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Analysis of Waiting Probability of Secondary Users in Cognitive Radio Networks

by

Ramesh Kumar Shrestha

A THESIS
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APPROVAL PAGE

The undersigned certify that it has been read and recommended to the Institute of Engineering for acceptance, a thesis entitled **"Analysis of Waiting Probability of Secondary Users in Cognitive Radio Networks"**, submitted by **Mr. Ramesh Kumar Shrestha** in partial fulfillment of the requirements for the award of the degree of **"Master of Science in Information and Communication Engineering"**.

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DEPARTMENTAL ACCEPTANCE

The thesis entitled **"Analysis of Waiting Probability of Secondary Users in Cognitive Radio Network"**, submitted by **Mr. Ramesh Kumar Shrestha** in partial fulfillment of the requirements for the award of the degree of **"Master of Science in Information and Communication Engineering"** has been accepted as a bonafide record of work independently carried out by him in the department.

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ABSTRACT

C*ognitive* R*adio* (CR) is an adaptive, intelligent radio and network technology that can automatically detect available channels in a spectrum and change transmission parameters enabling more communications to run concurrently. Thus the cognitive radio networks are emerging paradigm for future generation wireless networks where secondary users (SUs) opportunistically access the RF spectrum without causing harmful interference to primary users (PUs). SUs vacate the bands upon the arrival of licensed PUs.

This thesis analyse the waiting probability of SUs to get channel access based on PUs activities. Multi-user cognitive radio system is considered where SUs contend for spectrum access using time division multiple access over idle PU channels. Secondary users of cognitive radio network would have no knowledge of activities of other users. Thus the probability of being idle of SUs in cognitive radio network has to be assigned according to the available local information. Further, this thesis focuses on SUs' waiting probability analysis, for which a systematic understanding is lacking. Analysis and results have revealed that the waiting probability increases when the arrival rate of SUs increases. The waiting probability of SUs decreases with increasing number of slots. Also it is noted that the probability of getting one or at least two slots by SUs increases with increasing number of slots. The average service rate also decreases with increase in number of SUs, and the average service rate is lowest among all when the number of SU is the highest. The trade-off between different parameters is required to make an efficient opportunistic dynamic spectrum access by SUs in CR.

Keywords: Cognitive Radio, Secondary Users, Primary Users

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ABBREVIATIONS

CDMA	Code Division Multiple Access
CR	Cognitive Radio
CRN	Cognitive Radio Network
FCC	Federal Communication Commission
IEEE	Institute of Electrical and Electronics Engineers
OFCOM	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
OSA	Opportunistic Spectrum Access
PU	Primary User
QoS	Quality of Service
RF	Radio Frequency
SNR	Signal to Noise Ratio
SU	Secondary User
TDMA	Time Division Multiple Access

CHAPTER ONE

INTRODUCTION

1.1 Background

Frequency spectrum is considered as one of the limited resource available for communication using wireless technology. For the access of frequency spectrum lots of technique has been deployed till date e.g. OFDM, CDMA etcetera. However, this all access techniques are not dynamic in nature. Likewise, research regarding frequency spectrum utilization has shown that, licensed bands are idle for about 70% of the total time allocated for the primary users (licensed users).

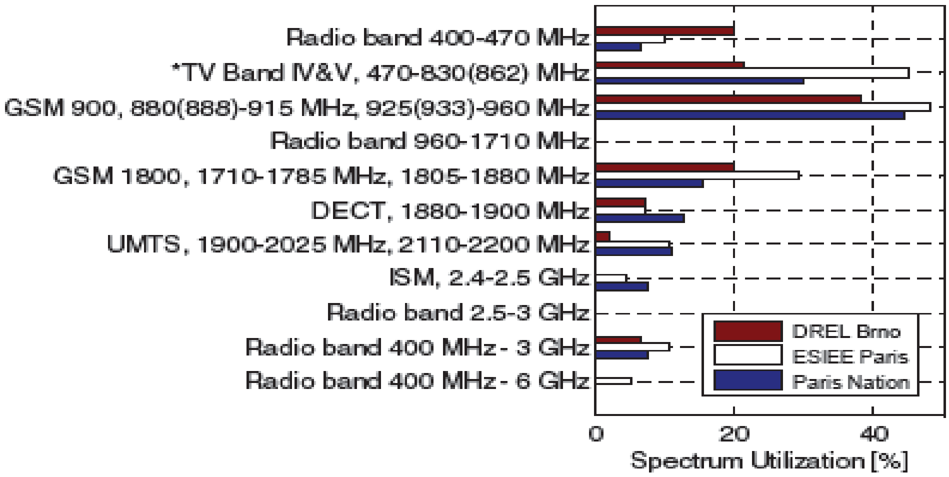

Figure 1.1: Spectrum Utilization in different regions in Europe [11]

Several studies including a recent report from FCC show that less than 15% of the spectrum is utilized on average [1]–[4].These facts, point in the direction that, spectrum is underutilized. In one side the allocated spectrum to certain organizations are remaining idle, the demand for spectrum for newer services and technology is increasing day by day.

It has been a big challenge for every licensing organization to accommodate all the new applications and services noted above with the limited electromagnetic spectrum. Thus that day is not too far, when the increasing demands of spectrum access will lead to spectrum scarcity and will be one of the main limitations in next-generation wireless systems.

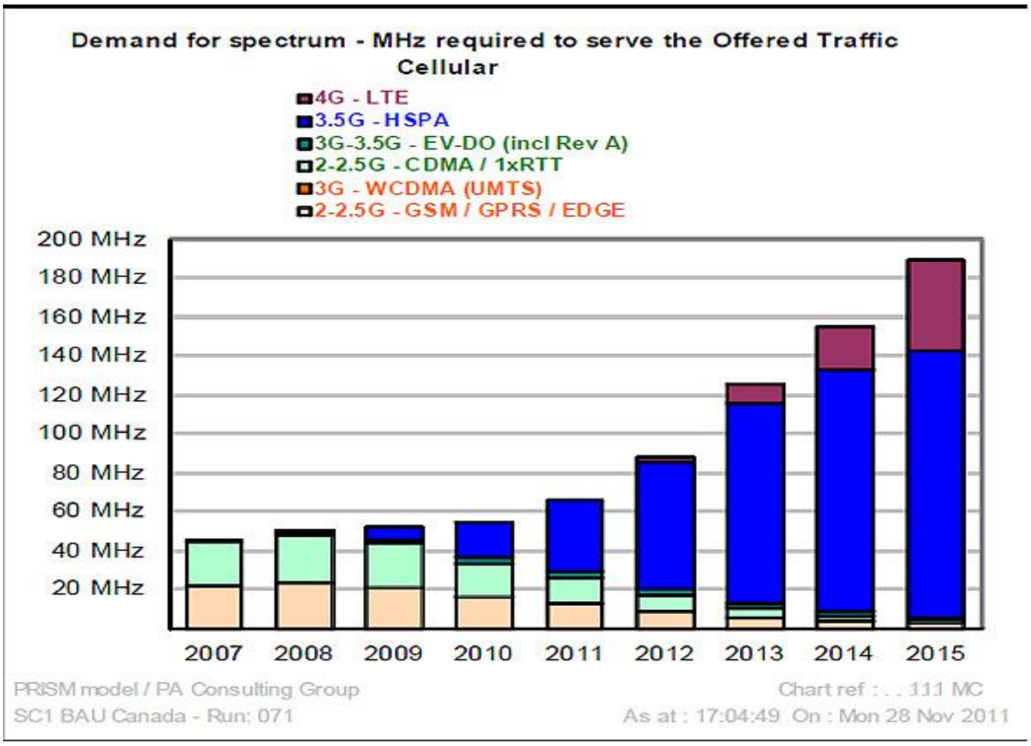

Figure 1.2: Cellular demand for spectrum by technology [12]

The demand for spectrum is increasing but reports show that almost all usable RF spectrums are already allocated to wireless systems and service providers. Thus, to exploit the licensed spectrum to the optimum level, different studies have taken place. In 1999, Joseph Mitola used the term Cognitive Radio for the first time. According to Joseph Mitola, Cognitive Radio is defined as an intelligent wireless communication system that is aware of the radio environment and is able to adapt to its changing parameters [1]. It was suggested as a way to increase radio spectrum utilization efficiency and to increase the communication reliability of modern wireless technologies.

Cognitive radio networks (CRNs), such as IEEE standards 802.22 is emerging paradigm for future generation wireless networks in which cognitive radio users (also known as unlicensed secondary users) dynamically access the RF spectrum opportunistically without creating harmful interference to licensed users.

SUs are required to sense and identify or search for the spectrum opportunities before using them for the given time and geographic location . Since SUs are using spectrum opportunities, that are not used by primary users, dynamically, they could communicate with high transmit powers as long as they do not exceed the mandated upper limit, specified by government bodies such as NTA in Nepal, FCC in the U.S. and similar bodies in other countries. But SUs have to wait for the spectrum opportunities. In particular, a key functionality needed by SUs is the capability of sensing the spectrum and identifying the idle bands or search for idle spectrum bands in a geolocation database for given time. Thus, SUs could use those idle bands opportunistically without causing harmful interference to PUs. One of the major challenges is to discover the ”spectrum opportunities” (also called ”spectrum holes”) for SUs and distribute them efficiently and fairly, especially when the system is overloaded. The system gets overloaded when many SUs contend for the same spectrum holes or the number of holes are less than the number of SUs). Waiting time or delay analysis is a important Quality-of-Service (QoS) metric in wireless networks that need to be considered. It is important to point out that the waiting time or delay based performance analysis is important to estimate the number of SUs that can be handled by a given system.

1.2 Problem Statement

Cognitive Radio is an emerging technology that helps to optimize the use of spectrum by allowing the unlicensed users to use the licensed frequency band whenever the primary user is not active in that range. SUs should not interfere the PUs and should vacate the band as soon as the PUs try to access that band. Many researches are done on spectrum sensing which detect whether the PUs are active in the frequency band or not. Lots of researches are done in different types of co-operative and non-co-operative types of spectrum sensing. Different spectrum sensing approaches with single and multiuser environment are studied. In real environment, secondary users of cognitive radio network would have no knowledge of activities of other users. The probability of being idle of SUs in cognitive radio network has to be assigned according to the available local information. Secondary users also should wait for certain time for frequency band to be vacant. Though it seems obvious that there is delay in the system in getting the free band and in changing the vacant band as the primary users in current band becomes active, there is lack of a systematic knowledge about the time the SUs should wait and the probabilistic model of waiting period of secondary users. QoS definition for a system initially will add clearance to the users about the system whether it can fulfill their requirements or not. This waiting probability and delay analysis will be a great matter of interest as it is one of important factor in defining the quality of service (QoS)of a system. This thesis is to focus on systematic analysis of waiting probability of SUs for opportunistic spectrum access.

1.3 Objective

The main objective of this thesis is:

To analyze the waiting probability of secondary users for opportunistic access in Cognitive Radio Networks.

1.4 Application and Scope

Cognitive Radio is emerging technology which is expected to arrive to provide optimum use of available spectrum. CR network and its performance is a matter of interest. This thesis aims to explore the concepts of waiting probability of the secondary users for opportunistic spectrum access in cognitive radio networks in single and multiuser environment. It gives a systematic probabilistic approach of waiting probability along with the effect of different parameters of delay in CR networks which can be used for analysing the delay performance in a cognitive radio network where SUs contend for channel access. It gives a clear view for secondary users in cognitive radio technologies about the delay they should face for spectrum access and the way they are affected by the number of secondary users competing to get channel access. This could be an important factor in defining QoS of the cognitive radio network. The waiting time or delay-based performance analysis is important to estimate the number of SUs that can be handled by a given system and how many users could be served by the system without any heavy starvation to other SUs.

1.5 Organization of Thesis Report

The first chapter deals with the introduction part and the rest of the thesis report is divided as follows:

Chapter 2 gives insight into the theoretical background of Cognitive Radio network and literature review of delay for Secondary Users.

Chapter 3 deals with methodology along with mathematical system model of waiting probability and stability condition for CR network.

Chapter 4 shows the Simulation result and gives an analysis of the results obtained during the experiment

Chapter 5 concludes the thesis work.

CHAPTER TWO

THEORITICAL BACKGROUND

2.1 Cognitive Radio

Cognitive radios offer the promise of being a disruptive technology innovation that will enable the future wireless world. Cognitive radios are fully programmable wireless devices that can sense their environment and dynamically adapt their transmission waveform, channel access method, spectrum use and networking protocols as needed for good network and application performance. It is an emerging solution to the problem of spectrum scarcity caused by under-utilized frequency slots of licensed or unlicensed frequency bands.

2.1.1 Vision of Cognitive Radio

If a radio were smart, it could learn services available in locally accessible wireless computer networks, and could interact with those networks in their preferred protocols, so you would have no confusion in finding the right wireless network for a video download or a printout. Additionally, it could use the frequencies and choose waveforms that minimize and avoid interference with existing radio communication systems. It might be like having a friend in everything that's important to your daily life, or like you were an executive with hundred assistants to find documents, summarize them into reports, and then synopsize the reports into an integrated picture. A Cognitive Radio is the convergence of the many pagers, PDAs, cell phones, and many other single-purpose gadgets we use today. They will come together over the next decade to surprise us with services previously available to only a small select group of people, all made easier by wireless connectivity and the Internet.

2.1.2 Defining Cognitive Radio

Cognitive radios merge AI and wireless communications. The field is highly multidisciplinary, mixing traditional communications and radio work from electrical engineering while applying concepts from computer science. The term Cognitive Radio was first coined by Joseph Mitola."Cognitive Radio is a radio that includes a transmitter in which operating parameters such as frequency range, modulation type or maximum output power can be altered by software [1]".

FCC defines CR as: "A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets.

"Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment and uses the methodology of understanding by building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g. transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind: highly reliable communication whenever and wherever needed: efficient utilization of the radio spectrum[8]."

Cognitive Radio's three basic units are.

- White Space detection unit.
- Channel identification unit: It deals with channel parameters estimation.
- Dynamic spectrum management unit: Its main purpose is to develop strategies to use the spectrum resources in an efficient and effective way.

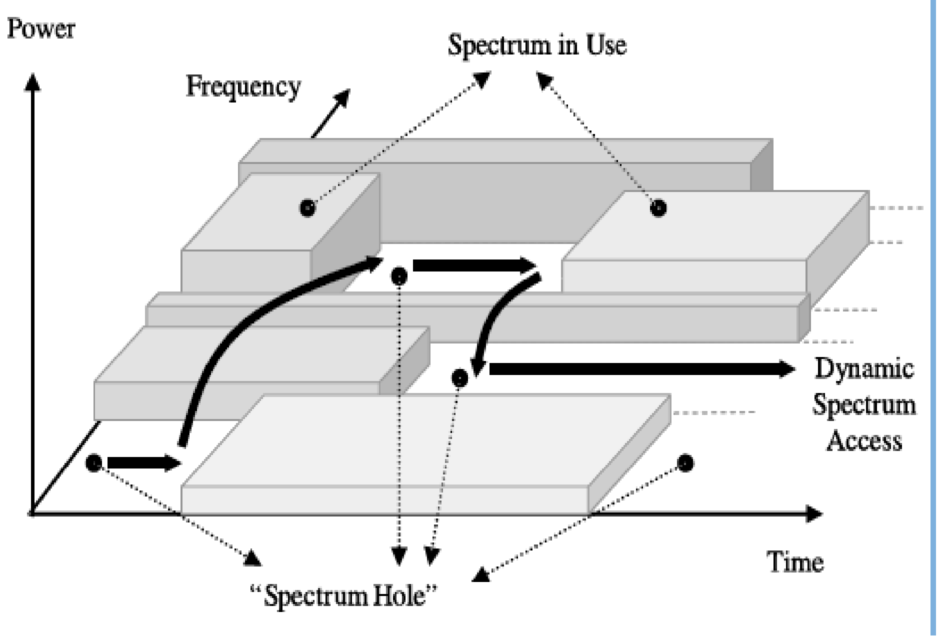

Figure 2.1 Spectrum Hole Concept [2]

The ultimate objective of the cognitive radio is to obtain the best available spectrum through cognitive capability and re-configurability as described before. Since most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users as illustrated in Figure 2.1.

The cognitive radio enables the usage of temporarily unused spectrum, which is referred to as spectrum hole or white space. If this band is further used by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference.

2.2 Cognitive Radio Cycle

Dynamic spectrum access techniques allow the cognitive radio to operate in the best available channel. Once the cognitive radio supports the best available channel, the next challenge is to make the protocols adaptive to the available spectrum. The secondary users are allowed to use the spectrum without interfering the primary users whenever the channel is idle. The secondary users make the occupied channel vacant as the Primary users tries to access the channel. To support this adaptivity, Cognitive radio require following functionalities [1].

- Spectrum Sensing: Detecting unused spectrum and sharing the spectrum without harmful interference with other users. The sensing device located at secondary user section measures certain characteristics of the radio waveform and then decides if a primary user is actively using the spectrum. The spectrum is sensed by either one of following two ways:

    a. Non-Cooperative Spectrum Sensing

    b. Co-operative Spectrum Sensing

- Spectrum Decision: Capturing the best available spectrum to meet user communication requirements without causing interference to Primary or licensed users

- Spectrum Mobility: Secondary Users should leave the spectrum once the primary user attempt to access the licensed band. As the PUs becomes active, SUs need to shift from current vacant band to other vacant band if available otherwise should be disconnected from the system until the channel becomes vacant. Spectrum Mobility maintains seamless communication requirements during the transition to better spectrum as a SU changes its frequency of operation when a PU appears in the same band.

- Spectrum Sharing: The number of secondary users trying to access the vacant licensed band may vary depending upon the instant of time. This Spectrum sharing phase provides the fair spectrum scheduling method among coexisting next generation users.

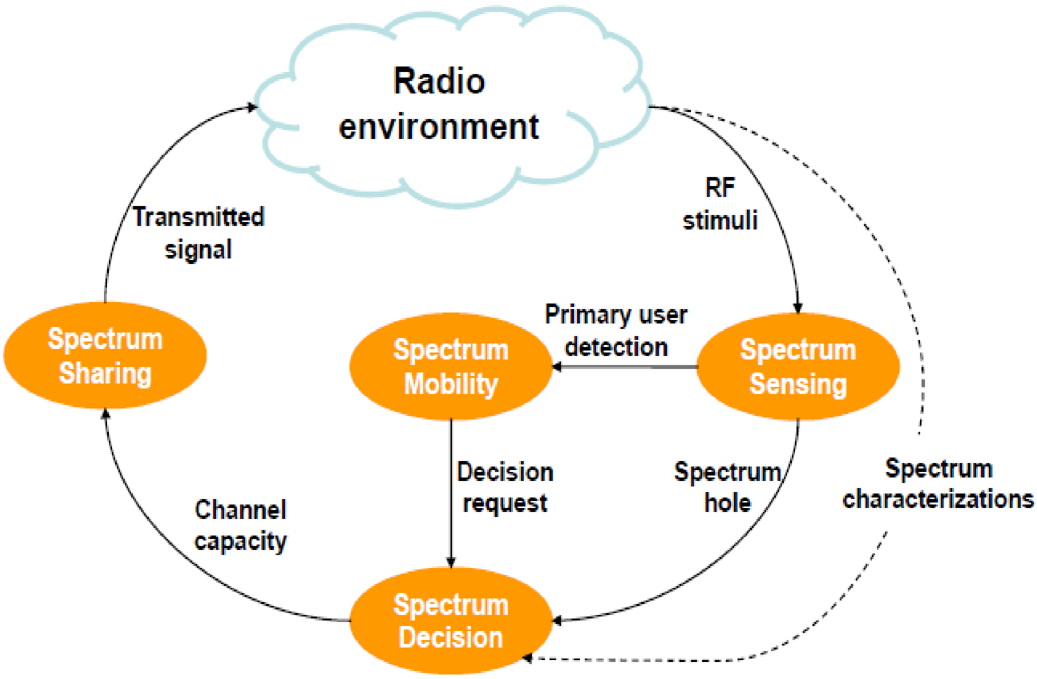

Figure 2.2 Spectrum Management in Cognitive Radio Network

The generic Cognitive Radio Architecture consist mainly of Cognitive Engine, Policy domain, User domain and Radio domain.The intelligent core of the cognitive radio exists in the cognitive engine . The cognitive engine performs the modeling, learning, and optimization processes necessary to reconfigure the communication system, which appears as the simplified open systems interconnection stack. The cognitive engine takes in information from the user domain, the radio domain, the policy domain, and the radio itself. The user domain passes information relevant to the user's application and networking needs to help direct the cognitive engine's optimization. The radio domain information consists of radio frequency and environmental data that could affect system performance such as propagation or interference sources. The policy engine receives policy-related information from the policy domain. This information helps the cognitive radio decide on allowable (and legal) solutions and blocks any solutions that break local regulations.

2.3 Spectrum Accessing Approaches

Cognitive Radio Networks is an emerging technology motivated towards increasing the spectrum usage efficiency to optimize the spectrum usage by allowing the unlicensed users to use the licensed frequency band. In CR network there are two types of users i.e. Primary and Secondary Users. Licensed spectrum is being opened for the secondary users, while interference they are creating for the primary users is controlled. Cognitive radio (CR) and opportunistic spectrum sharing are promising concepts for boosting the efficiency of radio spectrum utilization. Secondary users also called unlicensed users use the spectrum in an opportunistic manner dynamically without creating harmful interference to primary users using one of the two approaches [4]: spectrum underlay and spectrum overlay.

2.3.1 Spectrum Underlay

Spectrum underlay is approach in CR network where both the primary users and secondary users coexist and transmit simultaneously in the same frequency band. Underlay or interference avoidance model [4] allows concurrent transmission of primary and secondary users in ultra wideband fashion. The transmit power of the secondary user is limited so that the generated interference is below the noise floor for the primary user i.e. SUs are not allowed to transmit with high powers than the pre-specified ones so as not to create harmful interference to PUs. There is no detection, no exploitation of spectrum white space .Due to power constraints systems using underlay model can be used only for short-range communication. By spreading transmitted power over a wide frequency band (UWB), secondary users can achieve high data rates on short distance. SUs do not have to find spectrum opportunities in this approach and may not have to wait to use the spectrum. This type of system does not need the waiting probability analysis for secondary users as SUs get chance to transmit whenever they need it but this approach prevents the long range communications using CRNs.

2.3.2 Spectrum Overlay

Spectrum overlay was first envisioned by Mitola under the term spectrum pooling and then investigated by the DARPA Next Generation (XG) program under the term opportunistic spectrum access. Differing from spectrum underlay, this approach does not necessarily impose severe restrictions on the transmission power of secondary users, but rather on when and where they may transmit.

In spectrum overlay, SUs are required to sense and identify or search for the spectrum opportunities before using them for the given time. Spectrum overlay techniques are based on detect and avoid mechanism. Transmission power of secondary users is not constraint. But the important issue in Spectrum Overlay technique is where and when they may transmit. Spectrum white spaces are targets of Secondary Users. The secondary user senses the frequency spectrum; if a primary user is active the channel will not be used. Since SUs are using spectrum opportunities that are not used by primary users, dynamically, they could communicate with high transmit powers as long as they do not exceed the mandated upper limit, specified by government regulating bodies. In the spectrum overlay based cognitive radio network, SUs have to wait for the spectrum opportunities. A key functionality needed by SUs is the capability of sensing the spectrum and identifying the vacant bands. Thus, SUs could use those idle bands opportunistically without causing harmful interference to PUs.

CHAPTER THREE

LITERATURE REVIEW

3.0: Literature Review

It is now well–established and proven fact that there is a great amount of unused bands available sparsely which could be exploited by both licensed and unlicensed services. Thus uncoordinated, opportunistic deployment of spectrum chunks has led to an "artificial scarcity of spectrum". An experimental study conducted by Shared Spectrum Company during the 2004 Republic National Convention [13] found that spectrum utilization is typically time and space. As a result, it is intuitive that static spectrum allocation may not be the optimal solution toward efficient spectrum access for both licensed and unlicensed services. With the dis–proportionate and time–varying demand and hence usage of the spectrum, the notion of fixed spectrum assignment to providers is questionable. Though it might be argued that the implementation and administration is very easy, the fact remains that the current system is ineffective and deprives service providers, end–users, and FCC from maximizing their benefits. In order to break away from the inflexibility and inefficiencies of static allocation, a new concept of Cognitive Radio with Dynamic Spectrum Access (DSA) is being investigated by network and radio engineers, policy makers, and economists. In DSA, spectrum will be accessed dynamically depending on need of the service providers which in turn depends on end users' demands in a time and space variant manner. Emerging wireless technologies such as cognitive radios is poised to make DSA a reality. This method of spectrum sharing is more efficient and will help service providers, and regulatory bodies like FCC to avoid any artificial scarcity.

Cognitive Radio is a kind of wireless communication system in which either a network or a wireless node changes its transmission or reception parameters to communicate efficiently avoiding interference with licensed or unlicensed users. It is considered to be an intelligent wireless communication system that is aware of its surrounding environment (i.e. outside world) and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g. transmit-power, carrier frequency and modulation strategy) in real time.

CR network has two types of users. The unlicensed secondary users try to get opportunistic spectrum access whenever primary users are not active in the system. As explained earlier, multiple secondary users contending to get the same spectrum access at same time may wait for certain period. The waiting time for secondary users to get access to the vacant frequency bands is important in defining the service rate of a system. Delay analysis is important Quality-of-Service metric for wireless networks. Waiting time or delay based performance analysis is important to estimate the number of SUs that can be handled by a given system.

So far, the researchers are mainly focused on different techniques of spectrum sensing and comparison between different spectrum sensing techniques [4, 10]. Limited work has been done in waiting time or delay based performance analysis for cognitive radio networks. The related work [5], [6] studied delay analysis based on fluid queue model.

S. Wang, et. al. has carried out delay analysis for a cognitive radio network based on a stochastic fluid queue approach and modeled the system using Poisson driven stochastic differential equations [5]. The impact of the PU traffic on SUs' queue lengths and the gain of using multiple PU channels were examined. Adaptive algorithms, using local information only, have been developed to find the optimal contention probabilities that achieve the minimum mean queue lengths and thus the minimum queueing delays of secondary users. The analysis and numerical examples revealed that the mean queue lengths of secondary users increase as the duty cycle of the primary users' traffic increases, pointing to the impact of PU activity on the delay performance of secondary users. Also, when multiple PU channels were employed, a decrease in the mean queue lengths, indicating a multichannel gain was observed. Moreover, if each secondary user is equipped with two interfaces, there is a decrease in the mean queue lengths because of the gain of using two choices. The dependency on the queue lengths of the contention probabilities introduces a strong coupling across SUs', making it challenging to analyze SUs' queueing lengths and thus the delay performance.

Y. Liu and W. Gong has considered a single low priority queue flow [6] whereas S. Wang, et. al. considered fluid queue in which SUs contend for the channels using random access [5]. It has considered a fluid queue approximation approach to study the steady-state delay performance of SUs, for cases with a single PU channel and multiple PU channels. Using stochastic fluid models, it represents the queue dynamics as a Poisson driven stochastic differential equations, and characterize the moments of the SUs' queue lengths accordingly.

Recent studies have shown that wireless users in Wi-Fi networks exhibit semi-Markovian property when transiting between the idle and busy states [10]. Along this path, we characterize that the PU activity is driven by an ON-OFF process. We assume that during OFF period, PUs do not generate any data packets and channel is idle for this period. When SUs find idle channel, they generate data packets according to a Poisson distribution process and transmit their information using opportunistic spectrum access technique.

CHAPTER FOUR

METHODOLOGY

4.0: METHODOLOGY

PUs transmit when they are in either ON stage (i.e. actively use the channel and transmit the information) or OFF stage (i.e. idle and they do not transmit their information). Moreover, when PU is OFF, the spectrum is not used and there will be a 'spectrum hole' which is opportunistically used by SUs. This thesis considers a system with M number of secondary users trying to access the spectrum opportunistically when primary users are not using their licensed channels. The spectrum holes (idle band) are further divided into different time slots as shown in Figure 4.1. For given time slots, when there is only one SU, there is no competition or contention to get opportunistic channel access. However, in the case of multiple SUs in the network, they contend for the slots to get transmission opportunities. It is noted that the ON-OFF periods for PUs are typically much longer than that of one slot and information to be transmitted is generated during transition from OFF to ON state of PU. When PUs come back to use their licensed bands, they generate their data to be transmitted from OFF to ON stage and thus pre-empting transmission of SUs can be neglected. We assume that SUs generate data packets based on a Poisson distribution with rate λ where they use the opportunistic channel access to transmit their generated data packets.

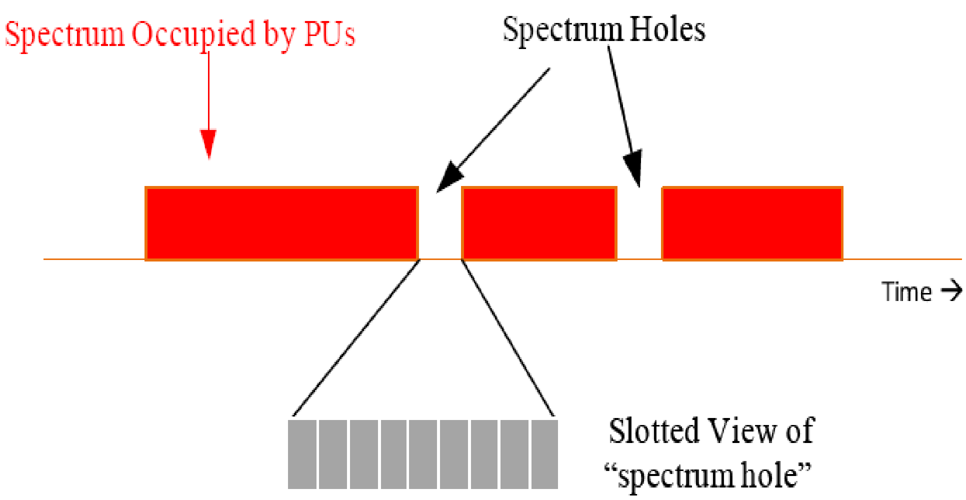

Figure 4.1: Slotted view of a given spectrum hole

The queue dynamic for SUs can be written as:

$$Qlen(n+1) = [Qlen(n) + Arrival(n) - Served(n)]_0^+ \quad (4.1)$$

Where $Q_{len} \geq 0$ is the queue that already exist in the system in which SUs are contending and waiting for transmission opportunities, *Arrival* (n) represents the arrivals to queue in the system, *Served* (n) represents served/departing from the queue in the system.

It is considered that SUs in a CRN use idle frequency/time slots which are derived from spectrum holes not used by PUs. As mentioned, SUs become active and generate the data according to Poisson process with arrival rate $\lambda > 0$. Service time slots are considered independent and exponentially distributed with the service rate $\mu > 0$. At any time t = 0, an observer notices that all n slots are busy and no SUs are waiting for the slot opportunities. If a SU joins the system, becomes active and would like to access the slot, this thesis find waiting probability for newly joining SU to get opportunistic dynamic spectrum access. We assume that there are different service times which depend on channel type or service to SU in different channels. We consider that $S = \min(S_1, S_2, \ldots\ldots\ldots. S_n)$ will be the shortest of the n service slot times. It is well known that S is exponentially distributed with parameter $n\mu$ (Papoulis and Pillai, 2001).

4.1 Waiting probability analysis

Considering X_i be the inter-arrival time of the next CR and assuming that $X_i = x$, we can write

$$P_r\{\{S \leq z\} \big| \{X_i = \mathrm{x}\}\} = 1 - e^{-n\mu x} \quad (4.2)$$

Considering W' be an event that the next SU does not have to wait, we can write

$$P_r[W'] = \int_0^\infty P_r[\{S \leq z\}|\{X_i = \mathrm{x}\}]\,\mathrm{dFxi\ (x)} \quad (4.3)$$

$$= \int_0^\infty (1 - e^{-n\mu x})\,\lambda e^{-\lambda x}$$

$$= \int_0^\infty \lambda e^{-\lambda x} - \lambda \int_0^\infty e^{-(\lambda + n\mu)x}\mathrm{dx}$$

$$= \frac{n\mu}{\lambda + n\mu}$$

$$=1-\frac{\lambda}{\lambda+n\mu}$$

Since $n\mu$ is total idle band that could be used by SUs in CRNs, the idle probability P_I of PUs,

$$P_I = 1-\frac{\lambda}{\lambda+n\mu} \tag{4.4}$$

Now, probability that a SU has to wait is given by

$$P_r[W] = 1 - P_r[W'] \tag{4.5}$$

$$P_r[W] = \frac{\lambda}{\lambda+n\mu}. \tag{4.6}$$

Since the SUs sense and select the licensed channel independently, and the probability of being idle for SUs is independent, considering the probability of being idle for SUs is P_o, probability of selection for SU m among M follows the binomial distribution with probability mass function (PMF) given by [9]

$$P_m = \binom{M}{m}(1-P_0)^m {P_0}^{M-m} \tag{4.7}$$

Where

$$P_0 = 1 - \frac{\lambda}{\mu} \tag{4.8}$$

We consider that when SU finds idle or unoccupied channel, SU contends for the channel with probability p. In the case of single channel, the value of mean service rate, μ, can be computed as

$$\mu = \min\left\{\frac{\lambda}{1-P_0}, 1\right\} \tag{4.9}$$

In the case of single PU channel and M number of SUs, the mean service rate can be calculated as

$$\mu = \min\left\{\frac{\lambda}{M(1-P_0)}, 1\right\} \tag{4.10}$$

4.2 Probability of acquiring one or more slots for transmission opportunities

We also investigate the probability that the next SU finds exactly one slot available for its transmission. We consider that $S(1) < S(2) < \ldots < S(n)$ are the ordered sequence of transmission completion time. It is well known that $S(1) = \min\{S1, S2, \ldots, Sn\}$ is exponentially distributed with parameter $n\mu$. Similarly, $S(2) = \min\{S2, S3, \ldots, Sn\}$ is exponentially distributed with parameter $(n - 1)\mu$. Consider $S(1) = s$ and X be the inter-arrival time of the next SU, and assume that $X = s + x$ for some $x \geq 0$. Then, we are interested in finding the probability that exactly one slot is available for SU (i.e., the event $A1$), that is,

$$\mathrm{P}[A1] = P_r[\{S(2) > s + x\}]|S(2) > \mathrm{s}|$$

Service time is memory less, so we can write

$$P_r[A1] = \Pr[\{S(2) > s + x\}|S(2)\mathrm{s}|] \qquad (4.11)$$

$$= \Pr[S(2) > x]$$

Using similar approach as in 3.3

$$P_r = \frac{\lambda}{\lambda + (n-1)\mu} \qquad (4.12)$$

To provide option for secondary users to select the slots, there should be presence of more than one idle slots. To find the probability that the next arriving CR user will find at least two slots available so that it could choose the better one, we consider $A0$, $A1$ and $A2$ be, respectively, the disjoint events that the CR user finds 0, 1 or at least 2 slots available. Now,

$$P_r[A_0 \cup A_1 \cup A_2] = 1 \qquad (4.13)$$

Now,

$$\begin{aligned} P_r[A_2] &= 1 - P_r[A_0 \cup A_1] \\ &= 1 - [1 - P_r[A_0 \cup A_1]' \\ &= P_r[A_0 \cup A_1]' \qquad (4.14) \\ &= P_r[A_0' \cap A_1'] \\ &= P_r[A_0]' P_r[A_1]' \\ &= (1 - P_r[A_0])(1 - P_r[A_1]) \end{aligned}$$

Following the same procedure as above,

$$P_r[A_0] = \frac{\lambda}{\lambda + n\mu} \qquad (4.15)$$

$$P_r[A_1] = \frac{\lambda}{\lambda + (n-1)\mu} \tag{4.16}$$

From equation 4.14, 4.15 and 4.16 we get

$$P_r[A_2] = \frac{n\mu}{\lambda + n\mu} \times \frac{(n-1)\mu}{\lambda + (n-1)\mu} \tag{4.17}$$

4.3 Stability condition and probability of successful transmission

Secondary users should be equipped with a buffer to store incoming packets in order to process the data. Time T taken by the receiver to process B bits of information of a packet can be expressed as

$$T = \frac{B}{BW\ \log_2(1 + \Gamma)} \tag{4.18}$$

Where BW is the bandwidth that is used by the secondary users and Γ is the signal to noise ratio at the receiver of secondary user.

Considering the received signal to be independent and identically distributed (i.i.d.) with zero mean and σ_s^2 variance, and noise that corrupts the received signal assumed to be the additive white Gaussian noise (AWGN) and i.i.d. with variance of σ_n^2 , the SNR of a SU is given by

$$\Gamma = \frac{\sigma_s^2}{\sigma_n^2} \tag{4.19}$$

As the number of SUs increases, the queue length will be long and many SUs will be waiting for the transmission opportunity. The stability condition for CR system is that the average arrival rate λ is less than the average service rate μ [9], that is

$$\lambda < \mu \tag{4.20}$$

Where

$$\mu = \frac{1}{E[T]} \tag{4.21}$$

$$\frac{1}{E[T]} = min\left\{\frac{\lambda}{1-P_0}, 1\right\} \tag{4.22}$$

The queue length given by equation 4.1 will be long and finally the system will be unstable which results in making the secondary users to wait for a long time to get access to the idle band.

We take a fluid queue approximation approach to study the steady-state delay performance of SUs, for cases with a single PU channel and multiple PU channels. Using stochastic fluid models, we represent the queue dynamics as Poisson driven stochastic differential equations, and characterize the moments of the SUs' queue lengths accordingly. Using the above derivation and assumptions this thesis analyzes the waiting probability with variations in secondary users, no of slots, arrival rate and service rate.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.0 : RESULTS AND DISCUSSIONS

When there is only one secondary user trying to access a system, there is no matter of contention and there is no issue of delay. But when there is more than one secondary user trying to access the hole sensed in the spectrum, there is certain delay in the network to provide access to secondary user. A system with M number of SUs in a CRN is considered where SUs contend for opportunistic channel access when PUs are not using their licensed channels. A spectrum hole (idle band) left idle by PUs is divided into different number of slots with slot duration normalized to be 1. As mentioned above, it is assumed that PUs follow the ON-OFF pattern so that SUs identify the spectrum holes using any one of available spectrum sensing techniques or search in a geo-location database for idle bands and use those opportunities avoiding the harmful interference to the PUs. If there are no idle bands, SUs are not allowed to transmit their information at all. However, it is assumed in the simulation that there are idle bands and M numbers of secondary users are contending to access the network.

Table 5.1 Simulation parameters

Λ	Arrival rate of secondary Users
μ	Service rate of system
P_r [W]	Waiting Probability
M	Number of Secondary Users
N	Number of Slots
P_r [A1]	Probability that CR user finds 1 slot available.
P_r [A2]	Probability that CR user finds at least 2 slots available

In the first experiment, it is assumed that all the primary users are not active in the system and there is presence of some idle bands but all slots are already used by

SUs. That means that there is no slot left for a new SU. After some time, new SU joins the system using Poisson distribution with the parameter λ = 0.40 and the service rate of the system is μ = 0.90.

For this scenario, the variation of waiting probability using equation 4.6 for a newly joined SU is computed and plotted. Number of slots 'n' is varied with slot duration normalized to be 1 to find the waiting probability for a given SU as shown in Figure 5.1 and 5.2.

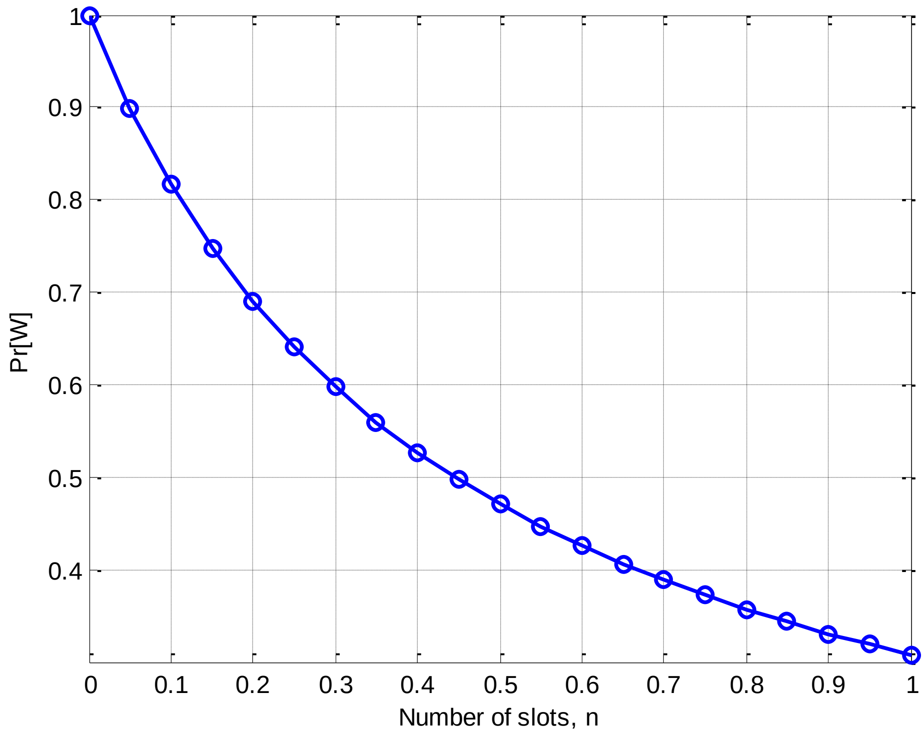

Figure 5.1: Variation of probability of waiting for SU for different number of slots (with λ = 0.40 and μ = 0.90)

It is observed that the waiting probability (i.e., waiting time) for a newly joined SU decreases when the number of slots increases. Increase in the number of slots provides more transmission opportunities for secondary users since there would be sufficient slots. The secondary users could get transmission opportunities more quickly which reduces the waiting period or delay for SUs to access the network. Increase in number of slots thus will be a boosting factor to give high QoS in regards to probability of waiting.

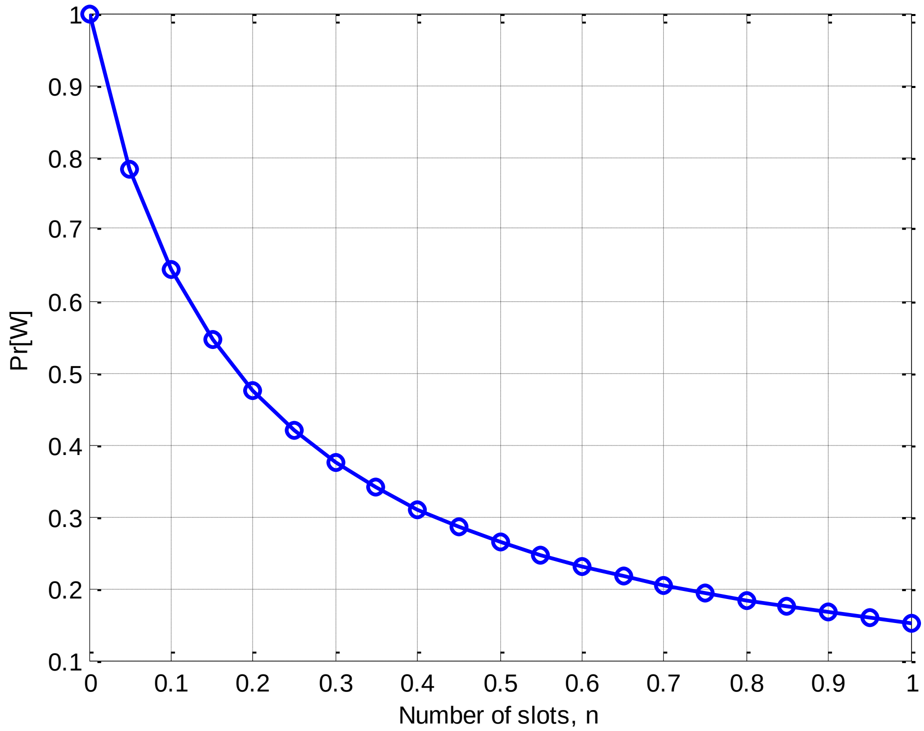

Figure 5.2: Variation of probability of waiting for SU for different number of slots (with $\lambda = 0.90$ and $\mu = 5$)

The arrival rate is another important factor in determining the delay for secondary users to get access in the network. It is already stated above that the service rate of a system should be higher than the arrival rate for the system to be stable.The variation of waiting probability for variable arrival rate of SUs as given by equation 4.6 for a given number of slots is plotted as shown in Figure 5.3 and 5.4.

It is observed that the probability of waiting (i.e. waiting time) increase when the arrival rate of SUs increases as shown in Figure 5.3 and 5.4. This results shows that increase in a number of SUs results in longer queue of SUs for a given number slots for opportunistic spectrum access. Furthermore, increase in a number of SUs results in increase in waiting time for SUs to get channel access and transmission opportunities.

Next, we we looked at the variation of service rate as a function of number of SUs for a given CR system. For a randomly generated probability of *po* and a given number of slots *n*, we computed the average service rate using equation (4.10).

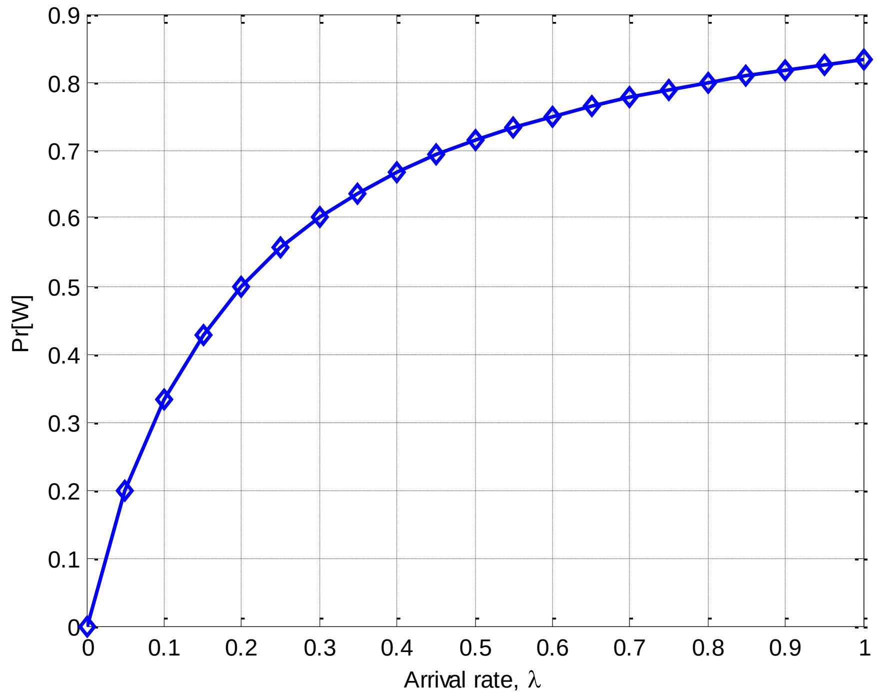

Figure 5.3: Variation of probability of waiting for SUs for different arrival rate (λ) (with λ = 1.0 and μ = 1.0)

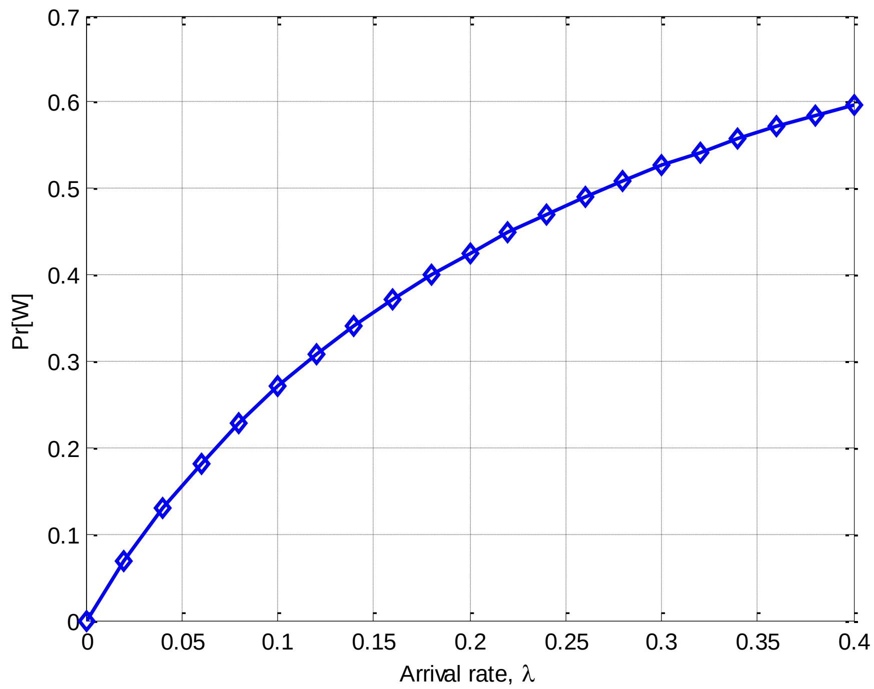

Figure 5.4: Variation of probability of waiting for SUs for different arrival rate (λ) (with λ = 0.4 and μ = 0.9)

The probability of selecting an idle band by a SU and the probability of being idle for the SU are independent events. We computed the average of the probability *po* for different number of SUs and plotted in Figure 5.5. The variation in average value of probability *po* is not noticeably different for different number of SUs M = {1, 3, 15, 40}.

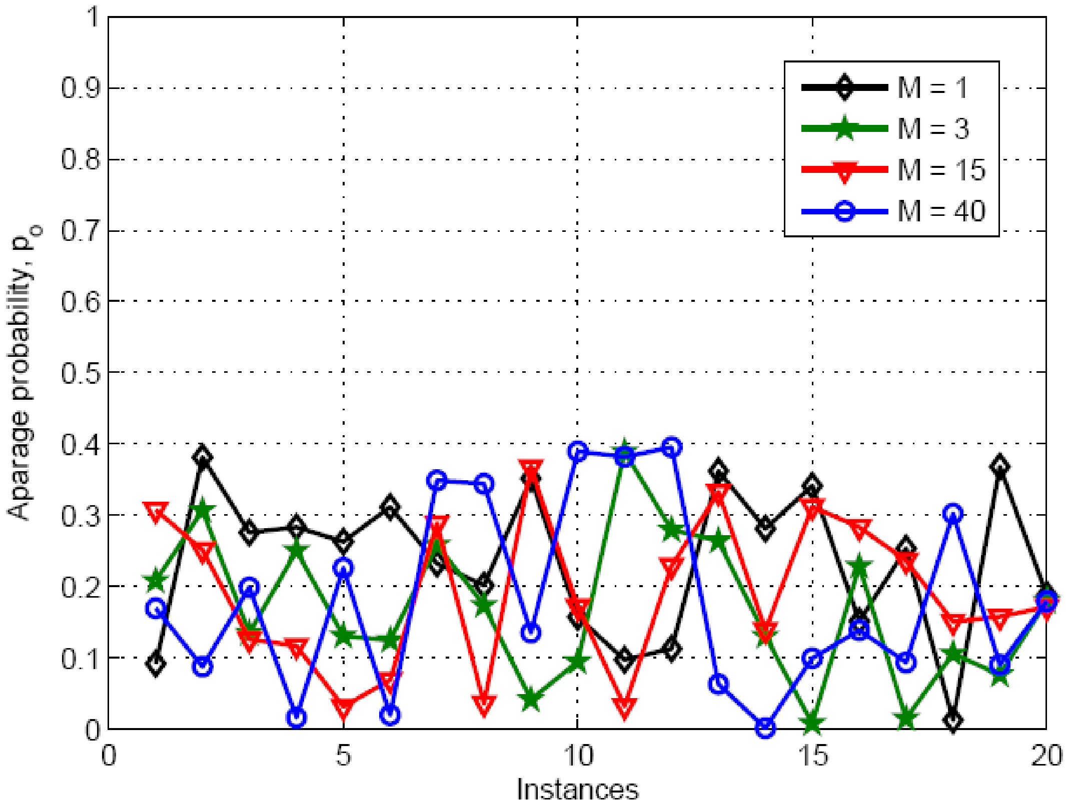

Figure 5.5 Variation of average probability (*po*) for different number of SUs (M)

We then plotted the variation of average service rate for SUs M = {1, 3, 15, 40} in Figure 5.6. When there is only one SU, as there is no competition, the average service rate achieved by the SU is the highest among others as shown in Figure 5.6.

We observed that the average service rate is decreasing with increasing number of SUs, and the average service rate is lowest among all when the number SU is the highest (i.e., 40 in this case).

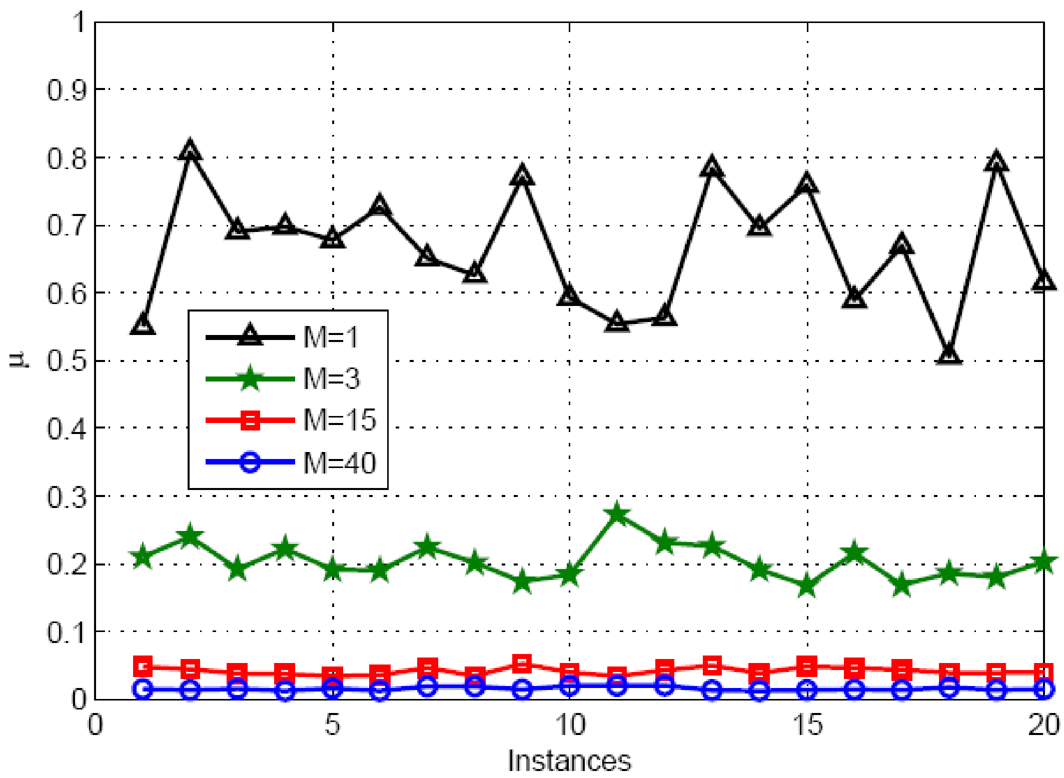

Figure 5.6: Variation of average service rate (μ) for different number of SUs (M) in CRN

Finally, we assumed that there are no slots left for new arriving secondary users. All the available slots are occupied by existing SUs. In this setup, we looked at the probability that the new SU finds only one slot in the case of single primary user channel or at least 2 slots in the case of multiple primary user channels. For a given arrival rate λ, service rate μ and for different number of slots *n*(normalized), we computed the probability that the newly joining SU finds exactly one slot by using equation (4.16) or at least 2 slots by using equation (4.17). We then plotted the variation of probabilities as shown in Figure 5.7 and 5.8.

By observing Figure 5.7 and 5.8, we noted that the probability of getting one or at least two slots is lower when there is few numbers of slots in the system. Also, it is noted that the probability of getting one or at least two slots by a SU increases with the increasing number of slots. The difference in probability of getting one or at least two slots is higher i.e. approximately 8% for less number of slots than that for the highest normalized number of slots i.e. less than 2% as shown in Figure 5.7.

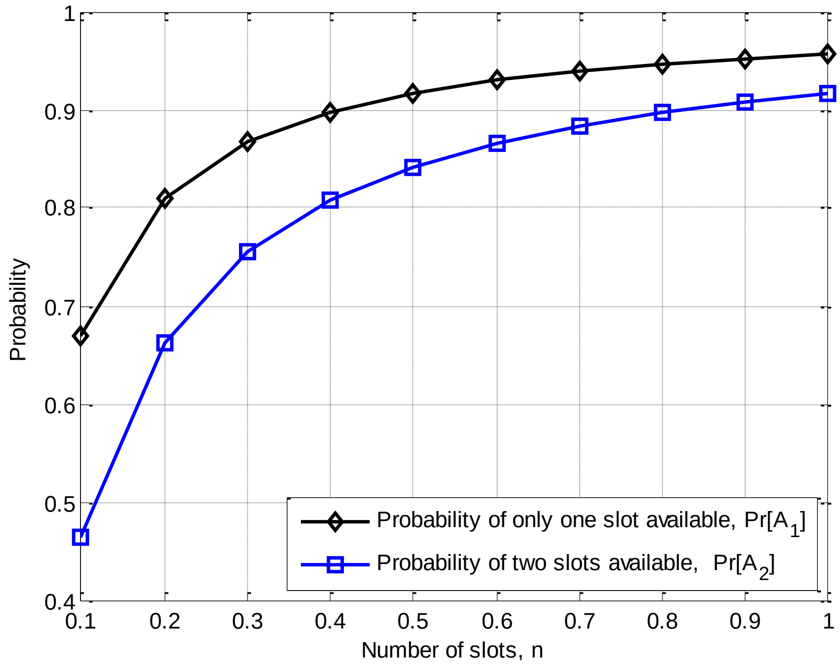

Figure 5.7: Variation of probabilities that the CR user finds only one slot or 2 slots available (with $\lambda = 0.4$ and $\mu = 0.9$)

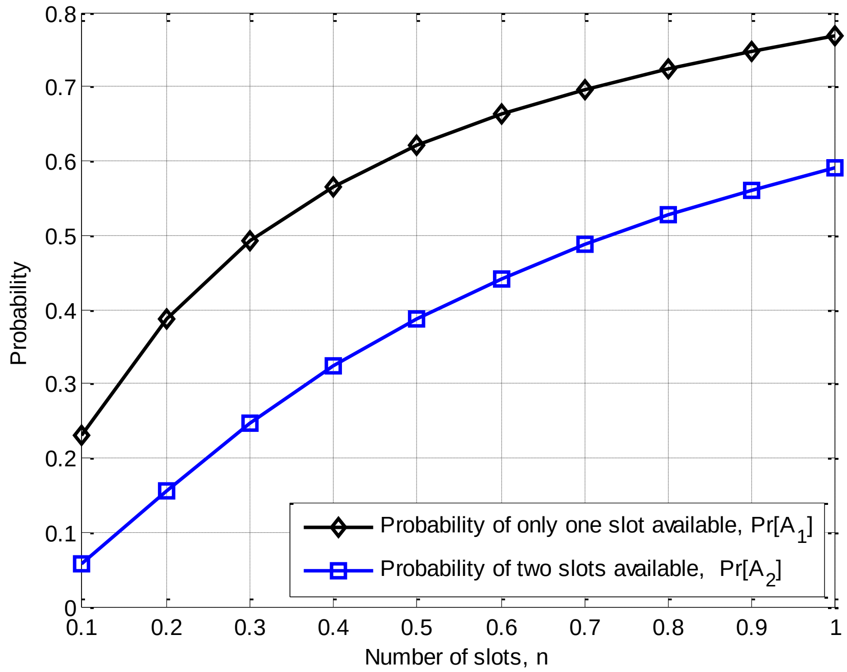

Figure 5.8: Variation of probabilities that the CR user finds only one slot or 2 slots available (with $\lambda = 0.9$ and $\mu = 0.3$)

CHAPTER 6

EPILOGUE

6.1 Conclusion

Cognitive Radio Network has two types of users i.e Secondary and Primary Users. SUs try to access the vacant band whenever PUs are not active in the system. Whenever there is only one SU, there is no matter of contention between users.The secondary users get direct access to the spectrum if there is only one secondary user trying to access the spectrum. But if two or more SUs become active at an instant, they contend for transmission opportunities in TDMA over idle PU channels.There should be some factor or rule to define whom to give access at that time when more than one users try to access the same range of spectrum at the same time. One users get access to the system and other user had to wait for certain time unless other range of spectrum is vacant. In the later case, waiting probability analysis is importantas it helps to define the delay that secondary users had to face for opportunistic spectrum acces in CRNs which is a important factor in defining the QoS of system. Waiting probability gives the secondary users a clear picture of the type of service they get from Cognitive Radio System.

Service rate that a system provides to the users, arrival rate or arrival pattern of secondary users in the system, no of secondary users and no of slots of the available frequency are important factor that affects the probability SUs has to wait to get access to network. Service rate given to secondary users should be greater than the arrival rate of seconday users for the system to be stable and efficient. It is observed that the average service rate is decreasing with increasing number of SUs and the average service rate is lowest among all when the number SU is the highest. The trade-off between different parameters is required to make an efficient opportunistic dynamic spectrum access by SUs in CRNs.The analysis shows that the the waiting probability of SUs decreases when number of slots are increased. As the number of secondary users increases the waiting probability of secondary users also increases as they have to compete for accessing the same spectrum in a defined time.

It is also analysed that the average service rate is decreasing with increasing number of SUs, and the average service rate is lowest among all when the number SU is the highest. When there is only one SU, as there is no competition, the average service rate achieved by the SU is the highest. The analysis and results have revealed that the probability of getting one or at least two slots is lower when there is few numbers of slots in the system and increases with the increasing number of slots either in single PU channel or multiple PU channel.

6.2 Future Enhancements

This thesis gives a systematic analysis of waiting probability of unlicensed users which aids to define the QoS of Cognitive Radio System. The proposed approach is applicable to single input single output systems. Future work can be done to address the issue of multiple-input and multiple-output for the broadband wireless communication.

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