, due to signal reflection by objects surrounding the transceiver;
4. Doppler effects, due to unit mobility.

Such disturbances may degrade the channel performance at the time of occurrence. Spectrum sensing may result whether PU is present or is vacant so that following hypothesis are satisfied:

H0: procedure may yield this outcome if channel is vacant so noise components are presented only.

$$H0 = n(t) \tag{3.6}$$

Otherwise, H1 hypothesis may be yielded which states that channel is experiencing a demand by PU, so hypothesis may return noise component plus signal detection as follow:

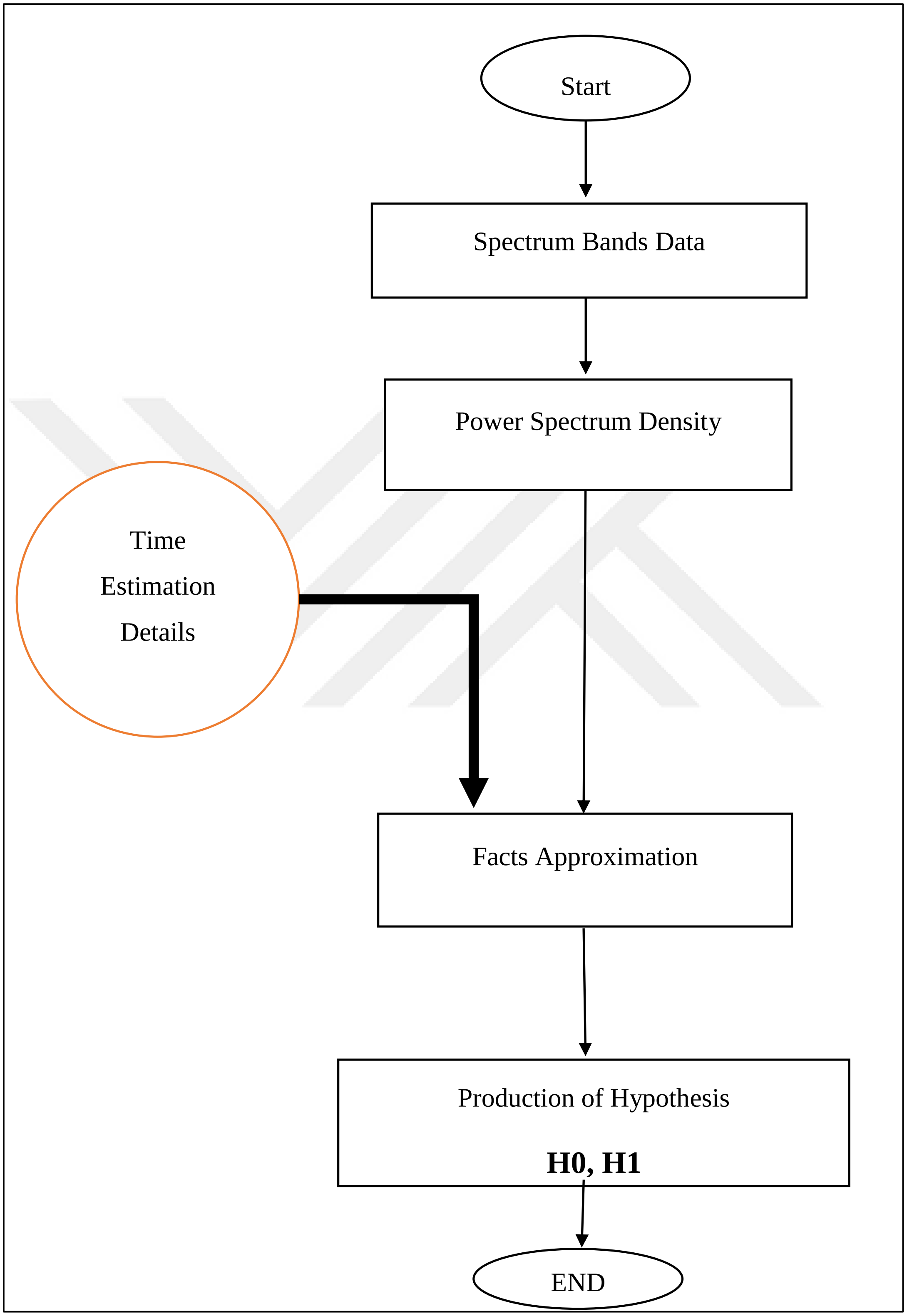


Figure 3.7: Spectrum Sensing Prototype Used In CR Network To Obtain PU Hypothesis Test.

$$H1 = n(t) + S(t) \tag{3.7}$$

Where n (t) is representing noise component and s (t) is representing signal from PU which declared that PU is existed in that particular radio band. Such information is necessary to avoid interference between primary and secondary user.

The available approach to investigate the radio spectrum is energy detector which makes use of power spectrum density (PSD) of the channel which gives all frequency components. Results of PSD can be forwarded to decision maker circuit that validates whether the channel is vacant. Only noise components are appeared so results will more likely become as H0, otherwise, H1 may be yielded. The outcomes of this paradigm can be expressed mathematically as: $H[n]$ is the impulse response of system and $X[n]$ is the input sequence which is the channel information, hereafter, and convolution can be applied to get the decision as follow:

$$Hx[l] = \sum_{l=-\infty}^{l=+\infty} X[l].H[n-l] \tag{3.8}$$

Spectrum sensing is done according to above hypothesis test to validate primary user (PU) availability in the spectrum.

3.7 SPECTRUM SHARING

In modern times, performance of licensed bands is scattered due to large spectrum demand. Furthermore, licensed users dominate the spectrum bands even though during idle stage where no transmission is reported across the band. Nonetheless, new technologies are keeping produced in domain of wireless communications which requires more spectrum vacancy in order to be functional. As emphasized by [4]–[6] cognitive radio (CR) may satisfy that demand by dispensing the need of new spectrum leasing.

A promising spectrum sharing technology is Cognitive Radio (CR) which is a solution to provide spectrum that used to be inaccessible by the high growth of wireless devices causing spectrum depletion. CR allows users to be two different systems to use the same spectrum, users of these systems are referred to Primary Users (PU) and Secondary Users (SU) based on spectrum access priority. Three operation schemes of CR are possible: Interweave, underlay, and overlay. In Interweave scheme the SU utilizes the PUs spectrum when the latter is idle, on the contrary, Underlay and Overlay schemes utilizes the spectrum for both PU and SU to coexist. In overlay, the PU gets compensated for the SU interference by utilizing some of the SUs power to assist the PU in transmission. As the name Underlay infers, the SU in this scheme must keep its power under a certain level to not disturb the PU. Other techniques can be used alongside CR to even further utilize the spectrum, such as Full Duplex (FD) and cooperative communication networks. FD allows the communication node to send and receive at the same time, and it has recently attracted attention since advancement in self-interference cancellation is being achieved toward practical realization, it's greatly promising. It is used in Underlay to compensate coverage-increasing cooperative systems' loss of spectral efficiency. Furthermore, FD in its concept would allow the SU to do both data transmission/reception and spectrum sensing concurrently. Sharing the spectrum with in-band FD-PU is avoided in CR research because of the increased interference limitation at PU side that would degrade the operation of Underlay. Therefore, it became of great need to further investigate communication systems that would improve the SU performance while minimizing interference on PU

To share the spectrum between primary and secondary users with fairly, two technologies may be used in this thesis: underlay spectrum sharing and interweave spectrum sharing techniques. In the first technique, both users can transmit simultaneously using the available spectrum bands but SU needs to maintain the tolerance level for interference. Within underlay technique, SU may draw a moderated throughput in which users participating the band are maximized under transmission agreement which states that only permissible bandwidth can be shared with SUs which means users to come first is served first and remaining users may maintain queues, so underlay technique has bigger time delay.

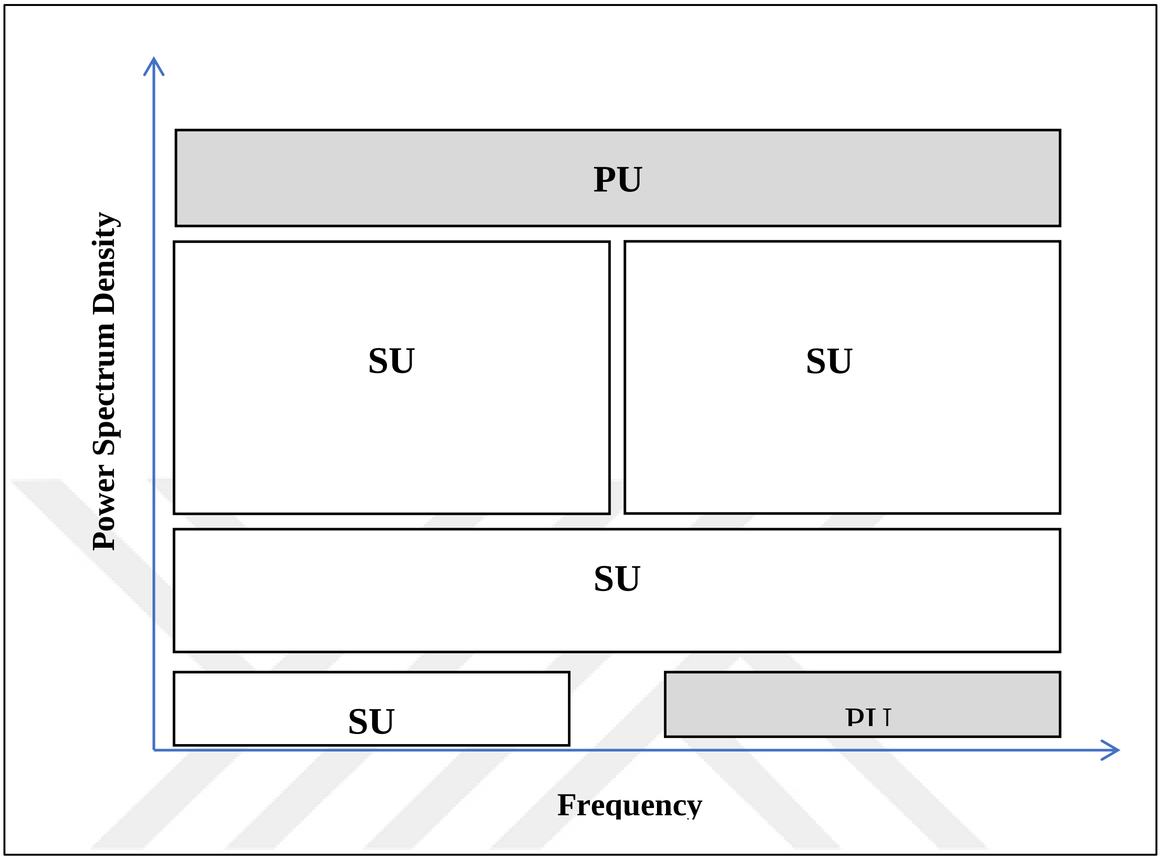


Figure 3.8: Underlay Spectrum Sharing Technique As Appeared In Power Spectra, Figure Demonstrate the Frequency Slots Of Secondary Users That Is Sharing The Same Band

Such procedure is reversed in case of interweave sharing technique where transmission can be achieved only when PU is not transmitting; the SU hereby start signalling at the vacant bands in the place of absent of PU. This method of transmission agreement may ensure lesser transmission delay as users do not need to stand in queue for transmission opportunity. On the other hand, only few users among secondary group can participate the band so throughput is lesser in here.

Since most of studies that seen during literature survey are keen on spectrum sensing mechanisms and most recommended approach is to train the sensing network for channel variation. In this thesis, we made time estimator paradigm which predicts the PU behaviours during simulation time and sends this information to all CR chain (layers). Network can share the spectrum between the users with no interference by using this proactive approach.

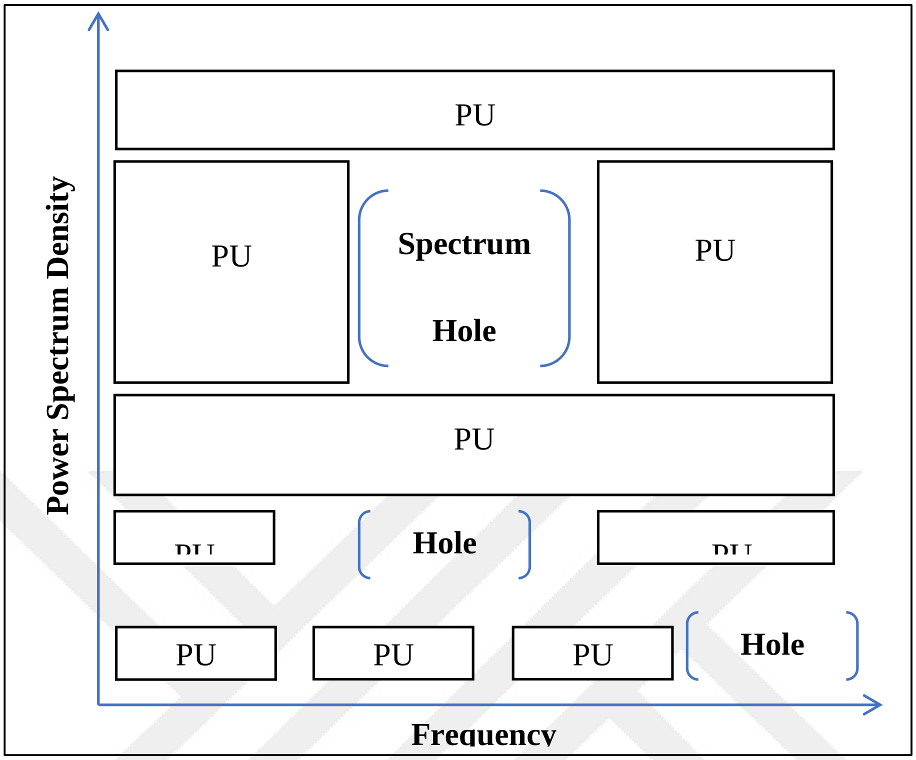


Figure 3.9: Interweave Spectrum Sharing Technique As Appeared In Power Spectra; Figure Demonstrate The Frequency Empty Slots That Intended To Be Assigned For Secondary Users.

3.8 PROTOTYPE STRUCTURE

Cognitive radio (CR) concept implemented in this research to reuse the spectrum bands according to spectrum sharing regulations emphasised by each technique. Figure 3.10 demonstrates the structure of this system; models are implemented in Matlab environment so that simulation may last for multiple of ten seconds where each ten seconds reflects one iteration. However, virtual model may start by preparing the radio environment that used for signals exchanging on hereafter. In order to meet the real life conditions, simulation is made to intake any number of PUs so then system creating a carrier frequency for each candidate of PUs by considering the radio spectrum limits predefined as standalone input of this hierarchy. Task of licenced band allocation is followed by another task to prepare the signal from all frequencies candidates; so then, modulation may attain the transportable format of each candidate (physical layer procedure), multiplexing process as defined previously is in turn responsible to insert all signals formed by each candidate (PU) into the channel (predefined bandwidth) at same time.

The number of SUs is another input which is kept to be defined in simulation; however this number to be more than primary user’s number. Approach of time estimation is in turn providing the necessary information about PU behaviours while it is present on licenced band. Spectrum sensing helped by time estimator information is validating the band occupation so that secondary users can transmit without noticeable interference.

The last stage of this system is to decide how to share the detected spectrum among the available bands. In order to do that, two techniques are used: underlay and interweave spectrum sharing. System may yield the throughput and transmission delay of SUs during each sharing technique.

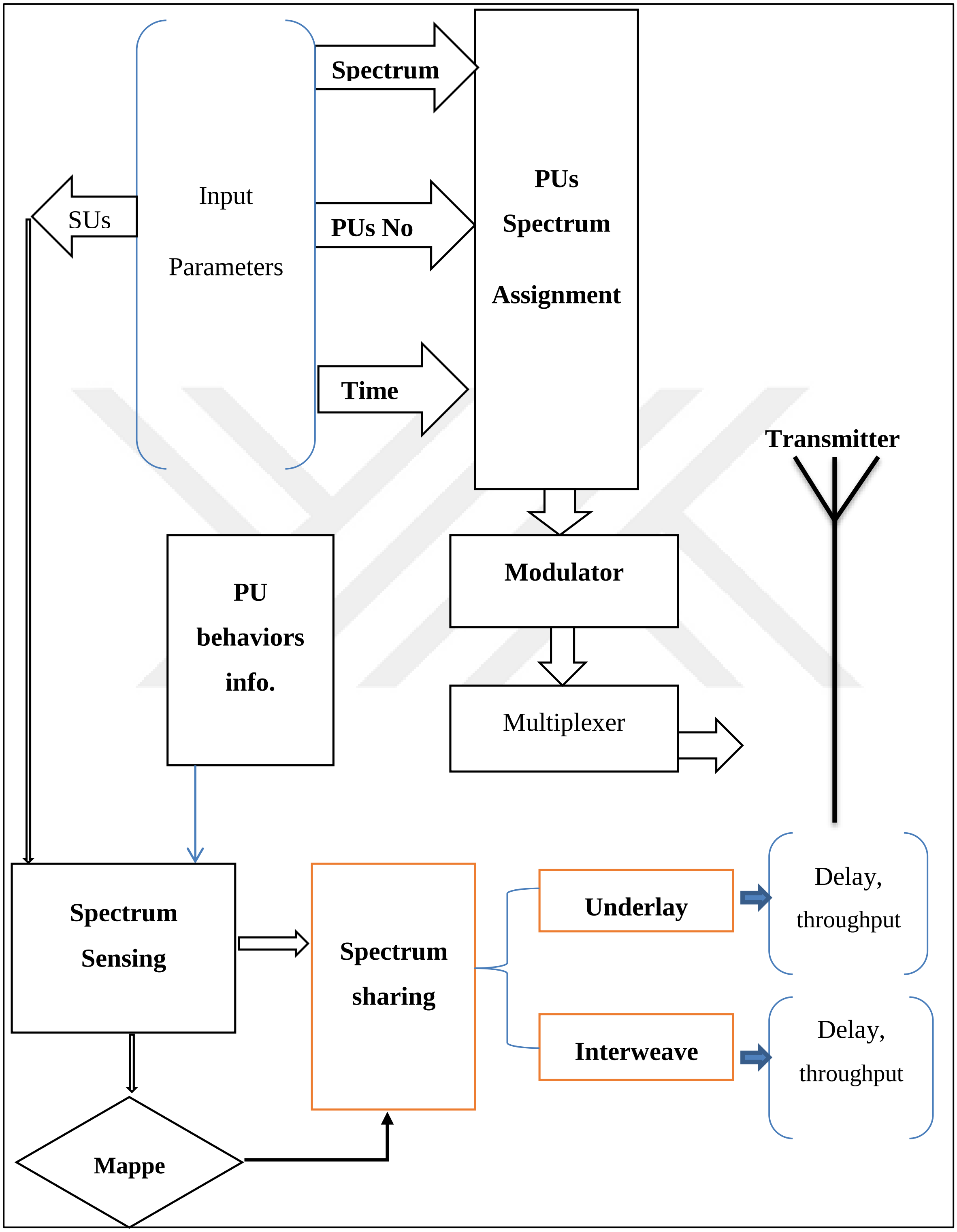


Figure 3.10: The Structure Of Proposed System Denoting The Simulation Steps And Thesis Expectations.

4. SIMULATION AND RESULTS

4.1 OVERVIEW

Virtual modelling is established to meet the design requirements and validate the assumption of cognitive radio (CR) which made to utilize spectrum and dispense the need of new bands creation. Simulation is begun by defining the working frequency (bandwidth) followed by licenced user band allotment. With presence of Additive White Gaussian Noise (AWGN) in the channel, signal with multiple users is transmitted for particular time. Frequency modulation and frequency multiplexing is preceding the transmission process which permits signals of various frequencies over band limited channel. This model is made and examined with help of Matlab; hereafter, all results are monitored and listed to prepare a conclusion.

4.2 SYSTEM MODELING

System is consisting of four functional tools to perform cognitive radio (CR) tasks as following:

4.3 RADIO SPECTRUM MODELING

Three arguments are inquired during this phase: the working bandwidth, required number of licensed users, and simulation time. In here, bandwidth is divided equally among the primary users (PUs) so that following assumption is yielded: (PUBW= total BW/total PUs). Simulation time is considered here to study the random behaviors of PUs of spectrum bands occupancy; hereafter, model may calculate each licensed user frequency and prepare a frequency modulation to transmit all those users into radio medium. At the end of this model, frequencies are made available and public as variables in form of vector to be used in further procedures also, transmitted signal is prepared. For example: 100 Hz bandwidth, 20 primary users and 80 seconds of running time; system supposed to produced F-bands= [5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100].

Sinusoidal signal is assumed as carrier for above frequencies, sampling frequency is assumed as larger 1000 samples per second to produce high resolution signal. For: $s(t) = sin\ (2\pi\ F\ Ts)$, where Ts is the sampling time (1/Fs); For transmission of twenty signals into AWGN channel, multiplexing of frequencies into this channel is required to ensure all signals transmission at one time (same time) . Figure 4.1 is depicting the modulated signal before it being sent through noisy environments.

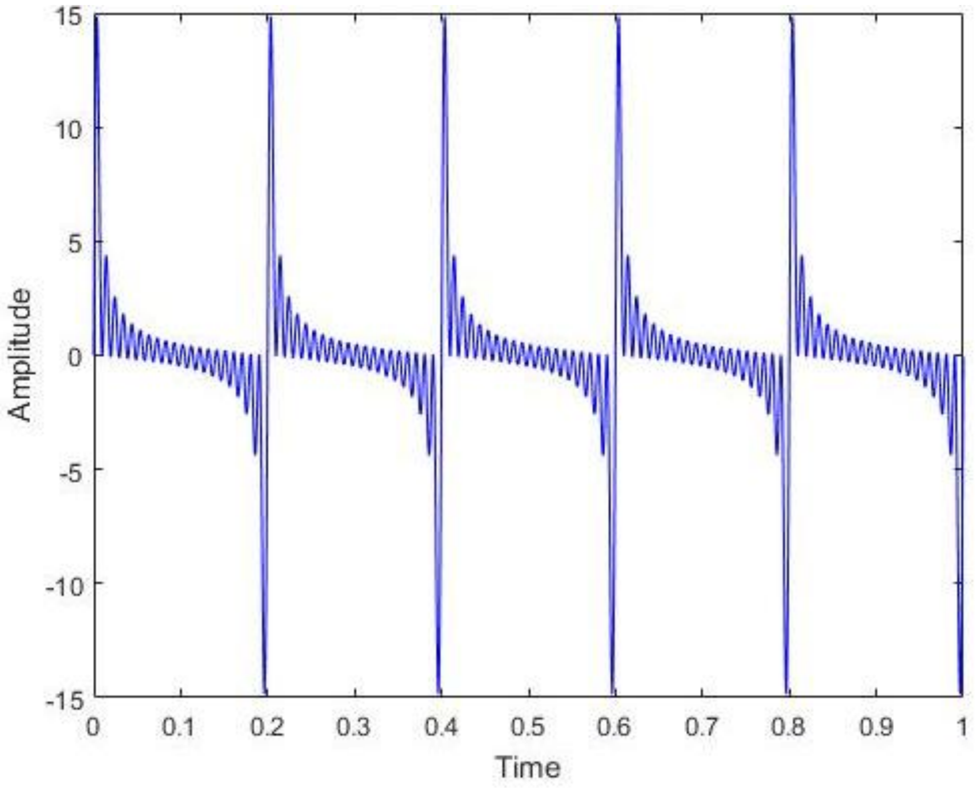


Figure 4.1: Time Domain Signal Referred To Primary User Information Where Noise Factor Is Not Considered.

In above time domain signal, spectrum is monitored and plotted in figure 4.2. In order to understand the frequency domain information, model is instructed to perform Fast Fourier Transformation (FFT). Furthermore, the values in both axis of resultant frequency domain signal are normalized to reveal the same values of transmitted frequencies and amplitudes so that signal's information can be clearly monitored. As depicted in Figure 4.2, x-axis terms to frequencies and y-axis is amplitude correspondence; frequency domain is showing up to 20 scales wherein each defined frequency is plotted. Figure depicted a twenty PUs of 100/20 bandwidth, important to notice that only PUs information is transmitted during this instant and no noise is yet considered. The same is quite cleared in frequency domain. On the other hand, amplitude is set as unity so that similar amplitudes can be seen for all signals. Ultimately, the paradigm is multiplexing of twenty signals into this channel at the same time.

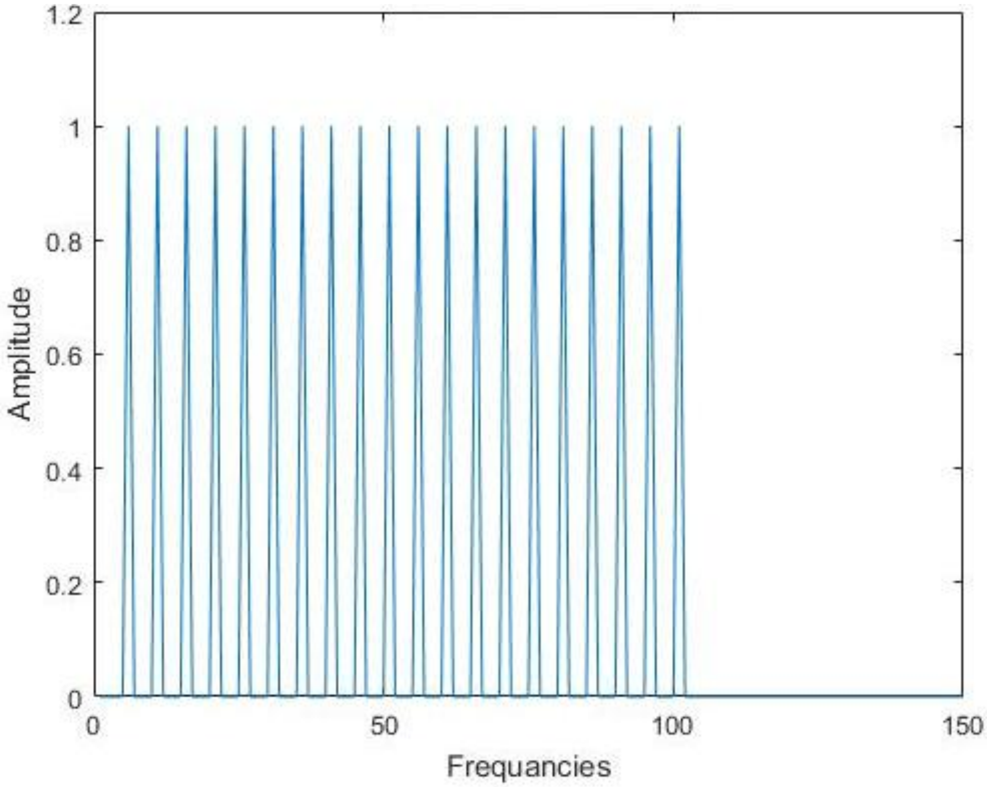


Figure 4.2: Spectrum Analysis For The Transmitted Signal Considering Noise Is Absent.

To perform more precise transmission, signals are always sent with noise, that is, Additive White Gaussian Noise (AWGN) is added to the signal. Signal to Noise Ratio (SNR) is defined with a value of 0.5 db. Ultimately, signal that sent through the noisy environment may look like in Figure 4.3. Similarly, frequency domain signal can be calculated for the new signal which always helpful to monitor the signal components individually while they are in channel as in Figure 4.4. Nonetheless, SNR can be varying however this will not affect the spectrum sensing procedure because system decision is noise independent.

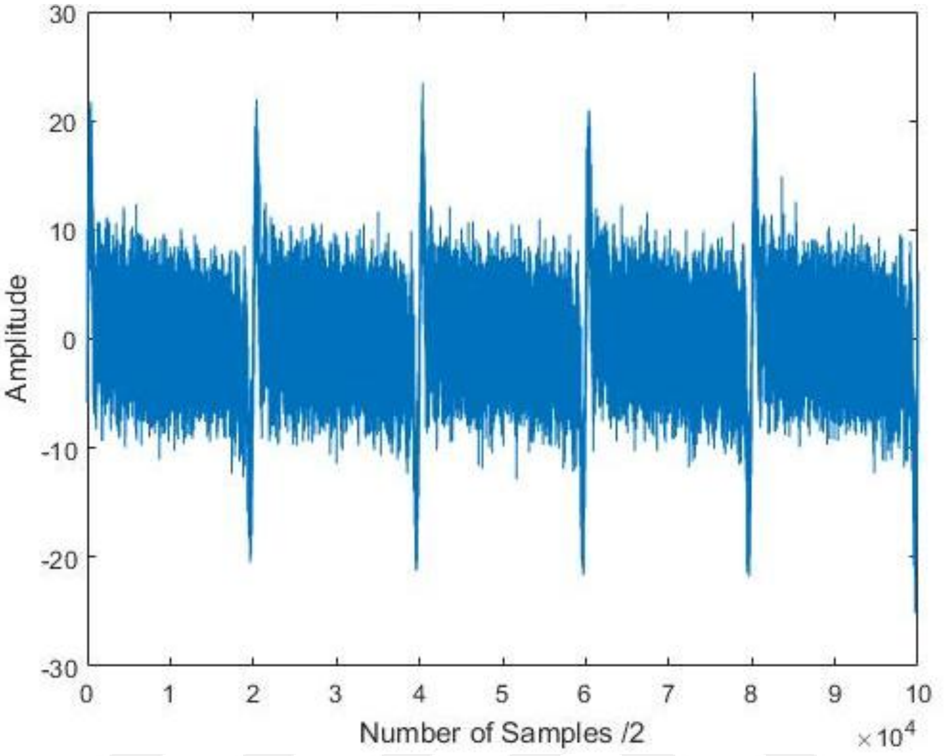


Figure 4 3: AWGN Channel Affecting The Transmitted Signal.

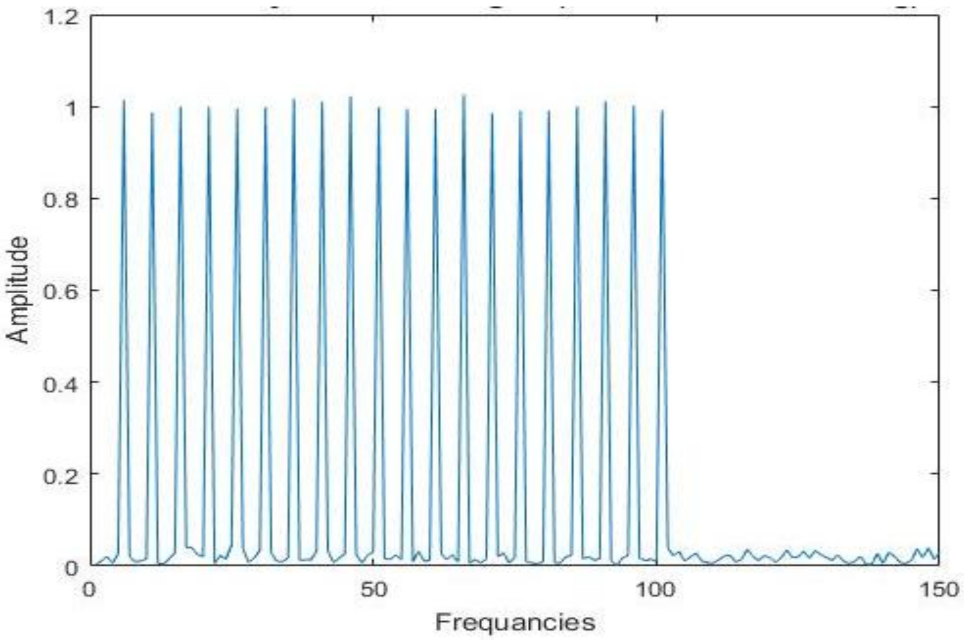
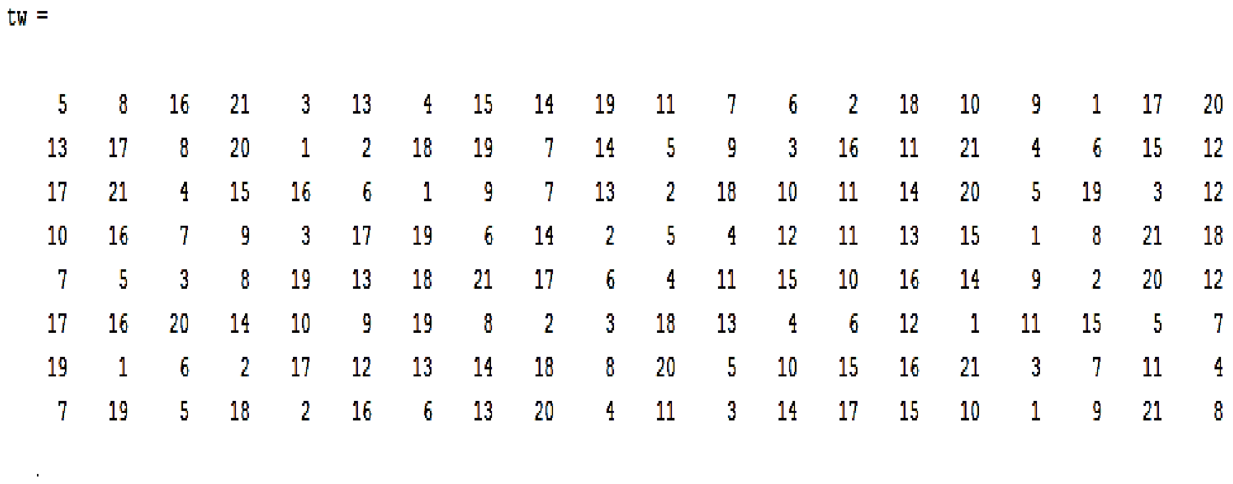


Figure 4 4: Transmitted Signal In Frequency Domain Where Noise Component Are Visible Clearly.

4.3.1 Behaviours Modeling

It is well known that primary users (PUs) are fully occupying the channel at all time even though idle transmission scenario, occupancy is 100% for all time. More real situation, more likely, will be when PU quits the channel at any time and returns to the channel after some time (unknown and un-controller actions). The licenced user is taking over for a time (T_w) and may return to occupy the same channel after T_{w+n} second. Hence, those factors are formulated as uncontrolled random variables. Each PU user can use the licenced band for T_w and exit after completion of that period; ideally, T_w is never identical for any two candidates unless other criteria are inferred. According to the time constrains, this model is instructed to initiate a matrix called as behaviours matrix; it contains of binary information stating the frequency availability for each time slot during the simulation. Figure 4.5 presents the flowchart. Simulation time may divide into n iterations, each lasts 10 seconds. If the simulation lasts for 80 seconds, eight iterations will be made. First stage of this tool is to divide the simulation time depending on the number of users a ten seconds are given if users are up to 10, otherwise if primary users are greater than ten, stop time may become as (total users plus one). Accordingly, behaviours matrix is set corresponding to simulation time and number of intended candidates.



```
tw =

     5     8    16    21     3    13     4    15    14    19    11     7     6     2    18    10     9     1    17    20
    13    17     8    20     1     2    18    19     7    14     5     9     3    16    11    21     4     6    15    12
    17    21     4    15    16     6     1     9     7    13     2    18    10    11    14    20     5    19     3    12
    10    16     7     9     3    17    19     6    14     2     5     4    12    11    13    15     1     8    21    18
     7     5     3     8    19    13    18    21    17     6     4    11    15    10    16    14     9     2    20    12
    17    16    20    14    10     9    19     8     2     3    18    13     4     6    12     1    11    15     5     7
    19     1     6     2    17    12    13    14    18     8    20     5    10    15    16    21     3     7    11     4
     7    19     5    18     2    16     6    13    20     4    11     3    14    17    15    10     1     9    21     8
```

As shown, T_w is waiting time matrix where each row corresponds to iteration number and each element in the column corresponds to time consumed by PU over licenced band. Looking at the values at each column (say first column and all rows/Tw (1, 1)) reveals that primary user (PU1) occupies its band for 5 seconds during the first iteration of simulation time and then leaves the band vacant; hereafter more likely during the next ten seconds of simulation the same user return to use this band for 13 seconds and then quits. It is obvious that, PU is using its band fully during second, third, fourth, sixth, seventh iteration and thus, this leaves no chance to reuse this spectrum band by any cognitive user. This concept is applied for all remaining users.

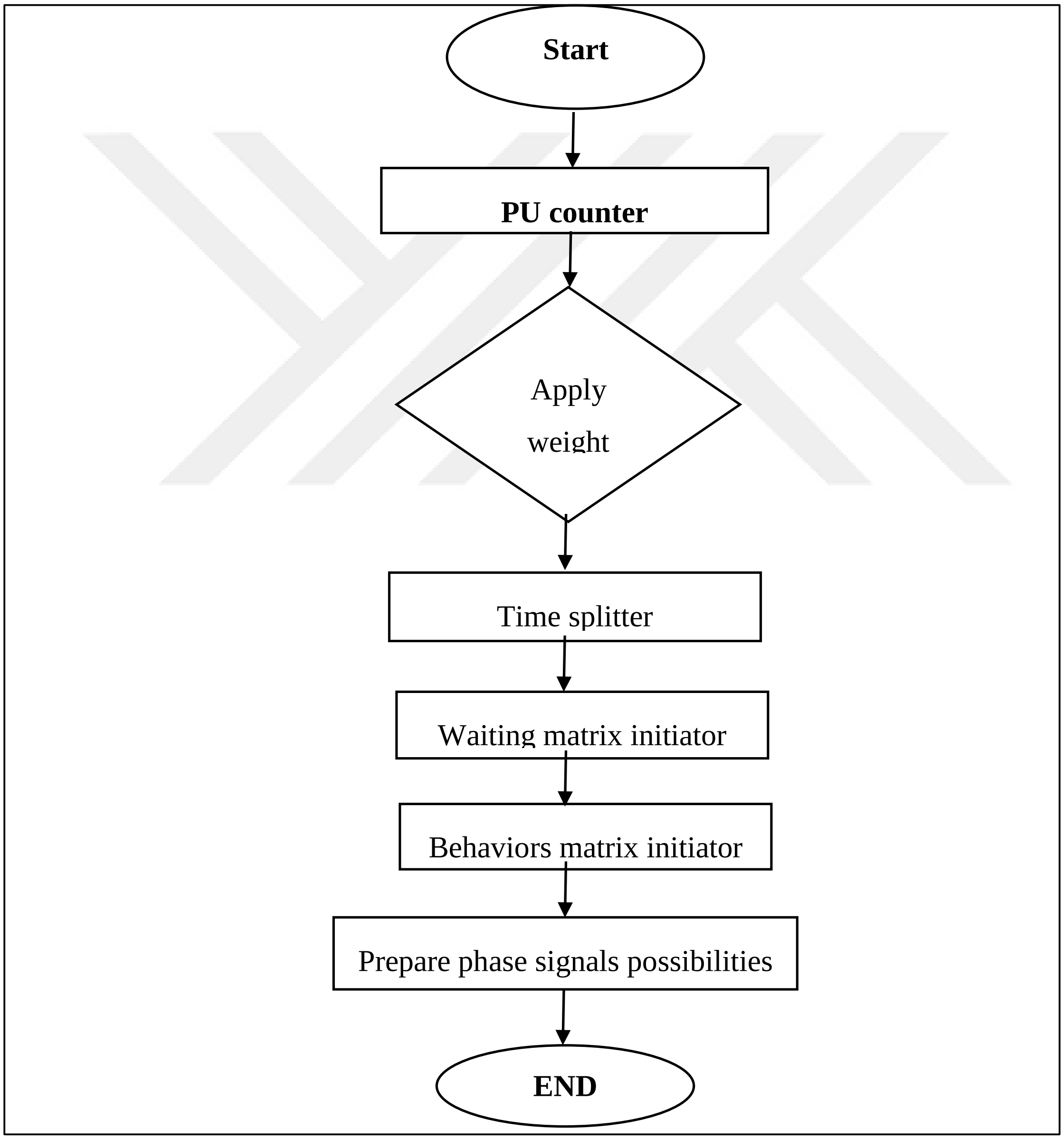
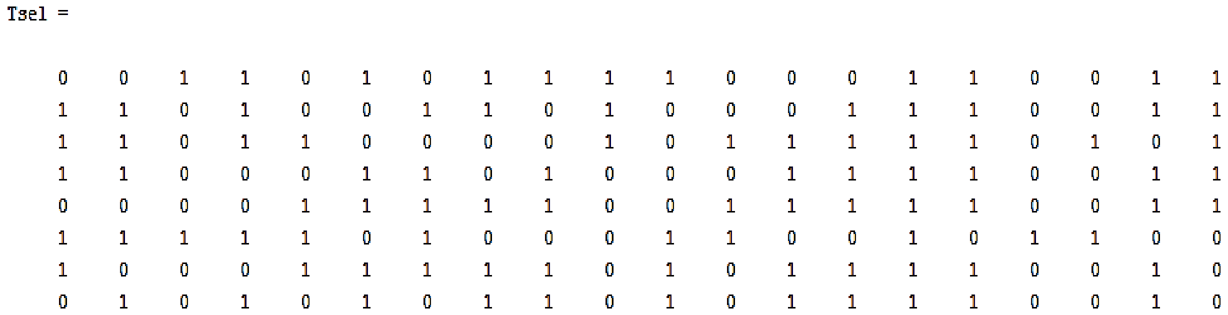


Figure 4.5: Licensed Users Behaviors Modelling

System is ready now to generate behaviors matrix, where the same can be produced by applying a proper weighting to the waiting matrix and then encoding the same with binary indications zeros and ones.



```
Tsel =

     0     0     1     1     0     1     0     1     1     1     1     0     0     0     1     1     0     0     1     1
     1     1     0     1     0     0     1     1     0     1     0     0     0     1     1     1     0     0     1     1
     1     1     0     1     1     0     0     0     0     1     0     1     1     1     1     1     0     1     0     1
     1     1     0     0     0     1     1     0     1     0     0     0     1     1     1     1     0     0     1     1
     0     0     0     0     1     1     1     1     1     0     0     1     1     1     1     1     0     0     1     1
     1     1     1     1     1     0     1     0     0     0     1     1     0     0     1     0     1     1     0     0
     1     0     0     0     1     1     1     1     1     0     1     0     1     1     1     1     0     0     1     0
     0     1     0     1     0     1     0     1     1     0     1     0     1     1     1     1     0     0     1     0
```

The process which generates the behaviors matrix can be graphically shown as in Figure 4.6.

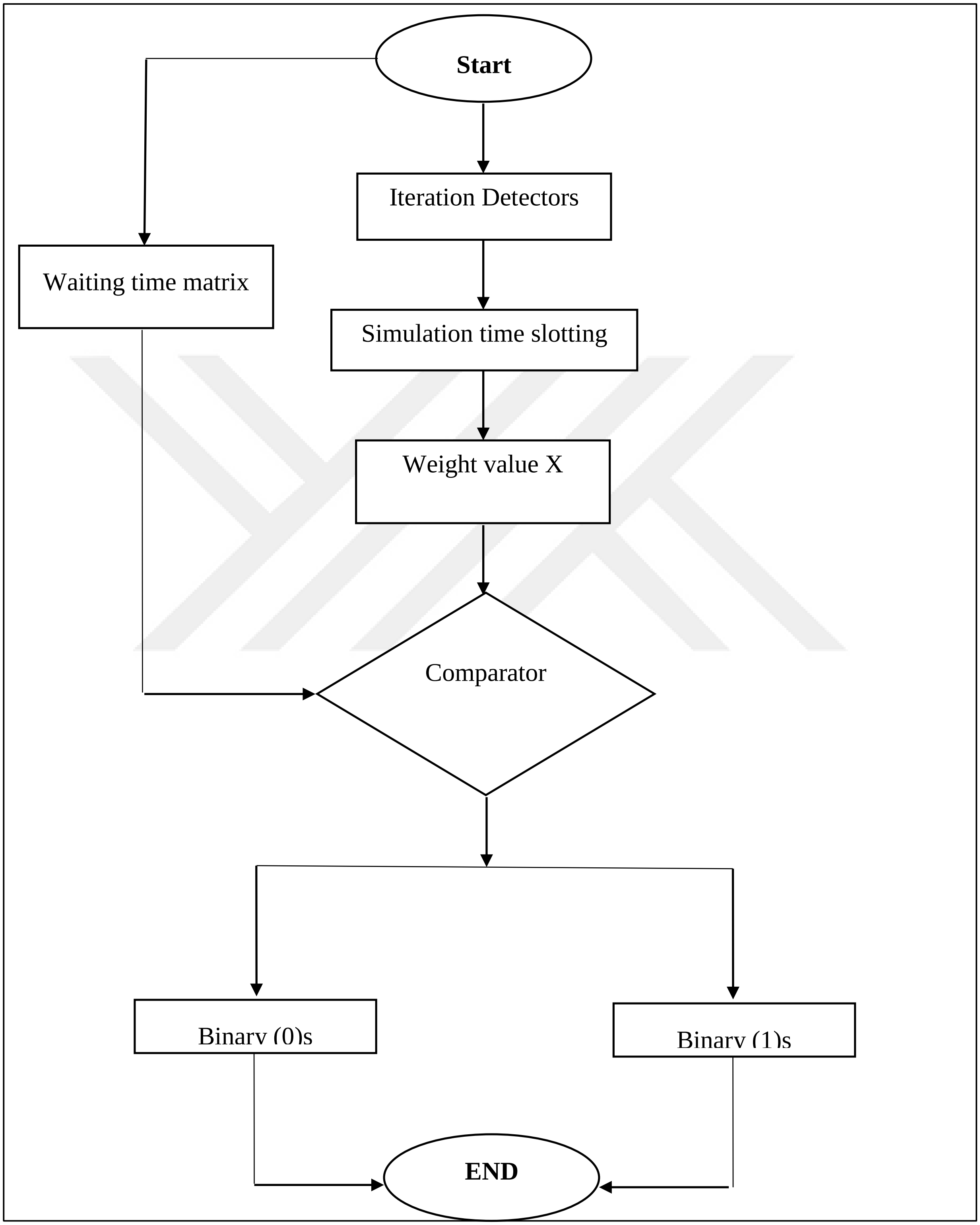


Figure 4.6: Behaviors Matrix Initiation Process.

4.3.2 Secondary Users Modeling

During this approach, number of secondary users (SUs) is inquired (to be manually entered into simulation), we started this phase of research by feeding a double of primary user (PU) numbers (2* PUs) as secondary user (SU) input, however, let’s assume 40 users are willing to share the licenced spectrum. As per Federal Communication Commission (FCC) regulations, the SUs can use a white band if and only if that band is declared vacant. Considering this assumption, we may establish a new matrix corresponds to secondary user’s activity and in accordance with primary user’s behaviour. Practically, the activity matrix is a reversed version of the behaviours matrix as depicted in Figure 4.7. The process to obtain activity matrix directs the behaviours matrix into **NOT** logic gate.

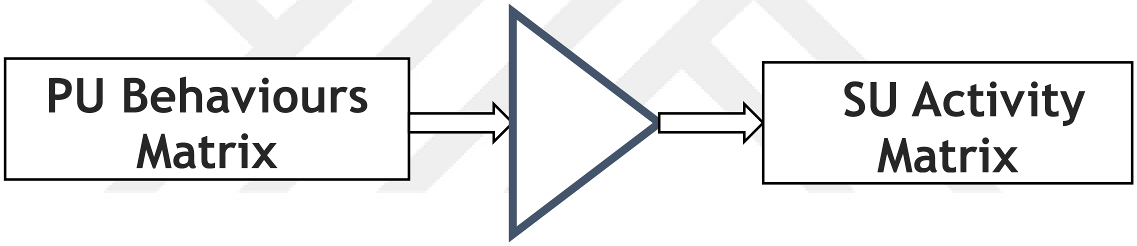
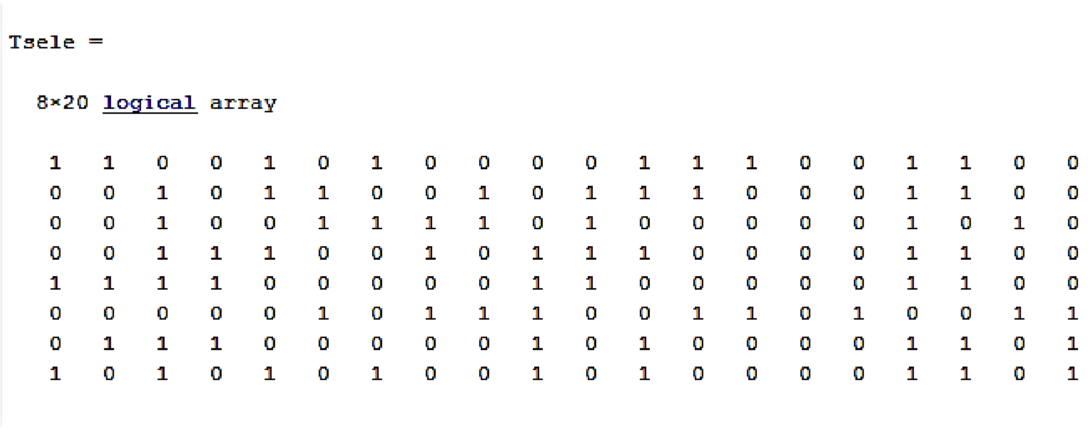


Figure 4.7: Activity Matrix That Refers To Secondary Users Activities On The Licensed Band

According to that we can form the SU activity matrix as below:



```
Tsele =

  8×20 logical array

   1   1   0   0   1   0   1   0   0   0   0   1   1   1   0   0   1   1   0   0
   0   0   1   0   1   1   0   0   1   0   1   1   1   0   0   0   1   1   0   0
   0   0   1   0   0   1   1   1   1   0   1   0   0   0   0   0   1   0   1   0
   0   0   1   1   1   0   0   1   0   1   1   1   0   0   0   0   1   1   0   0
   1   1   1   1   0   0   0   0   0   1   1   0   0   0   0   0   1   1   0   0
   0   0   0   0   0   1   0   1   1   1   0   0   1   1   0   1   0   0   1   1
   0   1   1   1   0   0   0   0   0   1   0   1   0   0   0   0   1   1   0   1
   1   0   1   0   1   0   1   0   0   1   0   1   0   0   0   0   1   1   0   1
```

4.3.3 Monitoring Model

For examining the channel during several iterations, Fast Fourier Transform (FFT) is used where frequency components can be displayed. However, here, we attempt to check the channel status in different possibilities of PU presence. For easily tracking of results, let us assume six PUs existence; hence for 80 seconds of simulation time and 600 Hz of total bandwidth let us demonstrate the channel status for each 10 seconds.

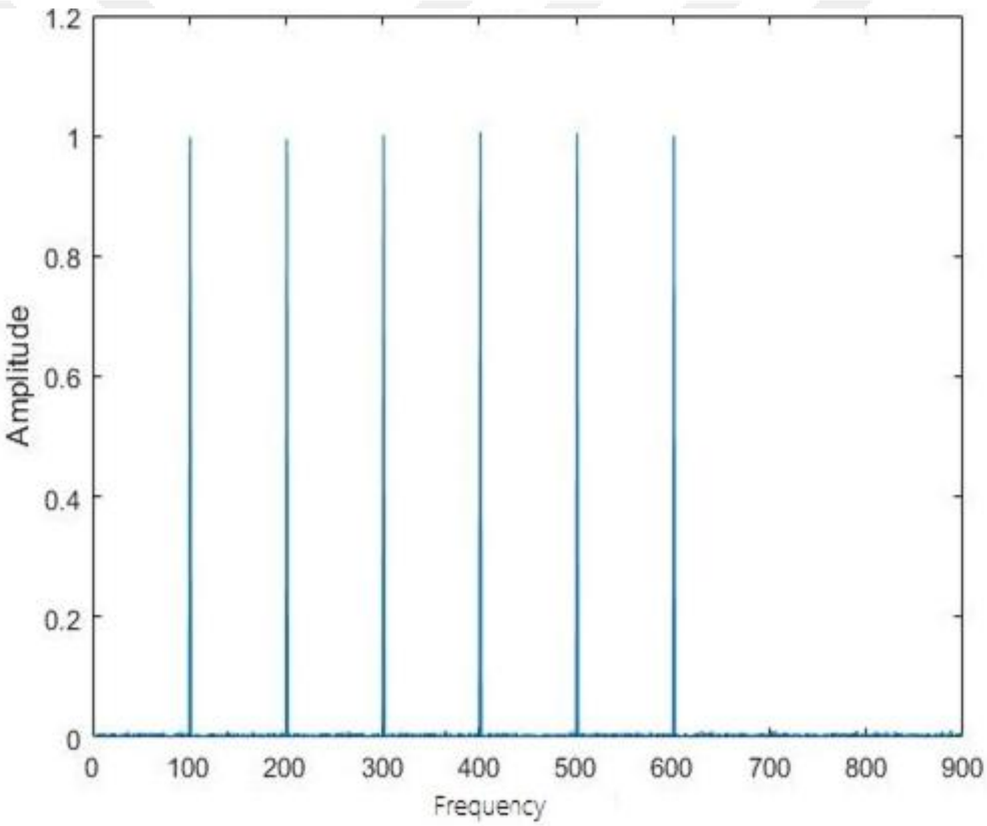


Figure 4.8: Primary Users For Very First Instants Of Transmission (Six Users Are Occurring The Channel).

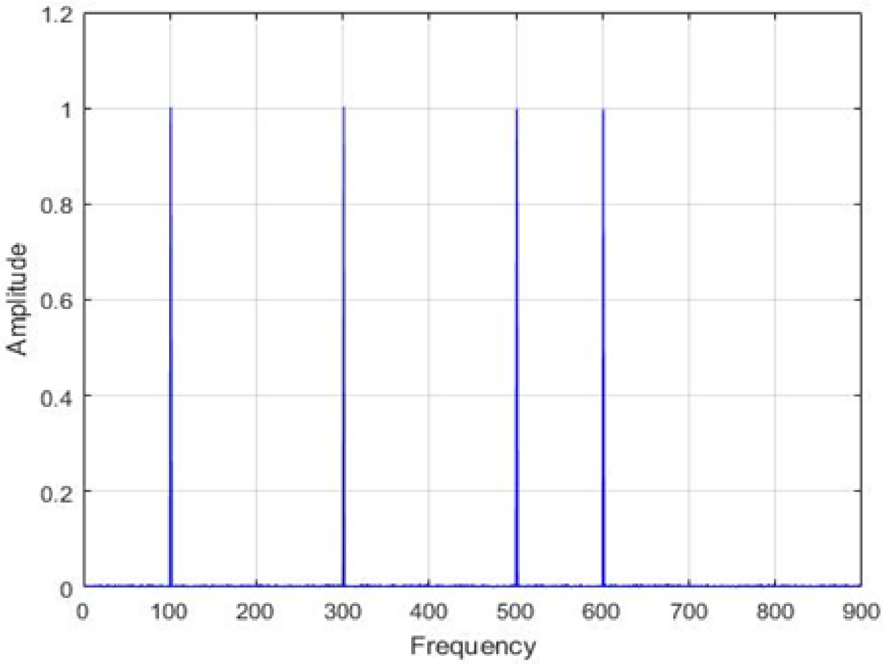


Figure 4.9: Licensed Band During First Iteration

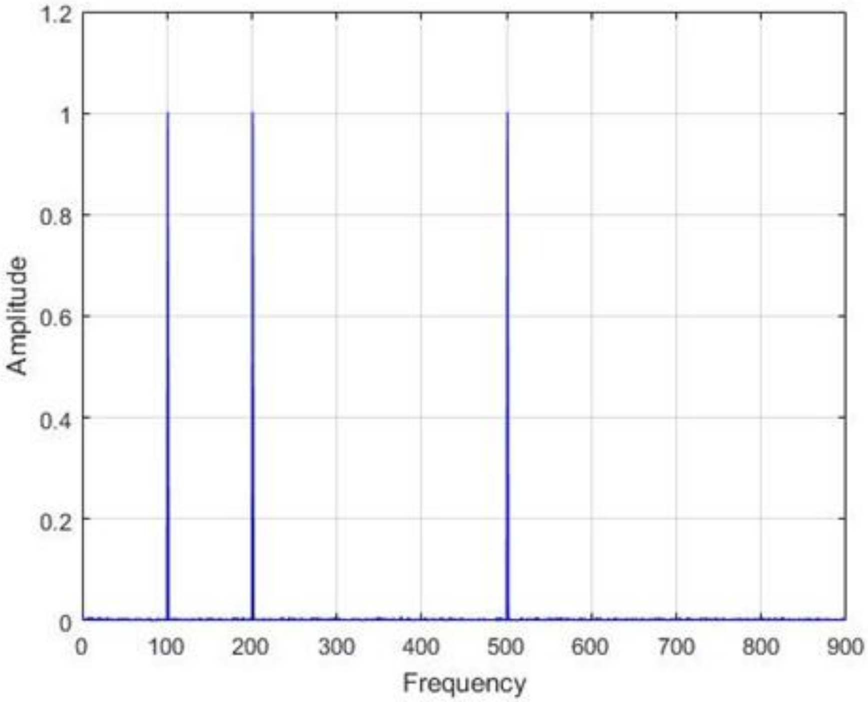


Figure 4.10: Licensed Band During Second Iteration.

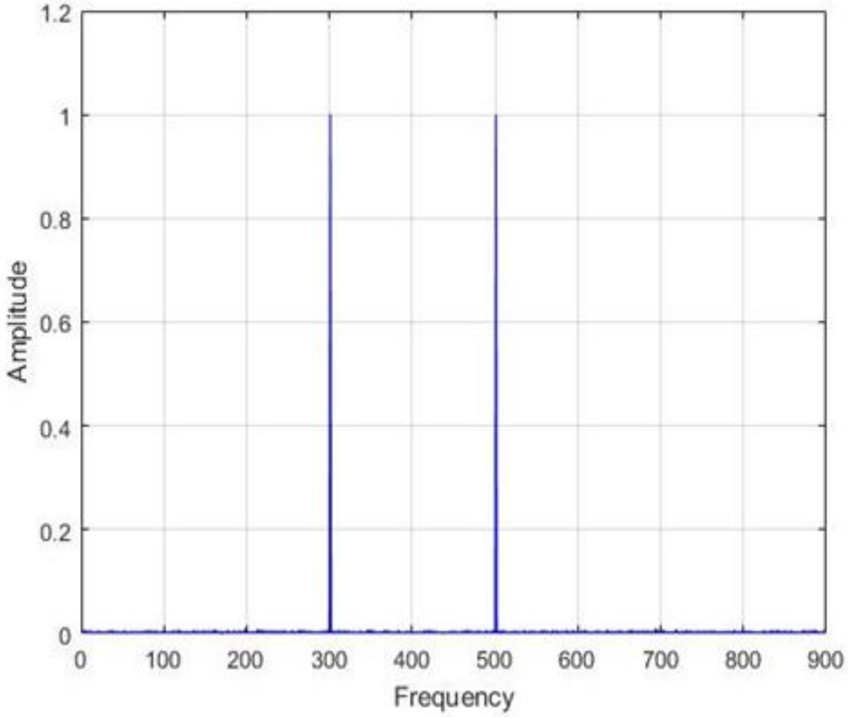


Figure 4.11: Licensed Band During Third Iteration.

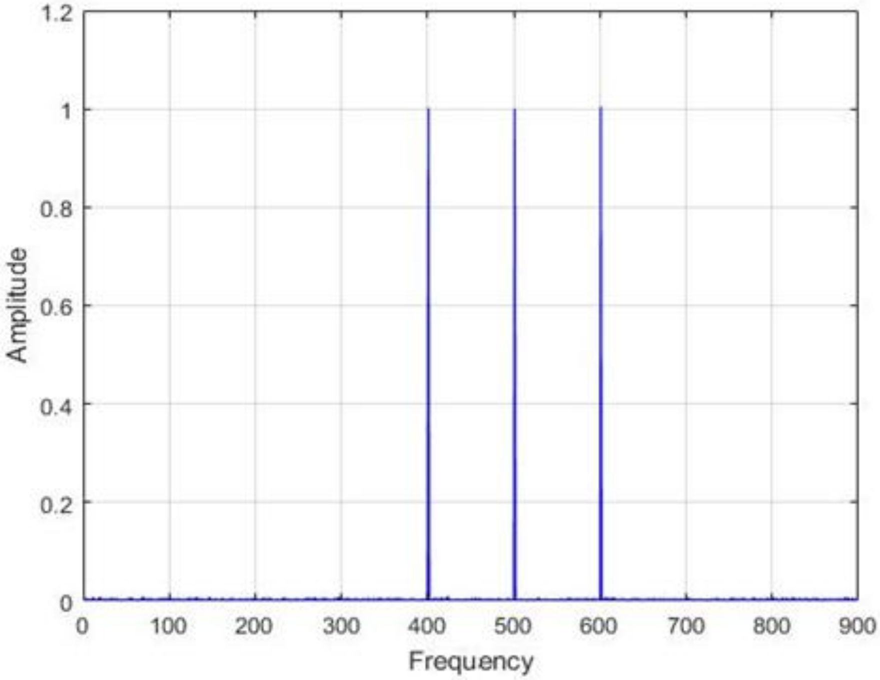


Figure 4. 12: Licensed Band During Fourth Iteration**.**

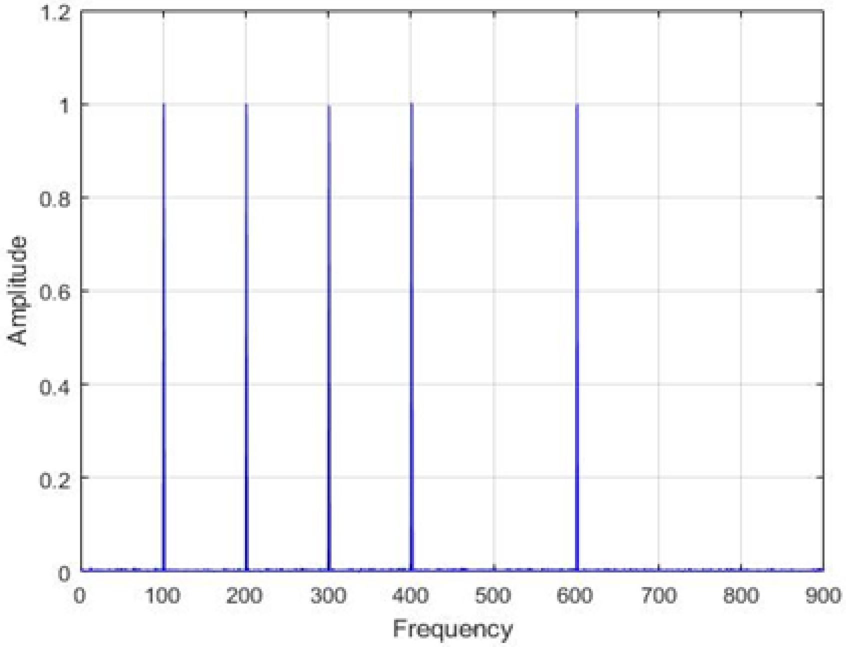


Figure 4.13: Licensed Band During Fifth Iteration.

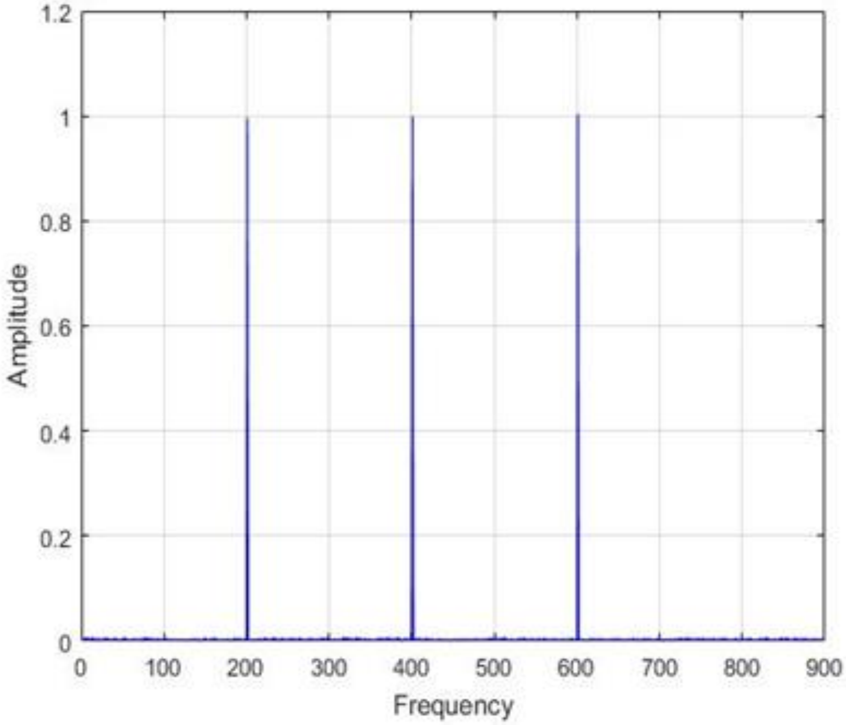


Figure 4.14: Licensed Band During Sixth Iteration

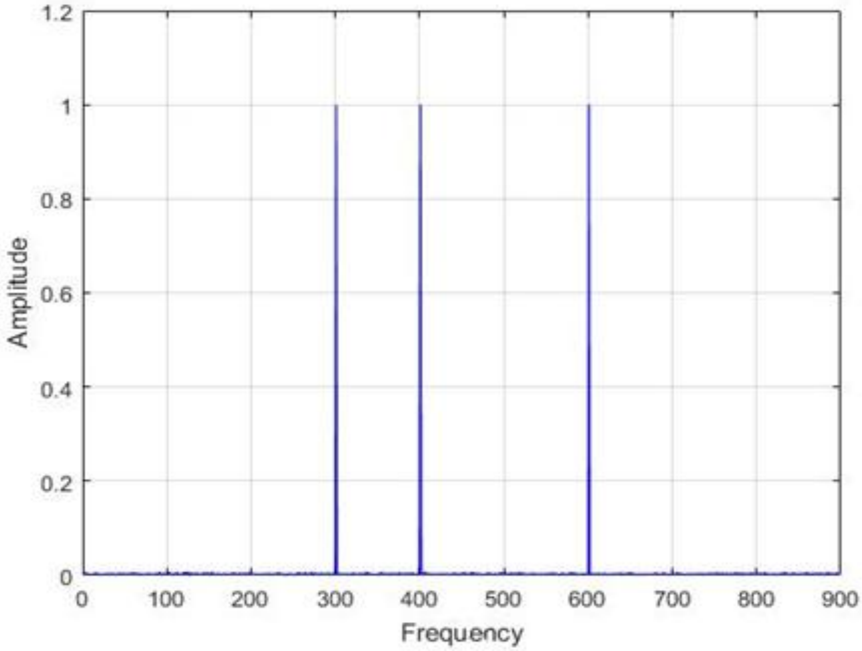


Figure 4.15: Licensed Band During Seventh Iteration.

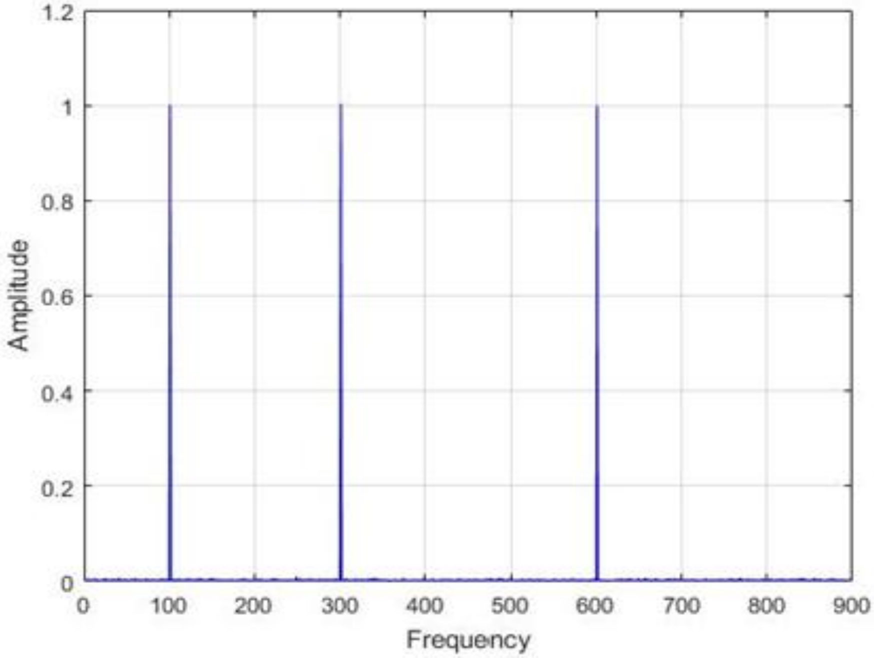


Figure 4.16: Licensed Band During The Eighth Iteration.

Observations:

a. During very first instants, band looks like it is in full occupancy as in Figure 4.8, six PUs on 100, 200, 300, 400, 500, and 600 Hz are active;
b. When iterations begins, each user may take over for particular time and then quits the band. However, 200 and 400 bands seem vacant, PU s may use that for less than 10 seconds and leave in hereafter, Figure 4.9;
c. During the second iteration, 300, 400, and 600 bands are vacant, Figure 4.10;
d. During the third iteration, 100, 200, 400, and 600 are vacant, Figure 4.11;
e. During the fourth iteration, 100, 200, and 300 are vacant, Figure 4.12;
f. During the fifth iteration, only 500 band is declared vacant, Figure 4.13;
g. During the sixth iteration, bands of 100, 300, and 500 are vacant, Figure 4.14;
h. During the seventh iteration, bands of 100,200, and 500 are vacant, Figure 4.15;
i. Finally, 400, 500 and 200 bands are found vacant while eighth iteration, Figure 4.16.

Furthermore, the 400 band is noticed to be most vacant band amongst the others. On the other hand, peak load is mitigated after 30 seconds of simulation run time.

4.4 SPECTRUM SENSING

The logic of cognitive radio (CR) more likely reuses the vacant band (s) of spectrum owned by primary user (PU) ‘X’, when PU is not using it. Such wisely usage of spectrum resources is drawing big economic gains from service provider vision. However, SU or cognitive user may be defined such as: any candidate who is not belonging to the network ‘NW’ and intending to utilize ‘BW’ bandwidth within this network. Hence ‘BW’ may be originally used by the PU candidates and it is not available at that particular instant. SU needs to verify whether the demanded band (s) is available. Spectrum sensing is a term defined as periodic sensing of the spectrum for finding the vacant bands. For spectrum sensing, Energy Detection Method was used, where white band is sampled and directed to frequency analyser that feeds the results to a matching filter, same is demonstrated in Figure 4.17.

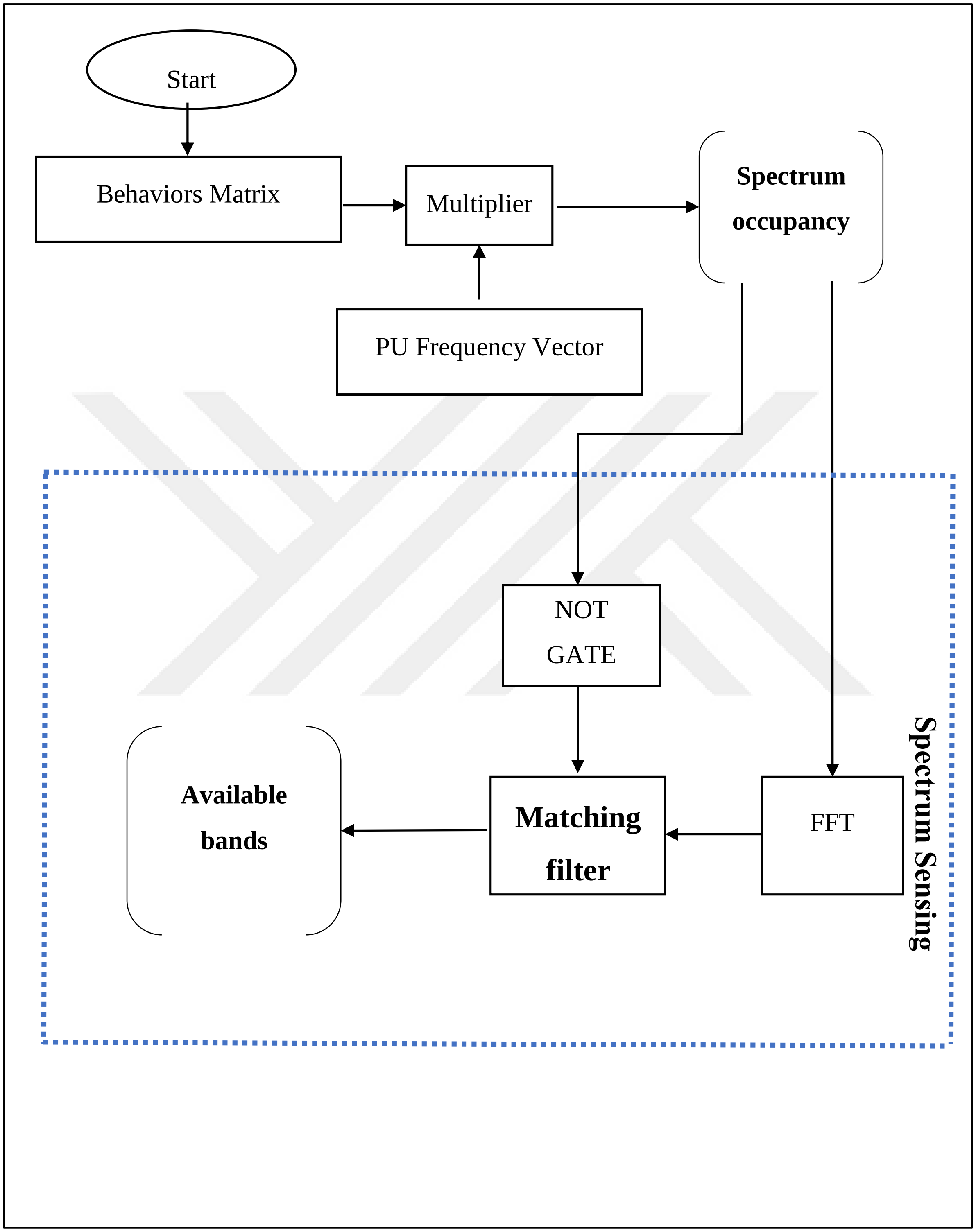


Figure 4.17: Spectrum Sensing Paradigm.

4.5 SPECTRUM SHARING

After sensing all available bands, new model is needed now to adopt a suitable approach to assign SUs in white band that is used by PUs. However, for ‘n’ number of SUs, spectrum availability is totally dependent upon PU. Because of this, SU can share only allowable portion of white band which may be permitted by PU base station (signalling centre) where control signals are exchanged between the base station and mobile unit through signalling channel. Prior of user transmission, some constrains alike: transmission delay and throughput limitations are required to be addressed. Time delay results by user’s mobility and number of candidate willing to share the band. Obviously, SU needs to wait for its role to participate the band alike rest candidates; if the present number of candidate is small (adaptable), user may get chance to transmit shortly unless otherwise. In this paradigm, two techniques have been proposed to share the spectrum between PUs and SUs: underlay and interweave spectrum sharing.

The logic of spectrum sharing method which defined earlier may be used to implement their model and display results on thereafter i.e. transmission delay and throughput. The time consumed by secondary user (each) during to transmit on the said channel during simulation slot is called as transmission delay. On the other hand, number of SUs that are able to share the licenced band effectively without termination (without fail) while ‘m’ iteration is called as throughput.

However, as network is defined as functional, PUs are supposed to be active. However, the behaviours of PUs can be visualized by spectrum monitoring model. Meanwhile, SUs are in standby position and are ready to participate the spectrum.

Known that spectrum sensing was achieved by secondary user control station (base station, back office), results may be monitored at this point. Ultimately, transmission delay is counted for each candidate and then throughput per iteration is obtained. Results are recorded and prepared for conclusion. However, there is trade-off between the delay and throughput in underlay and interweave techniques.

4.6 WAITING TIME ESTIMATOR

Primary (PUs) and secondary (SUs) users may share the white band depending on spectrum sharing technique governing this process. For underlay spectrum sharing technique, both PUs and SUs are transmitting at same time but SUs have to limit their activity to the level where there is no interference with licensed users. However, that may force SUs to develop queues. As revealed by Figure 4.18, at any consecutive candidates sharing same licensed slot, one of them can start transmission first (priory is given to the first arrival) and after next user may start. In here, next user will need to wait till previous user leaves the band. In Figure 4.15, if cognitive user1 or SU1 waits for 10.4 second, then user 2 will wait 20.8 second to take over the band. In the same Figure, it is also shown that band of users 11 and 12 may experience of the higher interference comparable to other bands as PU is occupying the band for long time. Due to that, lesser number of SUs can share this band. In other word, candidates need to wait for longer time in their queues. This logic remains same more likely bigger queues are developed as transmission rate getting high; Figure 4.19.

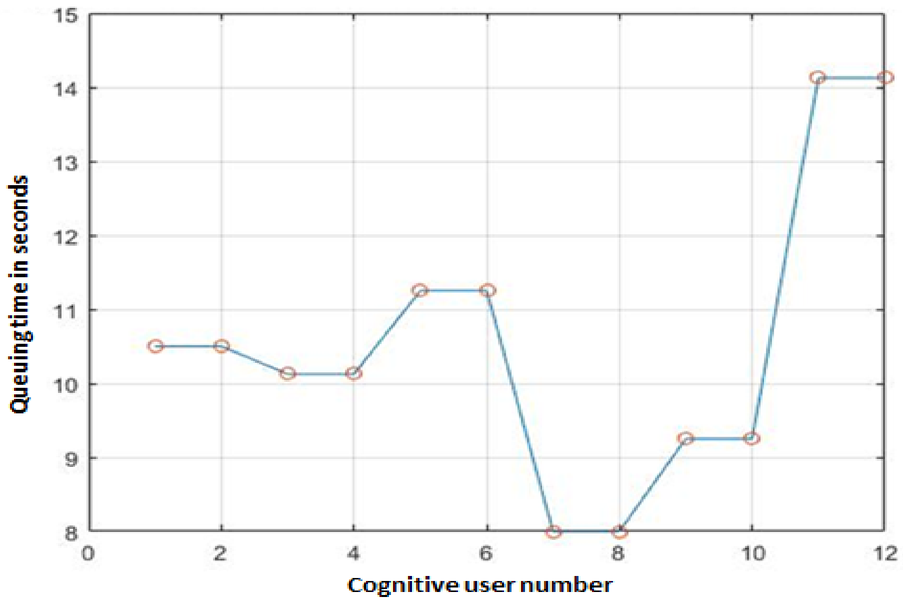


Figure 4.18: Transmission Delay As Per Undelay Spectrum Sharing Taken As Average Value For Eight Iterations And 12 Secondary Users.

Looking at Figure 4.20, interweave spectrum sharing can permit transmission only if particular band is declared vacant (never otherwise). Interweave spectrum sharing regulations may limit the most of secondary candidates from sharing the band. However, no queues will be developed and user will need to sweep the spectrum periodically to get-in. User will need to quit-out of band immediately before PU returning. Hence, transmission delay is lesser even though higher transmission rate as in Figures 4.21. Depending on vacant band capacity, some SUs can get access to that spectrum and all other users may get discarded. In Figure 4.20 and 4.21, time is slightly higher as SUs increased to 24. At every time simulation is restarted, time estimator model is generating random numbers for time slots allotted to every user which forces little mismatch in results

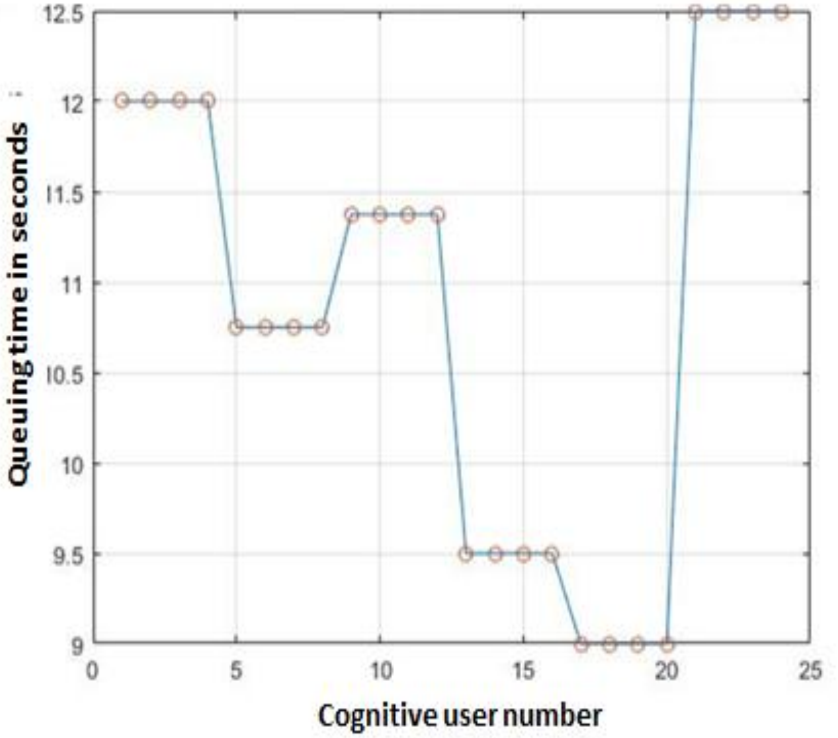


Figure 4.19: Transmission Delay As Per Undelay Spectrum Sharing Taken As Average Value For Eight Iterations And 24 Secondary Users.

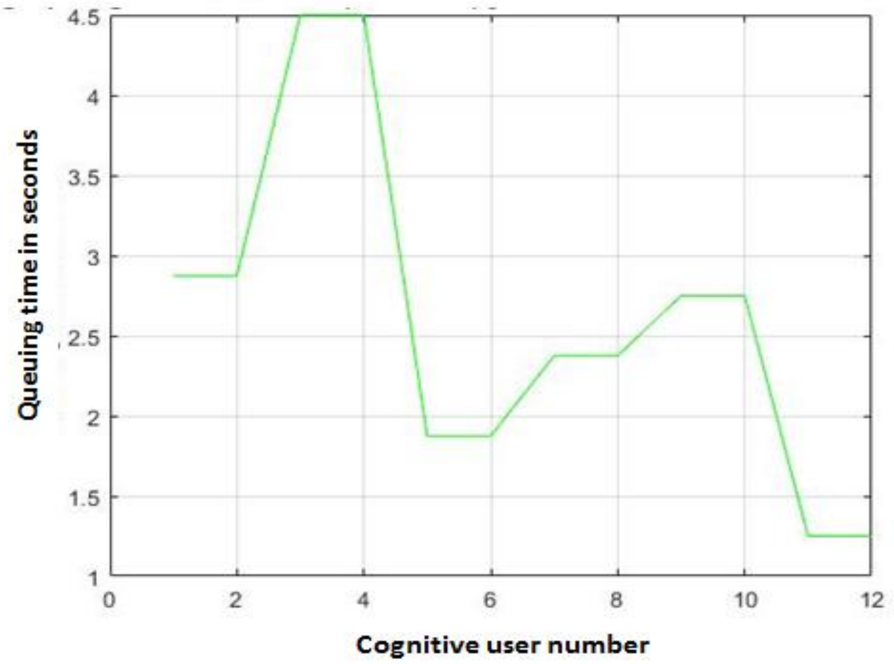


Figure 4.20: Transmission Delay As Per Interweave Spectrum Sharing Taken As Average Value For Eight Iterations And 12 Secondary Users.

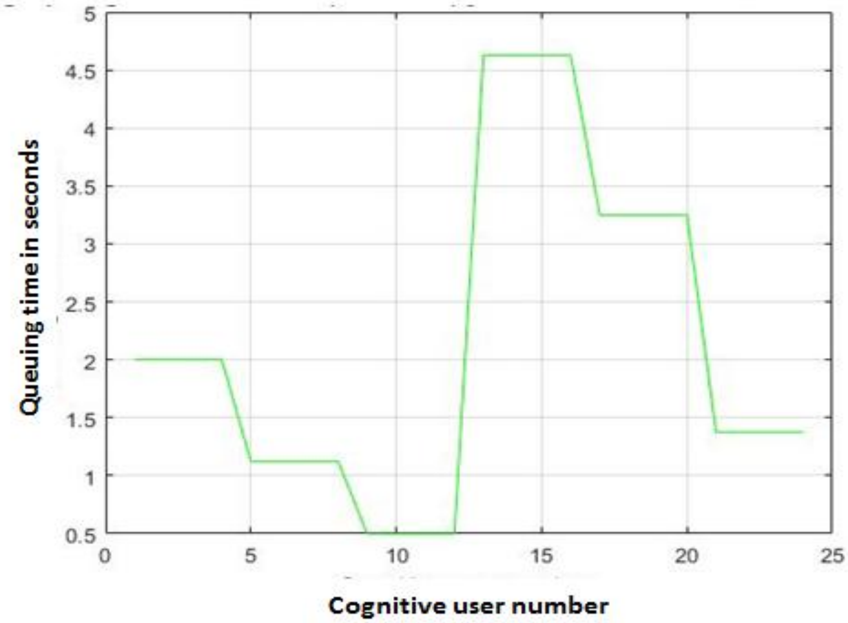


Figure 4.21: Transmission Delay As Per Interweave Spectrum Sharing Technique Taken As Average Value For Eight Iterations And 24 Secondary Users.

4.7 THROUGHPUT

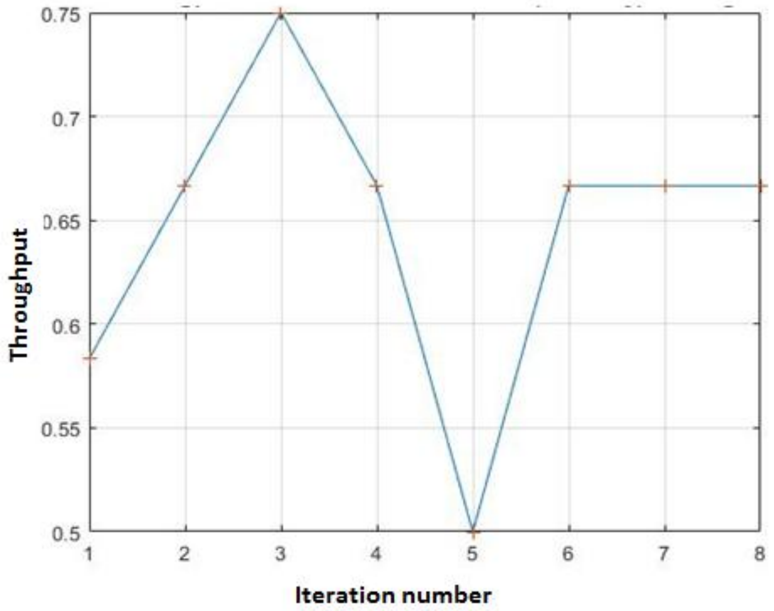


Figure 4. 22: Throughput VS Iteration Counted For 12 Secondary Users During Underlay Spectrum Sharing Technique

Starting with twelve secondary users (SUs), within underlay spectrum sharing they can transmit simultaneously with primary users (PUs) but care should be taken for interference avoidance. This may develop time delay prior transmission but throughput is enhanced here which means the actual number of users participating the band with respect to total available secondary candidates is bigger. Figure 4.22 demonstrates throughput in each iteration (eight iterations with ten seconds per each) and twelve SU. Throughput in case of underlay spectrum sharing is increasing if transmission rate increased as in Figure 4.24 when 24 secondary candidates are in turn.

On the other hand, interweave spectrum sharing is experiencing lesser throughput for same number of secondary candidates comparable to underlay spectrum sharing as in Figures 4.23 and 4.25. Reason behind these episodes is related to internal mechanism of the particulars, more likely vacant bands only can be accessed by SUs during iteration time.

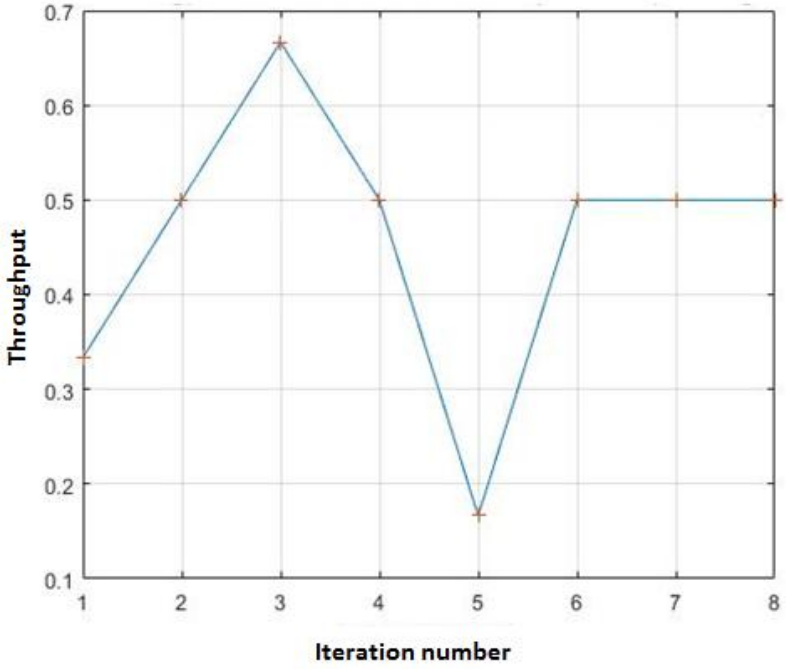


Figure 4.23: Throughput VS Iteration Counted For 12 Secondary Users During Interweave Spectrum Sharing Technique

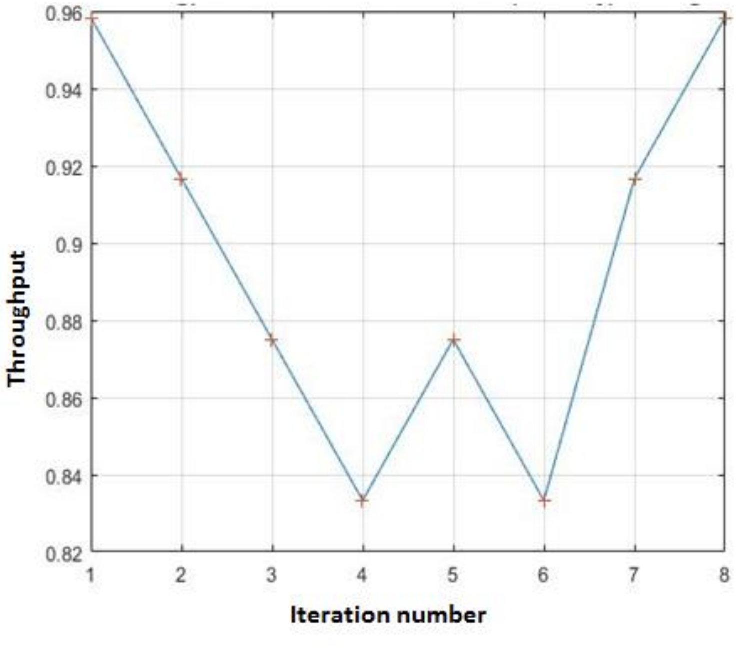


Figure 4.24: Throughput VS Iteration Counted For 24 Secondary User During Interweave Spectrum

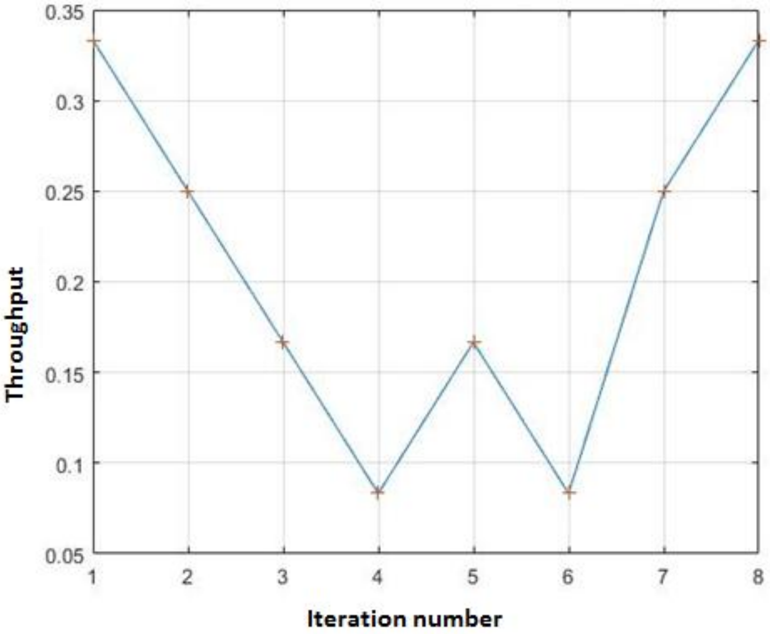


Figure 4.25: Throughput VS Iteration Counted For Secondary User 24 During Interweave Spectrum Sharing Technique.

4.8 THESIS STRENGTH

Since licensed bands are experiencing a high uncertainty in terms of occupancy, the secondary user (SU) need to keep track of white band periodically in order to relocate such bands. Practically, two spectrum sharing techniques were proposed in this thesis, aiming to permit SUs transmission through white band without interference. However, underlay technique is seen with moderated throughput and relatively higher transmission delay. On the contrary, interweave has moderated delay in transmission but lesser throughput. This approach involves waiting time estimator which determines PU behaviours which was done by considering multiple possibilities of PU occupancy. Such possibilities are randomly generated where each user resides in the white band for ‘n’ seconds. User mobility condition is such that PU may re-occupy the same bandwidth again when it is used with SUs. Such problem is handled by waiting time estimator model that contains information of primary user’s activity during the run time.

Most of previous studies [10] [13] are using power spectrum density with matching filters to sense the spectrum periodically. Problems like noise may force the band to appear full and spectrum sensing could fail with the severity of noise. Therefore, spectrum sensing that resists noise may be required to overcome this drawback. In this research, time estimating model may provide the information about band occupants to work side by side with energy detector to sense the spectrum. The spectrum sensing is enhanced against noise, furthermore, the chances of interference are reduced.

5. CONCLUSION

In this thesis, we intended to use proactive approach to predict primary user (PU) transmission status on the white spectrum for entire simulation time. PU behaviours are derived by using time waiting estimation paradigm which provide time interval of each band occupancy actions; at the same time we aim to reduce computational budget of simulation to reach the targeted enhancement to eliminate user's interference by achieving accurate spectrum sensing and performing exact handoff.

Furthermore, the proposed approach may minimize the risks of user mobility and faces the challenges of transient state channels. For applications of different nature, spectrum sharing technique would be selected according to the prototype requirement, more likely, those applications of real time transmission agenda are involved interweave spectrum sharing technique which provide lesser transmission delay and those of high throughput requirements are involving underlay spectrum sharing technique which satisfy the application demand.

Sine noise and fading effects are following each transmission process, in practical simulation we observed that noise and other disturbances presence in the channel may affect the decision of spectrum sensing, the same has revealed as well by some previous studies as shown in literature. It is seen that most of spectrum sensing methods are done by filtering the power spectrum density obtained for working channel and comparing the resulted samples of frequency components to validate user occupancy. Thesis met the design requirements by producing noise independent sensing paradigm underlying by proactive time estimation. Finally, results have concluded with less latency and good computational cost

In future work, Spectrum sharing is limited by channel capacity and primary user's behaviours; however, secondary users (SU) will either need to develop queues until the approval of transmission comes or it needs to variety the throughput in order to share the spectrum efficiently. Nonetheless, more advancement could be proposed to optimize the transmission performance. Firstly, the users which is out of reach (in case of interweave) can also transmit by deploying an approach called Device to Device communication (D2D). Such is achievable by permitting the spectrum sensing on hand unit where each user (not in range) can sense the nearest active user and then it can forward a request to that active user and communicate with it without the need of Base Station (BS) inference. D2D communication may help the unlicensed users or secondary user (SUs) to communicate with each other potentially where transmission delay and throughput deficiency will be subside.

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