MODELING AND PERFORMANCE ANALYSIS OF COGNITIVE RADIO NETWORKS

by

Derya Çavdar

B.S., Computer Engineering, Boğaziçi University, 2007

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Computer Engineering
Boğaziçi University
2009

MODELING AND PERFORMANCE ANALYSIS OF COGNITIVE RADIO NETWORKS

APPROVED BY:

Assoc. Prof. Fatih Alagöz (Thesis Supervisor)	....
Assist. Prof. Hacı Ali Mantar	....
Assist. Prof. Tuna Tuğcu	....

DATE OF APPROVAL: 23.01.2009

DEDICATION

This thesis is dedicated to

my family, who offered me unconditional love and support throughout my life.

ACKNOWLEDGEMENTS

I would like to thank my thesis supervisor Assoc. Prof. Fatih Alagöz. His encouragement and convincing nice talks lead me to start my academic life. I want to thank him for being so kind and tolerant to me. I have been really lucky to have the chance of knowing him and working with him.

I especially want to thank to Assist. Prof. Tuna Tuğcu, for his guidance during my research. His perpetual energy and enthusiasm in research motivated me. In addition, he was always accessible and willing to help me.

I am also really grateful to Birkan Yılmaz for his accompany and interest, concern, and valuable counsel on research. Also he always motivates me during the critical stages of this study. As a result, research life became easier, smooth and rewarding for me. This thesis would certainly not come to an end without him. I am very pleased to study with him and I wish to continue studying with him.

I also would like to express my deep and sincere gratitude to all my friends (Gürkan, Birkan, Suzan, Şükrü, Didem, Gaye, İlker, Yunus, Rabun, Çetin, Gül ...) in Computer Engineering department, for all graduate students in Satlab, Netlab and in other labs. I want to thank these nice people for the pleasant time I had with them. Special thanks to Gürkan Gür and Suzan Bayhan for always answering my questions, concerning me and being very helpful to me.

My deepest gratitude goes to my family, my parents Sema, Halil Çavdar and my "little" brother Burak Çavdar for their unflagging love and support throughout my life. I also want to thank to my cousin Reyhan Taşpınar that she always listens to me, encourages my interests and supports me unconditionally.

This research is partially supported by The State Planning Organization of Turkey (DPT), under grant numbers $DPT03K120250$ and $DPT2007K120610$ and Scientific and Technical Research Council of Turkey (TUBITAK) under grant number $108E101$.

ABSTRACT

MODELING AND PERFORMANCE ANALYSIS OF COGNITIVE RADIO NETWORKS

Cognitive radio heralds the next step in the evolution of wireless communications. Cognitive radio networks are inherently priority based and preemptive. Hence, keeping track of each resource in each cell is mandatory. In this thesis, an analytical model for infrastructure based cognitive radio systems is proposed, and its performance is evaluated under even and uneven traffic scenarios in a multiple cell environment. Performance metrics like probabilities of dropping and blocking for primary and secondary users as well as forced termination and forced frequency handoff for secondary users are investigated, and the analytical model is verified with simulations. In addition to the analytical model, a new capacity assignment method is proposed to compensate for uneven traffic load distribution. The proposed method considers offered traffic, hop count to the heavily loaded cell, and velocity of mobile users during capacity assignment and performs better in terms of probability of blocking, dropping, and forced termination.

ÖZET

AKILLI RADYO AĞLARININ MODELLENMESİ VE PERFORMANS ANALİZİ

Akıllı radyo kablosuz iletişim teknolojilerinde yeni bir açılıma öncülük etmektedir. Akıllı radyo ağları doğası gereği sonsuz öncelikli düzenceye sahiptir. Bu nedenle her kaynağın hücre bazlı olarak takip edilmesi zorunludur. Bu tezde altyapı destekli akıllı radyo mimarisi için analitik model önerilmiş ve bu modelin tektürel ve çoktürel trafik senaryoları altında, çok hücreli ortamda performansı incelenmiştir. Performans ölçütleri olarak, birincil ve ikincil kullanıcılar için bloke olma ve bağlantı kopması olasılıkları, ikincil kullanıcılar için ayrıca zorunlu sonlandırma ve zorunlu frekans değiştirme olasılıkları incelenmiştir. Analitik model simülasyonlarla doğrulanmıştır. Analitik modele ek olarak çoktürel trafiğin etkilerini telafi etmek için yeni bir kapasite planlama yöntemi önerilmiştir. önerilen yöntem sunulan trafik, ağır yüklü hücreye hoplama uzaklığı ve hareketli kullanıcıların hızını dikkate alarak atama yaparak bloke olma, bağlantı kopması ve zorunlu sonlandırma ölçütlerinde daha iyi sonuçlar elde etmektedir.

TABLE OF CONTENTS

DEDICATION . . . iii
ACKNOWLEDGEMENTS . . . iv
ABSTRACT . . . vi
ÖZET . . . vii
LIST OF FIGURES . . . x
LIST OF TABLES . . . xiii
LIST OF SYMBOLS/ABBREVIATIONS . . . xiv
1. INTRODUCTION . . . 1
1.1. Contribution of the Thesis . . . 2
1.2. Organization of the Thesis . . . 2
2. BACKGROUND INFORMATION . . . 4
2.1. Cognitive Radio . . . 4
2.1.1. Spectrum Sensing . . . 6
2.1.2. Spectrum Decision . . . 7
2.1.3. Spectrum Sharing . . . 8
2.1.4. Spectrum Mobility . . . 9
2.2. Markov Chains . . . 9
2.3. Related Work in the Literature . . . 11
3. MODELING OF CRN . . . 15
3.1. Network Architecture . . . 15
3.2. Analytical Model of the CR System . . . 17
3.2.1. State Definition . . . 18
3.2.2. Elementary Events . . . 19
3.2.2.1. New Connection Event . . . 19
3.2.2.2. Handoff Event . . . 21
3.2.2.3. Connection Release Event . . . 21
3.2.3. Traffic Arrival Process . . . 21
3.2.4. Cell Dwell and Connection Holding Time . . . 22
3.2.5. State Transitions . . . 24

3.2.6. Analytical Solution 25
4. CAPACITY PLANNING PROBLEM IN CRN 29
4.1. Problem Definition 30
4.2. Proposed Solution 30
4.2.1. Elementary events 31
4.2.2. Capacity planning 32
4.2.2.1. Capacity Planning Algorithms 32
5. SIMULATION RESULTS 34
5.1. Parameters, Assumptions, and Metrics 34
5.2. Evaluation of Analytical Model 36
5.3. Effect of System Parameters on CRN System Performance 37
5.3.1. Effect of Sensing Error 38
5.3.1.1. Holding Time Analysis 38
5.3.1.2. Connection Request Rate Analysis 43
5.3.1.3. Velocity Analysis 44
5.3.2. Effect of Heterogeneity 45
5.3.3. Effect of Heterogeneity with Sensing Error 47
5.4. Effect of Capacity Planning on CRN System Performance 49
6. CONCLUSIONS 54
REFERENCES 55

LIST OF FIGURES

Figure 2.1. Hole concept 5

Figure 2.2. Cognition cycle 6

Figure 3.1. Network architecture of IbCRN 16

Figure 3.2. Flow diagram for handling new connection request ($\epsilon = 0$) 20

Figure 3.3. Flow diagram for handling handoff request ($\epsilon = 0$) 22

Figure 3.4. Transitions from example state due to a new connection 24

Figure 3.5. Transitions from example state to possible states by connection handoff 26

Figure 5.1. Comparison of simulator results and analytical results ($r = 250\,m$, $v = 0.5\,m/s$, $\lambda_i^{pri} = 0.002$ $conn/s$, $\lambda_i^{sec} = 0.004$ $conn/s$) 36

Figure 5.2. Comparison of simulator results and analytical results ($r = 250\,m$, $T_{hold} = 2000\,s/conn$, $\lambda_i^{pri} = 0.004$ $conn/s$, $\lambda_i^{sec} = 0.008$ $conn/s$) . . 37

Figure 5.3. System topology for the tests 38

Figure 5.4. Effect of connection holding time on utilization ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$) 39

Figure 5.5. Effect of connection holding time on P_b^{sec} and $P_d^{pri}(sensing)$ ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$) . . . 40

Figure 5.6. Effect of connection holding time on N_a^{sec} ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$) 41

Figure 5.7. Effect of connection holding time on N_a^{pri} ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\ conn/s$, $\lambda_i^{sec} = 0.028\ conn/s$) 42

Figure 5.8. Effect of connection holding time on $P_d^{sec}(forced)$ and $P_d^{sec}(mobility)$ ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$) 43

Figure 5.9. Effect of connection request rate on P_b^{sec} and $P_d^{sec}(forced)$ ($r = 250\,m$, $v = 1.2\,m/s$, $T_{hold} = 650s$) 43

Figure 5.10. Effect of velocity on (a)number of events ($r = 250\,m$, $T_{hold} = 650s$, $\lambda_i^{pri} = 0.014 conn/s$, $\lambda_i^{sec} = 0.028 conn/s$) (b)average forced handoff ($r = 250\,m$, $T_{hold} = 650s$, $\lambda_i^{sec} = 2 \times \lambda_i^{pri}$) 44

Figure 5.11. Effect of heterogeneity on P_b^{sec} and $P_d^{sec}(mobility)$ ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$ for $i \neq 3$) . . 46

Figure 5.12. Effect of heterogeneity on $P_d^{sec}(forced)$ and number of events ($r = 250\,m$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$ for $i \neq 3$) 46

Figure 5.13. Effect of connection holding time on P_b^{sec} and $P_d^{sec}(mobility)$ ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$ for $i \neq 3$) 47

Figure 5.14. Effect of connection holding time on N_a^{pri} and N_a^{sec} ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$ for $i \neq 3$) . . 48

Figure 5.15. System topology for the tests 49

Figure 5.16. Total utilization for different hop numbers $v = 1.2\ m/s$ 51

Figure 5.17. $P_d^{sec}(forced)$ and $P_d^{sec}(mobility)$ for different hop numbers ($v = 1.2\,m/s$) 51

Figure 5.18. Effect of velocity on P_b^{sec} for different hop numbers 52

LIST OF TABLES

Table 4.1. Effect of bursty traffic on performance metrics 29

Table 5.1. Primary, secondary, and total utilization values with different T_{hold} values 39

Table 5.2. Dropping probability values for secondary users 42

Table 5.3. Capacity assignment values for different algorithms 50

LIST OF SYMBOLS/ABBREVIATIONS

$\mathbb{B}$	Set of CogBSs in the system
b_i	i^{th} CogBS
C_i	Number of frequencies belonging to CogBS b_i
C_{tot}	Total number of frequencies
d	Metric that represents the difference between two probability vectors
$\mathbb{F}_{b_i}$	Set of frequencies assigned to CogBS b_i
f_j	Frequency j
$f_V(v)$	Probability distribution of moving speeds of users
H	Set of hop counts
L	Perimeter of the cell
M_i	Performance metric value for i^{th} hop distant cells
$\overline{M}$	Mean value of the performance metric
N_a	Number of total active connections
N_a^{pri}	Number of active primary connections
N_a^{sec}	Number of active secondary connections
N_b^{sec}	Number of secondary blocking
$N_d^{sec}(forced)$	Number of secondary forced termination due to primary preemption
$N_d^{sec}(mobility)$	Number of secondary dropping due to mobility
n_i	Hop distance to the most loaded cell
$\mathbf{P}$	transition matrix
$\mathbf{P^k}$	kth power of the transition matrix
P_b^{sec}	Probability of secondary blocking
$P_d^{sec}(forced)$	Probability of secondary forced termination due to primary preemption
$P_d^{sec}(mobility)$	Probability of secondary dropping due to mobility
$P_d^{pri}(sensing)$	Probability of primary dropping due to sensing error
$\mathbf{p}_{ij}^{(n)}$	Probability of going from state i to state j in n time steps

$\mathbf{P}_{s_i}(t)$	Probability that the system is in state s_i at time t
$\mathbf{Pr}(X_n = x)$	The marginal probability distribution over states at time n
$\mathbf{Pr}(X_{n+1} = j \mid X_n = i)$	Probability of the next state is j given that current state is i
r_{b_i}	Radius of cell b_i
S	Area of the cell
$\mathbb{S}$	Set of states of the whole system
s_i	ith state
T_{dwell}	Cell dwell time of users
$T_{dwell}(b_i, j)$	T_{dwell} of the connection at frequency f_j and in cell of b_i
T_{hold}	Connection holding time of active users
T_{hold}^{pri}	Connection holding time for primary users
T_{hold}^{sec}	Connection holding time for secondary users
$U_{b_i}(t)$	Number of users in cell of b_i at time t
X_i	ith random variable with Markov property
v	Mean user speed

γ_{ij}	Rate of flow from state s_i to s_j
Δ	Cumulative difference of performance metric
Δ_i	Difference of performance metric for i^{th} hop cells
$(\epsilon, \sigma_\epsilon)$	Mean sensing error and variance of the sensing error
κ_i	Weight parameter of Load and Hop based Assignment method
$\overline{\kappa}(n_i)$	Mean κ_i for cells with n_i hop distance to most loaded cell
λ_i^{pri}	Mean connection request arrival rate for primary users in cell of b_i
λ_i^{sec}	Mean connection request arrival rate for secondary users in cell of b_i
μ_{dwell}	Mean outgoing rate of users from a cell
μ_{hold}	Mean connection release rate
ρ_i^{sec}	Expected number of secondary connection request arrivals in cell of b_i within $1/\mu_{hold}$ seconds
ρ_i^{pri}	Expected number of primary connection request arrivals in cell of b_i within $1/\mu_{hold}$ seconds

π	stationary distribution
ρ_{max}^{pri}	Maximum number of primary connection request arrivals in within $1/\mu_{hold}$ seconds
ρ_{max}^{sec}	Maximum number of secondary connection request arrivals in within $1/\mu_{hold}$ seconds
τ	Time that the system reaches equilibrium
φ_i	Weight parameter of Averaged Load and Hop based Assignment method
Ω_{b_i}	Cell of b_i

ALHA	Averaged Load and Hop based Assignment method
AN	Ambient Networks
AWGN	Additive White Gaussian Noise
BS	Base Station
CogBS	Cognitive Base Station
CogMT	Cognitive Mobile Terminal
CR	Cognitive Radio
CRN	Cognitive Radio Network
CRSP	Cognitive Radio Service Provider
DSA	Dynamic Spectrum Access
EqA	Equal Assignment method
FCC	Federal Communications Commission
FSA	Fixed Spectrum Allocation
GLL	Generic Link Layer
HE	Homo Egualis
IbCRN	Infrastructure-based Cognitive Radio Network
LABT	Listen and Avoid Before Talk
LBT	Listen Before Talk
LHA	Load and Hop based Assignment method
OFDM	Orthogonal Frequency Division Multiplexing
OPNET	Optimized Network Evaluation Tool
QoS	Quality of Service

SB	Spectrum Broker
SDR	Software-Defined Radio
SM	Spectrum Manager
SNR	Signal to Noise Ratio
TDD	Time Division Duplex

1. INTRODUCTION

Rapid growth of wireless telecommunication systems results in an increasing demand for long term spectrum allocation. Most of the spectrum is currently regulated by fixed spectrum assignment strategy, and a considerable amount of the assigned spectrum is wasted due to high variation in usage patterns [1]. Since spectrum is a very valuable and scarce resource, it should be used intelligently. However, fixed spectrum assignment strategy is not capable of managing the spectrum efficiently.

The most efficient method of increasing spectrum efficiency is to allow wireless users to share a wide range of available spectrum. Hence, *Cognitive Radio (CR)* has been introduced as a new paradigm for achieving much higher spectrum utilization by dynamically accessing and sharing the spectrum with current radio devices. CR was first proposed by Mitola [2, 3] as a way of seeking fragments of idle spectrum and adapting signals accordingly. In the United States, the *Federal Communications Commission (FCC)* has published a notice of inquiry [4] in which the television band is made available as a set up for cognitive radio research purposes. The analysis of digital TV protection from CR based on *Orthogonal Frequency Division Multiplexing (OFDM)* is proposed in [5]. These developments have led to a rapid increase in research about CR, in fields like network architecture design, spectrum sensing, resource allocation, physical layer issues, MAC layer issues, and economics.

The goal of the resource coordination approach is to dynamically allocate spectrum to several systems based on their current traffic demand instead of a *Fixed Spectrum Allocation (FSA)* strategy [6]. To this end, centralized decision-making as well as a means of exchanging information/decisions are necessary and can be implemented either as an integrated or interworking solution. Many studies for resource coordination are such as [7], [8], and [9]. In [7] *Generic Link Layer (GLL)*, as proposed in the context of the *Ambient Networks (AN)* project [10], has been used as a solution for multi-radio environments beyond 3G.

1.1. Contribution of the Thesis

The contribution of our thesis can be summarized as follows:

- An analytical model for the IbCRN architecture in a multi-cell environment is proposed. The main difference from similar work in the literature is the adaptation of multi-cell environment for analysis.
- A CRN simulator is implemented in order to evaluate the performance of CRN in multi-cell environment.
- Effect of bursty traffic and sensing error on performance metrics are analyzed.
- The analytical solution is computed for a small topology and compared with the simulation results.
- Three capacity assignment methods EqA, LHA and ALHA are proposed, and performance evaluation of these methods is performed.

1.2. Organization of the Thesis

In this thesis, first we give a network architecture for *Infrastructure-based Cognitive Radio Network (IbCRN)* in Section 3.1. The architecture is composed of multiple cognitive radio base stations and the state of the system depends on the activity of primary and secondary users in each cell. Detailed information about network architecture can be found in our previous work [11]. Secondly, we present the analytical model for the IbCRN architecture in Section 3.2, which defines the states of the system in a multi-cell environment. Then, we implement a CRN simulator to evaluate the performance of CRN in multi-cell environment. With the help of this simulator, we analyze system performance for different scenarios. In the first scenario, effect of sensing error is analyzed. Our model is capable of simulating multi-cell environment with different parameters. This capability enables us to investigate the effect of neighbor cell with bursty traffic. Then, we look at the effect of neighbor cell with bursty traffic in the second scenario. In the third scenario, both sensing error and bursty traffic case is evaluated.

Finally, we study the capacity planning problem in CRN in Section 4.2. We propose three capacity assignment methods EqA, LHA, and ALHA. Then, we evaluate the effect of the proposed algorithms on performance of CRN by utilizing the implemented multi-cell CRN simulator in Section 5.4.

2. BACKGROUND INFORMATION

2.1. Cognitive Radio

As the Federal Communications Commission (*FCC*) remarks in [4], the spectrum we use today is underutilized. A large part of the spectrum is actually not used at all. Therefore, currently many researchers try to discover new methods that can utilize the spectrum efficiently. The solution is the "Cognitive Radio" which presents a challenging topic for the researchers.

CR is a new paradigm for wireless communication. It is first proposed by Joseph Mitola III and Gerald Q. Maguire, Jr [2]. According to Mitola CR is a radio driven by a large store of *a priori* knowledge, searching out by reasoning ways to deliver the services the user wants. After Mitola, Haykin makes a definition of CR as: "Radios that improve spectral efficiency by sensing the environment and then filling the discovered gaps of unused licensed spectrum with their own transmissions" [12].

A CR device operates on *Software-Defined Radio (SDR)* platform. This platform should continuously evolve and adapt: a fully reconfigurable wireless black-box that automatically changes its communication variables in response to network and user demands. In other words, CR reconfigures itself either a network or a wireless node changes its transmission or reception parameters to communicate efficiently avoiding interference with licensed or unlicensed users. This alteration of parameters is based on the active monitoring of several factors in the external and internal radio environment, such as radio frequency spectrum, user behavior, and network state.

CR networks impose unique challenges due to high fluctuation in the available spectrum, as well as the diverse *Quality of Service (QoS)* requirements of various applications [13]. Each CR must have the following capabilities:

- Determining the available portion of the spectrum,

- Selecting the best available channel,
- Coordinating access to this channel with other users,
- Vacating the channel when a primary user is detected.

The main aim of the CR is to determine the best available spectrum and reconfigure its parameters with the help of SDR. CR can operate on the spectrum which is already assigned to licensed users. The cognitive radio enables the usage of temporally unused spectrum, which is referred to as spectrum hole or white space [12]. CR determines the white spaces and operate without interfering licensed users. Alternatively CR shares the same spectrum with licensed users at the same time by adapting its power and/or modulation. So that CR can operate without interfering with the transmission of other licensed users Figure 2.1 [1]. In [12], "cognition cycle" of Mitola

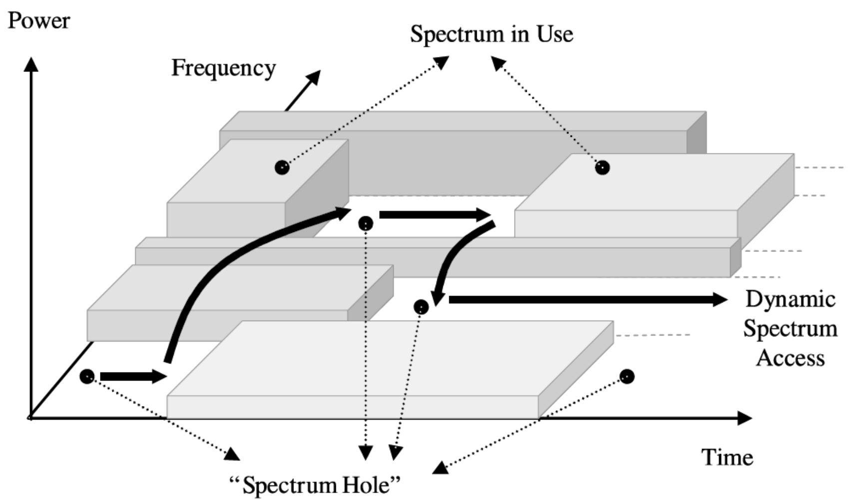


Figure 2.1. Hole concept

is simplified and presented as three interconnected phases. Then "spectrum mobility" phase is added to this cognition cycle. The first phase is spectrum sensing, the second one is spectrum decision, the third one is spectrum sharing and the last one is spectrum mobility.

- Spectrum sensing: The physical layer of the cognitive radio retrieves information from the radio environment and detects the spectrum holes. Spectrum sensing

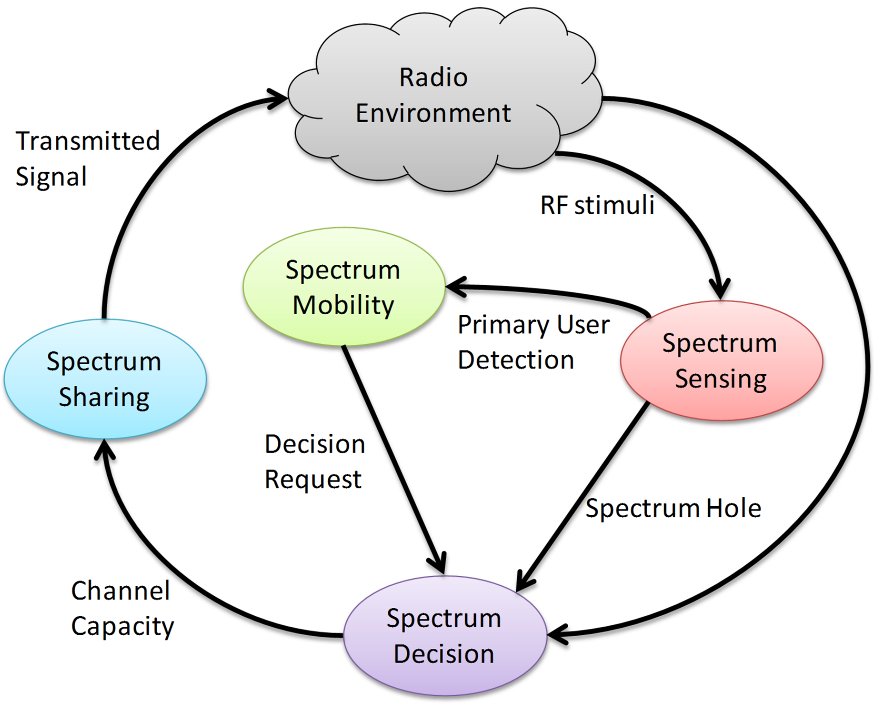


Figure 2.2. Cognition cycle

allows CR to access the licensed bands without interfering with the primary user transmissions.

- Spectrum decision: Spectrum holes are analyzed in terms of interference, path loss, wireless link error rate, link layer delay and expected primary user activity. Cognitive radio selects the best operating channel among the analyzed bands according to its QoS requirements.
- Spectrum mobility: Due to changing radio environment and primary user activity a cognitive radio can perform spectrum and technology handoff and it can continue to communicate on newly gained frequency bands.
- Spectrum sharing: A cognitive radio can fairly share the spectrum with other cognitive radios.

2.1.1. Spectrum Sensing

Spectrum sensing can be divided into two categories according to the detection method: transmitter detection or receiver detection. In the receiver detection method, CR detects the local oscillator leakage power emitted by primary user when primary user receives signals [14]. In the literature there are basically three sensing for transmitter detection: matched filter detection, energy detection and cyclostationary feature detection [15].

When characteristics of the primary user are known by the CR users, matched filter detection is suitable since it maximizes the received *Signal to Noise Ratio (SNR)* in an *Additive White Gaussian Noise (AWGN)* channel [16]. But matched filter detection requires signal information of the primary systems. When the CR does not know the characteristics of the primary user signal but knows the power of the AWGN then energy detection method can be suitable [17,18]. However, energy detector makes false alarms when AWGN is fluctuating. The cyclostationary feature detection method is based on periodic parts of the primary user signal. Modulated signals are composed of sine wave carriers, pulse trains, repeating spreading, hopping sequences, or cyclic preambles, which results in built-in periodicity. These modulated signals can be detected because of their cyclostationary features [15,19]. These features can be detected by using a correlation function [20].

Transmitter detection can be done individually or cooperatively. Cooperative detection provides more accurate information but it has an overhead on the data traffic [21]. Furthermore CR consumes extra power to exchange sensing information with other CRs.

2.1.2. Spectrum Decision

Unused spectrum may be noncontiguous and spread over a wide spectrum. CRs should have the capability to understand the environment and select the best suitable portion of the spectrum. Selecting the best suitable channel is closely related to the primary user activity and channel characteristics. Primary user network statistics like the probability of the primary user appearance on the channel and the expected holding time (channel occupation time) of the primary user on the licensed band are studied in [22, 23] as channel characteristics. In [24] a device-centric spectrum management scheme is proposed in which the user acts according to local interference observations.

The advantage of this scheme is low communication cost. Also the spectrum capacity is another important measure for spectrum decision. The main effect on spectrum capacity calculation is the SNR value.

Spectrum is characterized based on the primary user activity, path loss and interference. According to spectrum characterization and user QoS requirements the most suitable portion of the spectrum is assigned to the CR user. The assigned spectrum can be contiguous or noncontiguous (made up from multiple spectrum portions). In the noncontiguous spectrum case high throughput can be achieved but spectrum handoff is more sporadic and complicated.

2.1.3. Spectrum Sharing

Spectrum sharing techniques can be classified according to architecture, allocation behavior and access technique. Spectrum sharing can be distributed or centralized according to architecture. In the centralized architecture there exists a central controller which manages the spectrum access [25]. Distributed spectrum sharing is preferred when an infrastructure can not be deployed. In distributed architecture each CR decides its spectrum access [26, 27].

According to allocation behavior spectrum sharing techniques can be divided into two methods: cooperative and noncooperative. In cooperative method nodes exchange interference measurements with their neighbors [28, 29]. However in noncooperative method CR only considers itself and no extra message overhead occurs in the network.

The third classification for spectrum sharing in CR networks is based on the access technology. CR determines the white spaces and operate on this spectrum without interfering licensed users. This is called *overlay spectrum sharing* [25, 29]. Alternatively CR share the same spectrum with licensed users at the same time by adapting its power and/or modulation which is called *underlay spectrum sharing* [28].

2.1.4. Spectrum Mobility

Spectrum handoff occurs when CR changes its current operating frequency due to primary user appearance or deteriorated channel conditions. Spectrum handoff can be proactive or reactive. In the reactive spectrum handoff CR detects the primary user after primary user accesses the channel and CR vacates the channel. On the contrary in the proactive spectrum handoff CR estimates the primary user access time and vacates the channel at that time [22]. With more accurate prediction algorithms CR network can operate avoiding interference with primary users.

2.2. Markov Chains

In order to find the analytical solution we use Markov chain and power method in Section 3.2.6. The state probabilities in our dynamic system can be calculated by solving the eigenvalue problem of the transition matrix. In this section we provide a background on discrete time Markov chains.

A Markov chain is a stochastic process $\{X_n \mid n = 0, 1, 2, 3.....\}$ with the Markov property. Because of the Markov property, future states are independent of the past states but depends only on the current state. This is also called memoryless property. Due to the memoryless property future states can be calculated through a probabilistic process instead of a deterministic one. At each step the system may jump to another state from the current state, or remain in the same state, according to a certain probability distribution. The changes of state are called *transitions*, and the probabilities associated with various state-changes are called *transition probabilities*.

$$\mathbf{p}_{ij} = Pr(X_{n+1} = j \mid X_n = i, \ldots, X_0 = i_0) = \Pr(X_{n+1} = j \mid X_n = i) \tag{2.1}$$

where

$$\mathbf{p}_{ij} \geq 0 \quad \sum_{j=0}^{\infty} \mathbf{p}_{ij} = 1 \tag{2.2}$$

Transition probability of going from state i to state j in n time steps as

$$\mathbf{p}_{ij}^{(n)} = \mathbf{Pr}(X_{m+n} = j \mid X_m = i), \quad n \geq 0, i, j \geq 0 \tag{2.3}$$

The marginal distribution $\mathbf{Pr}(X_n = x)$ is the distribution over states at time n. The initial distribution is $\mathbf{Pr}(X_0 = x)$. The evolution of the process for one time step is described by

$$\mathbf{Pr}(X_n = j) = \sum_{r \in S} \mathbf{p}_{rj} \, \mathbf{Pr}(X_{n-1} = r) = \sum_{r \in S} \mathbf{p}_{rj}^{(n)} \, \mathbf{Pr}(X_0 = r) \tag{2.4}$$

If the Markov chain is a time-homogeneous Markov chain, then the process can be described by a single, time-independent matrix. If sum of π_j is one and it satisfies Equation 2.5 then the vector π is called a stationary distribution. If $\mathbf{S}$ is finite, then transition probability distribution is represented by the transition matrix. The (i, j)th element of $\mathbf{P}$ is equal to p_{ij}

$$\pi_j = \sum_{i \in S} \pi_i p_{ij} \tag{2.5}$$

$$\mathbf{P} = \begin{bmatrix} P_{00} & P_{01} & P_{02} & \cdots \\ P_{10} & P_{11} & P_{12} & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ P_{i0} & P_{i1} & P_{i2} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix}. \tag{2.6}$$

If the Markov chain is a time-homogeneous Markov chain, then transition matrix $\mathbf{P}$ does not change at each step. So the k-step transition probability can be computed as the kth power of the transition matrix, $\mathbf{P^k}$. The stationary distribution π is a (row) vector whose entries sum to one that satisfies the equation

$$\pi = \pi \mathbf{P} \tag{2.7}$$

Since $\mathbf{P}$ is a stochastic matrix, $\lim_{k\to\infty} \mathbf{P}^k$ always exists [30, 31]. Let $\mathbf{P}$ be an $n \times n$ matrix, and define $\mathbf{Q} = \lim_{k\to\infty} \mathbf{P}^k$ then

$$\mathbf{QP} = \mathbf{Q}. \tag{2.8}$$

2.3. Related Work in the Literature

Since cognitive radio is a new concept and it also does not have a standard, the performance evaluation studies are generally based on assumptions and proposals. Before doing performance evaluation of cognitive radio, the system should be modeled. In the literature cognitive radio technology is modeled with continuous Markov chains and game theoretical approaches.

CR's are interacting with the outside world so a CRs state is determined by the adaptations of other CRs and with primary radios. In [32] some methodologies suitable for quickly analyzing many cognitive networks with interactive and recursive decision processes are proposed. In order to model CR network three types of approaches are used; formal model of CR, traditional engineering analysis techniques, applying game theory. In Markov chain model the basic assumption is that produced traffic is a Poisson process. Most of the studies which uses Markov chain approach worked with very few numbers of radio systems and users, since the state space will be so large and the chain will be much more complex with the increasing number of radio systems and users. Not only the Markov chain model but also the game theoretic approach cannot deal with a reasonable number of radio systems and users because of the state space complexity.

In [33] a simple analysis is used to show how the utilization of the spectrum can be improved by using cognitive radio. Utilization of spectrum with and without cognitive radios are compared. If the modulation type and/or coding technique is known then channel capacity can be calculated with the use of utilization. In [34] CR is modeled with a continuous Markov chain. In this study both queuing and not queuing cases are considered. In the first case there is no queuing; i.e., if the desired channel is busy the message is not buffered but dropped. It is assumed that both radio systems have equal traffic load and channel occupation time. By writing the state transition equations the probabilities being in any state can be found. By using this model we can calculate the airtime which refers to the ratio of allocation time per radio system type over a reference time (one hour) [35]. In queuing case, equal traffic and traffic load case is considered. To provide fairness among radio system a random access method is proposed in this study. If there is a greedy access mechanism, then the radio system which requires broader bandwidth has less chance to access channel. One way to provide more fairness is to have each radio system contend for accessing the medium with a probability. Then the system can be modeled by modifying the corresponding continuous Markov chain. And another access scheme *Homo Egualis (HE)* society model-based access scheme is proposed. HE exhibits a weak urge to inequality when doing better than the others and a strong urge to reduce inequality when doing worse than the others. The HE version of spectrum access protocol yields near-optimal results. It is seen that spectrum agile radios produce superior airtime performance and blocking probabilities. Another study that uses continuous Markov chain model is [36], which considers channel reservation method to increase throughput and to reduce forced termination probability. However in that study Markov chain is used to model the spectrum access behavior with forced termination of cognitive users by the presence of primary users. There is a tradeoff between forced termination and blocking probability. Thus the goal is to find the optimal number of channels to be reserved.

A different study which focuses on optimal spectrum sharing is [37]. The performance metric of interest in that study is the total amount of data (primary and secondary) that is successfully delivered per unit time, which they refer to as the goodput. Trade off between minimizing the interference to the primary users and maximizing the performance of the entire system by limiting the number of secondary users is investigated. The work tries to find the optimal number of cognitive users subject to primary users in the system where maximum total throughput is achieved. The simulations are done for both perfect sensing, zero interference tolerance and imperfect sensing, non-zero interference tolerance limits cases. In [38] the network performance without and with cognitive radio technology with the function of detecting radio signals to avoid the primary radio system is studied. And it is shown that cognitive radio technology cannot avoid the interference to primary systems whenever hidden primary terminals exist in the network. Two access methods are proposed for cognitive radio system *Listen Before Talk (LBT)* and *Listen and Avoid Before Talk (LABT).* In LBT the CR first senses the channel and decides if all channels belonging to N are idle or not, if idle it begins transmitting. Airtime is used as a performance metric as in [34] and also interference time is considered. Simulation results show that cognitive radio systems with LBT avoid interference. However, with increasing arrival rate of system, cognitive radio systems cannot obtain the opportunity of communication. Cognitive radio systems can obtain the opportunity of communication by using LABT.

In [39] an asynchronous *Time Division Duplex (TDD)* scenario is considered. In this work it is shown that the overall system spectral efficiency can be improved by considering cognitive communications with respect to the traditional system. When channel state information is made available at the transmitters, users know their own channel gains and thus they will adapt their transmission strategy relative to this knowledge. The optimum power allocation is known as water filling allocation. The spectral efficiency is significantly increased with respect to the traditional system without cognition. A game theory approach estimating the throughput of cognitive radios is studied in [32]. Two cognitive radios operating in the same environment are attempting to maximize their throughput. Each radio can implement two different waveforms, lower-power narrow band and higher-power wide band waveform. If both radios choose to implement their narrow band waveforms the signals will be separated in frequency and each radio will achieve a throughput of medium throughput. If one of the radios implements its wide band waveform while the other implements a narrow band waveform then interference occurs. Then the narrow band signal achieves a low throughput while wide band yields high throughput. In the event that both radios choose to implement wide band waveforms then each radio achieves medium throughput but lower than both implementing narrow band.

In literature many works exist about capacity planning for cellular networks. In [40, 41] capacity assignment problem is analyzed. In [42] authors aim at estimating the minimal blocking probability for some simple cellular networks. Some dynamic allocation schemes are analyzed. In [43], Raymond *et al.* present a demand-based engineering method for designing radio networks of cellular mobile communication systems. Automatic selection and configuration of base stations is proposed in [44] for planning effective cellular mobile radio networks. Capacity planning for CR networks is an immature topic and a challenge in CR networks with infrastructure.

3. MODELING OF CRN

In order to find an analytical solution to CRN system, first we give a network architecture for CRN. The system is composed of multiple cognitive radio cells and the state of the system depends on the activity of primary and secondary users in each cell. The elementary events which influence the system state is described. Next, we present the analytical model for the IbCRN architecture, which defines the states of the system in a multi-cell environment.

3.1. Network Architecture

Basically two types of CRN operation modes are studied in the literature: ad hoc and infrastructure-based. In the IbCRN architecture, users communicate through a central controller, which is *Cognitive Radio Base Station (CogBS)*. There exists many advantages of using an infrastructure-based architecture.

Advantages of IbCRN:

- Cellular structure allows effective frequency reuse plans. Hence, spectrum efficiency is improved.
- Time and location dependent frequency usage patterns can be constructed for better resource management to achieve higher throughput and lower outage probability.
- Connection management can be performed by CogBS with a global perspective to maximize utilization.
- Efficient spectrum sensing can be achieved easily by using collaborative methods.
- With the coordination of the cognitive base stations, QoS support can be provisioned better. Also delay and jitter are minimized since multihops are avoided.
- Frequency handoff procedure due to primary activity can be achieved seamlessly.
- Infrastructure allows access to other networks and Internet.
- Infrastructure-based approach also provides solutions to problems such as security

and frequency access rights.

We choose to work with IbCRN and develop the system model for the architecture introduced in [11]. In IbCRN, there is a CR operator, which deploys and maintains an infrastructure and oversees the efficient management of spectral resources. CR system not only consists of CR architecture elements but also other wireless access technology elements. CR system uses its own overlay architecture; there is no need for a change in the primary system. The primary system works independently and unaware of CR system.

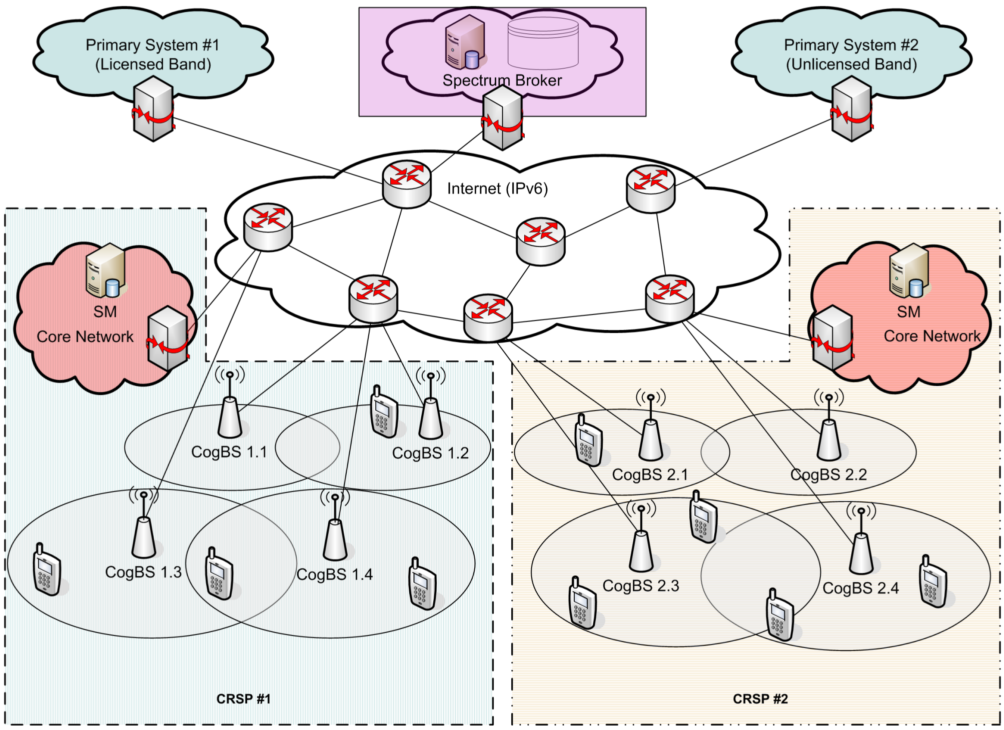


Figure 3.1. Network architecture of IbCRN

Components of IbCRN:

- *Cognitive Radio Service Provider (CRSP)*: Operator that provides CR service to its users (a.k.a., secondary users).
- *Spectrum Broker (SB)*: Broker between CRSP and frequency holders for frequency sub-leasing.
- *Spectrum Manager (SM)*: Resource management component within CRSP.

- *Cognitive Base Station (CogBS)*: Radio network component in secondary network that is at the network side of the air link.
- *Cognitive Mobile Terminal (CogMT)*: Mobile terminal with CR capabilities.

With the help of the cellular property of IbCRN architecture, CR system collocated with primary systems gives service to CogMTs in different areas without disturbing primary system users. CogBSs and CogMTs search and utilize white spaces in the spectrum that are changing in time and location.

IbCRN architecture is depicted in Figure 3.1. SB provides a marketplace where the spectrum holders sublease the rights for secondary usage of their frequency bands to the CRSPs through an auction. This step constitutes the long term scheduling of the frequencies. Each CRSP manages the frequency bands it has rented via the SM entity in its core network. SM plans frequency assignment and reuse between CogBSs as a part of medium term scheduling. Finally, CogBS assigns frequency bands to CogMTs on a need basis. These two entities possess CR capabilities. The details of long, medium, and short term scheduling are given in [11].

3.2. Analytical Model of the CR System

In the literature, CR system modeling is mostly done with the assumption of identical cells, hence, focusing on one reference cell. This assumption causes, missing the effect of dissimilar neighbor cells and heterogeneity in the system. We model the CR system by allowing the cells to have different properties to provide the heterogeneity effect for the network.

We denote the i^{th} CogBS by b_i and let $\mathbb{B}$ be the set of CogBSs. For example if the system consists of four CogBSs, then $\mathbb{B} = \{b_0, b_1, b_2, b_3\}$. For a given b_i, the set of assigned frequencies are symbolized by $\mathbb{F}_{b_i}$. System traffic parameters, λ_i^{pri} and λ_i^{sec} represent the connection request arrival rate of primary users and secondary users in b_i, respectively. Users of the system reside in cells with mean $1/\mu_{dwell}$, and connection holding times have mean $1/\mu_{hold}$.

We denote the cell of b_i by Ω_{b_i}. For each (b_i, Ω_{b_i}), we have the following parameters:

- $U_{b_i}(t)$: Number of users in Ω_{b_i} at time t.
- $\mathbb{F}_{b_i}$: Set of frequencies assigned to b_i.
- r_{b_i}: Cell radius of Ω_{b_i}.
- v: Mean user speed.
- $1/\mu_{dwell}$: Mean cell dwell time of users.
- $1/\mu_{hold}$: Mean connection holding time of active users.
- λ_i^{pri}: Mean connection request arrival rate for primary users in Ω_{b_i}.
- λ_i^{sec}: Mean connection request arrival rate for secondary users in Ω_{b_i}.
- $(\epsilon, \sigma_\epsilon)$: Mean sensing error and variance of the sensing error.

These parameters affect performance metrics and results of the system. We investigate the effect of the parameters like v, $1/\mu_{dwell}$, $1/\mu_{hold}$, λ_i^{pri}, and λ_i^{sec} on system performance. Using these results, system designers can decide on system parameters according to desired QoS metric.

3.2.1. State Definition

We need to keep track of the status of each frequency at each cell. Hence, the state of the whole system depends on the current usage of the frequencies at each $b_i \in \mathbb{B}$. Let n_i be the number of frequencies in b_i. Thus, any state of the system can be represented by n_i-tuples for each element b_i. Let $s(b_i, f_j)$ denote type of the connection for j^{th} frequency in b_i.

$$s(b_i, f_j) = \begin{cases} -1 & unavailable \\ 0 & free \\ 1 & primary \\ 2 & secondary \end{cases}$$

For example, if we have two frequencies in each cell of Figure 5.3, then the state of the system at time t represented by $((b_0 : 0, 1), (b_1 : 0, 0), (b_2 : 0, 0), (b_3 : 2, 0))$ corresponds to having one primary connection at second frequency of b_0 and one secondary connection at first frequency of b_3. Initially, the system starts with state s_0 in which there is no ongoing connection at any frequency in any cell.

3.2.2. Elementary Events

There are various elementary events that cause the system to switch from one state to another. Let's assume, a primary user starts a new connection request in Ω_{b_i} (not via b_i since b_i is part of the infrastructure of secondary system) while frequency f_j is occupied by a secondary user, and there is no other free frequency. This new connection event causes $s(b_i, f_j) = 2$ to switch to one and the secondary connection to be forcefully terminated. Also, handoffs cause system to switch from one state to another. Handoff behavior in wireless mobile networks for single cell is studied in [45,46]. In our model, if there are no available frequencies in the new cell, then this is called a *connection drop*. Connection drop can be due to mobility and primary user preemption, where latter is called *forced termination*. If a secondary user is preempted by a primary user and the secondary user finds a new frequency to hop, we call this *forced handoff*. Elementary events, which cause the system to change its state, can be categorized into three main groups: new connection event, handoff event, and connection release event.

<u>3.2.2.1. New Connection Event.</u> The method of handling connection requests differs for primary and secondary users since primary users have priority over secondary users. If the received request is from a primary user, then a frequency used by a secondary user or an unused frequency is allocated. In case of having no such frequency available, the request is blocked. If the selected frequency is empty, then the request is accepted and the current state is changed. If the selected frequency is used by a secondary user, then the secondary user is preempted. In this case, there are two possibilities. If there is an empty frequency for preempted user, then the secondary user changes its current frequency to new one. Otherwise, preempted user is forced to terminate. According

to these situations, the current state is changed. If sensing error occurs while primary user is trying to use a frequency occupied by a secondary user, then both primary and secondary users are dropped. In case of receiving a secondary request, unused resources are sensed and used. If there is no such frequency, then the secondary user request is blocked. Possible outcomes of a new connection request are shaded in the Figure 3.2.

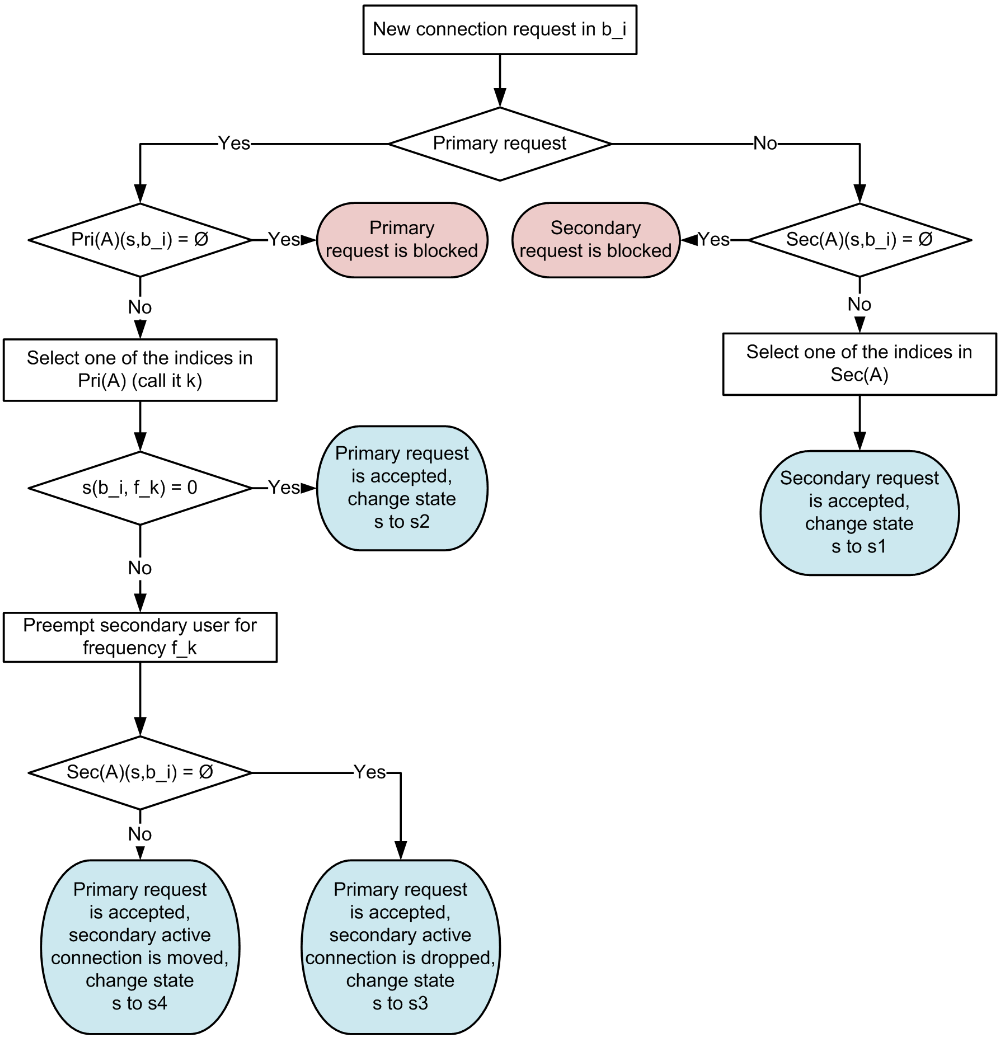


Figure 3.2. Flow diagram for handling new connection request ($\epsilon = 0$)

$$Pri(A)(s, b_i) = \{j \in \mathbb{F}_{b_i} | s(b_i, f_j) = 0 \text{ or } s(b_i, f_j) = 2\}, \tag{3.1}$$

$$Sec(A)(s, b_i) = \{j \in \mathbb{F}_{b_i} | s(b_i, f_j) = 0\}. \tag{3.2}$$

3.2.2.2. Handoff Event. Similar to the new connection event, handling of handoff request differs depending on whether it is a primary handoff request or secondary handoff request since the system is preemptive. Handoff event is shown in Figure 3.3. If the handoff request is initiated by a primary user, then resources that are used by secondary users or free resources are listed and one of them is selected. In case of having no such frequency available, the handoff request cannot be handled and the call is dropped. If the selected frequency is free, then the handoff request is accepted and the current state is changed. If the selected frequency is used by a secondary user, then the secondary user is preempted. In this case there are two possibilities. If there is a free frequency for preempted secondary user, then the secondary user changes its current frequency to the new one. Otherwise, preempted user is forced to terminate. According to these possibilities the current state is changed. If a sensing error occurs while primary user is trying to use a frequency occupied by a secondary user, then both primary and secondary users are dropped.

3.2.2.3. Connection Release Event. When a user decides to release the active connection, she[1] just releases the occupied frequency in use voluntarily. Primary users interact with their system infrastructure and secondary users interact with IbCRN via CogBSs. Release of resources used by primary users are sensed by secondary users and CogBSs.

3.2.3. Traffic Arrival Process

We can assume that the connection request arrival is a Poisson process. If there are enough mobile users in one cell, then aggregate call arrival is a Poisson process, even if the request arrival for an individual mobile user is not [47]. This approach is based on the users' mobility, the shape and size of the cell. Since the focus of this study is an analytical model for the CR, instead of a traffic model, we choose this approach and select exponential distribution for the call holding time and the cell dwell time to make the Markov model tractable in the analytical solution.

[1] Throughout this thesis, "she" should be read as "she or he", "her" as "her or his", etc.

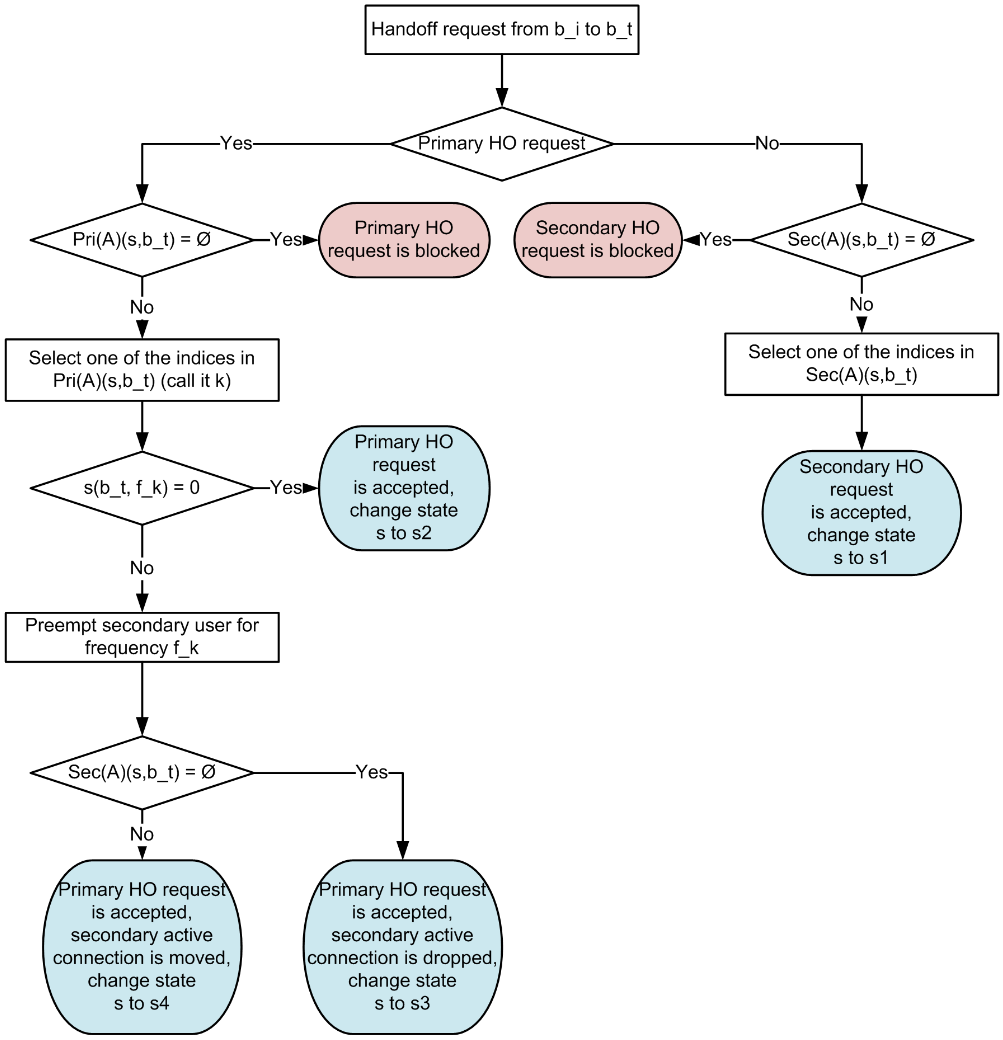


Figure 3.3. Flow diagram for handling handoff request ($\epsilon = 0$)

λ_i^{pri} and λ_i^{sec} represent the connection request arrival rate of primary users and secondary users in Ω_{b_i}, respectively. We assume traffic interarrivals are exponentially distributed random variables with mean $1/\lambda_i^{pri}$ and $1/\lambda_i^{sec}$ for primary and secondary users, respectively. In CR systems, rarely used or unused frequencies are subleased to secondary users, so the traffic arrival rate of secondary users for those frequencies is more than the traffic arrival rate of primary users.

3.2.4. Cell Dwell and Connection Holding Time

We denote the probability distribution of moving speeds of users with mean $E[V]$ as $f_V(v)$. We assume users are equally likely to move in any direction with arbitrary speeds according to the given probability distribution function. We choose the fluid flow model in which the average outgoing rate μ_{dwell} of a mobile user within a cell is given by

$$\mu_{dwell} = E[V]L/\pi S, \tag{3.3}$$

where L is the perimeter and S is the area of the cell with arbitrary shape. We use the formula derived by Xie and Kuek in [48] and [49] for μ_{dwell} using biased sampling formula.

μ_{hold} and μ_{dwell} affect the handoff behavior of the primary users. T_{dwell} and T_{hold} have exponential distributions with means $1/\mu_{dwell}$ and $1/\mu_{hold}$, respectively. Probability of experiencing a handoff for primary users is related to these two random variables. If a primary user having T_{hold} greater than T_{dwell}, primary user continues her connection while changing the current cell. During this process, a new connection is established in the new cell while the frequency used in the previous cell is released.

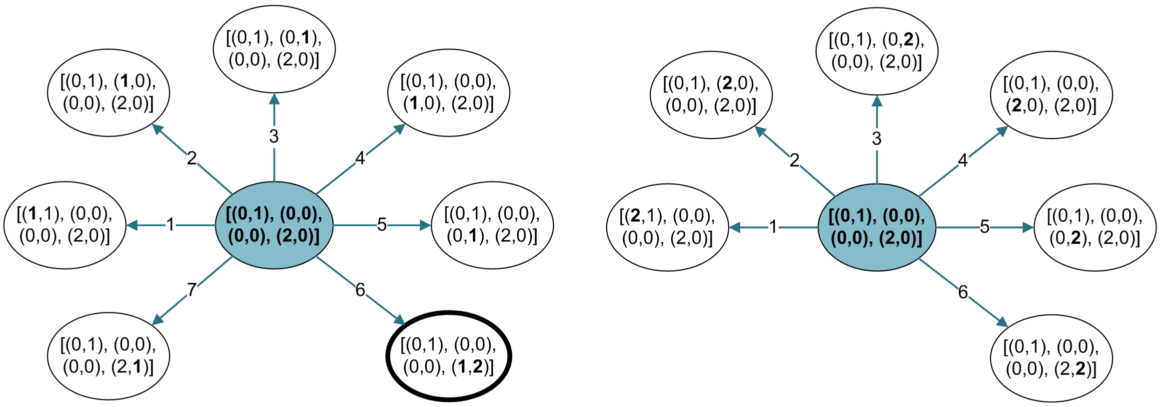
For secondary users, the arrival of primary users also affects the frequency handoff since the system is preemptive. We denote the frequency holding time of primary and secondary users by T_{hold}^{pri} and T_{hold}^{sec}, respectively. Frequency handoff for primary users, which determines T_{hold}^{pri}, can occur if $T_{dwell} < T_{hold}$. For secondary users, frequency handoff, which determines the T_{hold}^{sec}, can occur if $T_{dwell} < T_{hold}$ or in case of primary activity. The memoryless property of the exponential variables leads to

$$E[T_{hold}^{pri}] = \frac{1}{\mu_{dwell} + \mu_{hold}}, \tag{3.4}$$

$$E[T_{hold}^{sec}] = \frac{1}{\mu_{dwell} + \mu_{hold} + \lambda_i^{pri}}. \tag{3.5}$$

3.2.5. State Transitions

Elementary events cause system state to change. The status of each frequency is tracked within the state definition. We recall the example state; $((b_0 : 0,1),(b_1 : 0,0),(b_2 : 0,0),(b_3 : 2,0))$ corresponds to having one primary connection at second frequency of b_0 and one secondary connection at first frequency of b_3.



(a) Primary connection

(b) Secondary connection

Figure 3.4. Transitions from example state due to a new connection

States that can be visited from the example state by primary or secondary connection are depicted in Figure 3.4. In Figure 3.4(a), we have transitions due to primary connection. The rate of transition represented by each arrow can be calculated according to the associated elementary event. The arrow labeled with 1 in Figure 3.4(a) corresponds to a primary connection request that is accepted for the first frequency of b_0. We denote the transition rate of arrow 1 in Figure 3.4(a) as $\gamma_1^{3.4(a)}$ and arrow 1 in

Figure 3.4(b) as $\gamma_1^{3.4(b)}$. Transition rates are given in Equation 3.6.

$$
\begin{aligned}
\gamma_1^{3.4(a)} &= \lambda_0^{pri}/1 & \gamma_1^{3.4(b)} &= \lambda_0^{sec}/1 \\
\gamma_2^{3.4(a)} &= \lambda_1^{pri}/2 & \gamma_2^{3.4(b)} &= \lambda_1^{sec}/2 \\
\gamma_3^{3.4(a)} &= \lambda_1^{pri}/2 & \gamma_3^{3.4(b)} &= \lambda_1^{sec}/2 \\
\gamma_4^{3.4(a)} &= \lambda_2^{pri}/2 & \gamma_4^{3.4(b)} &= \lambda_2^{sec}/2 \\
\gamma_5^{3.4(a)} &= \lambda_2^{pri}/2 & \gamma_5^{3.4(b)} &= \lambda_2^{sec}/2 \\
\gamma_6^{3.4(a)} &= \lambda_3^{pri}/2 & \gamma_6^{3.4(b)} &= \lambda_3^{sec}/1 \\
\gamma_7^{3.4(a)} &= \lambda_3^{pri}/2
\end{aligned} \tag{3.6}
$$

In Figure 3.4(a), the state with thick border is visited due to primary connection on the first frequency of b_3. However, the first frequency is occupied by a secondary user, so the secondary user is preempted and forced to make frequency handoff.

States that can be visited from example state by both primary and secondary connection handoff are depicted in Figure 3.5, and transition rates are $\mu_{dwell}/4$ for all cases ($\gamma_i^{3.5} = \mu_{dwell}/4$).

Similarly, we have transition rates of connection release event and resulting states. Transition rate of release event is μ_{hold} for both primary and secondary connection. In example transitions, we just show the transitions originated from the example state depicted in the center of figures as shaded.

3.2.6. Analytical Solution

Calculating the state probabilities for such a complex system analytically is a challenge on its own. The state probabilities in our dynamic system can be calculated by solving the eigenvalue problem of the transition matrix.

Let $\mathbb{S} = \{\text{States of the whole system}\}$. We enumerate states in $\mathbb{S}$ and denote the

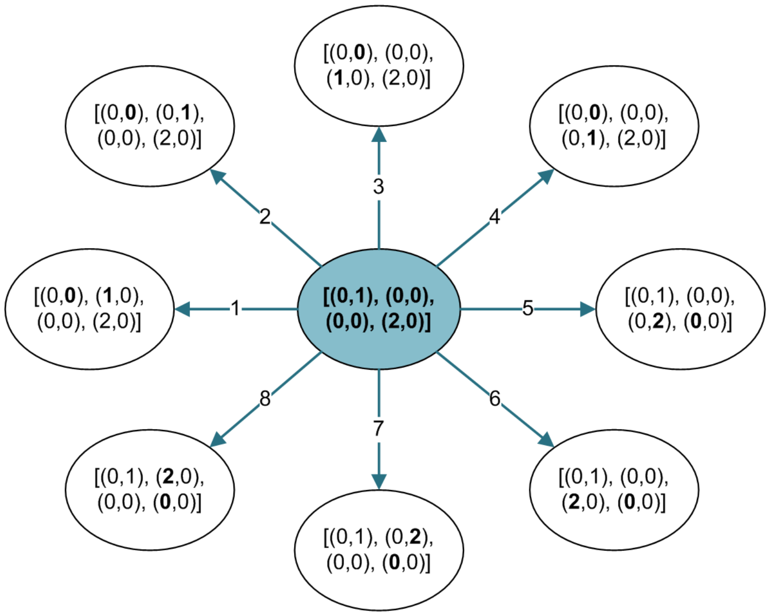


Figure 3.5. Transitions from example state to possible states by connection handoff

i^{th} state as s_i. We denote the probability that the system is in state s_i at time t as $\mathbf{P}_{s_i}(t)$. Initially, the system starts in state s_0 in which there are no ongoing connections. Thus, $\mathbf{P}_{s_0}(t=0)=1$, while $\mathbf{P}_{s_i}(t=0)=0$ for all other states s_i $(i \neq 0)$.

As time elapses, the elementary events occur carrying the system from state to state. This causes the state probabilities to change in time. Although we do not know the system state exactly at a given time, we can calculate the probability of being in each state s_i at time t, literally $\mathbf{P}_{s_i}(t)$. During an infinitesimally short time interval Δt, the system may switch to/from s_i due to an elementary event. Therefore, $\mathbf{P}_{s_i}(t+\Delta t)$ is different from $\mathbf{P}_{s_i}(t)$. The rate of change in the state probabilities of s_i during Δt, $\mathbf{P'}_{s_i}(t)$, is given by

$$\mathbf{P'}_{s_i}(t) = \sum_{j \neq i} \mathbf{P}_{s_j}(t)\gamma_{ji} - \mathbf{P}_{s_i}(t) \sum_{j \neq i} \gamma_{ij} \tag{3.7}$$

where γ_{ij} is the rate of flow from s_i to s_j. In theory, when the system reaches equilibrium at time τ we have

$$\forall s_i \in \mathbb{S} \quad \mathbf{P'}_{s_i}(t) = 0 \text{ for } t \geq \tau. \tag{3.8}$$

From Equation 3.8, we present a method to solve the state probabilities with the assumption that the system is in equilibrium. Power method, which is an iterative process, can be used for determining the state probabilities analytically. In theory, probabilities converge to equilibrium state probabilities that correspond to the eigenvector of largest eigenvalue of the transition matrix. In the power method, the procedure starts with an initial probability vector that sums up to one. We represent the vector of state probabilities, i.e., the vector composed of state probabilities of all states at time t, as $[\mathbf{P}_{s_i}(t)]_{s_i \in \mathbb{S}}$. Then, starting the iterations means correcting the state probabilities with the assistance of the transition matrix in each step. In each iteration, new probabilities for the next iteration according to Equation 3.9 are evaluated. After sufficient iterations, state probabilities converge to the steady state probabilities. We use the metric $d(\cdot\,,\cdot)$ in Equation 3.10, to represent the difference between two probability vectors. For the rest of our work we use metric $d(\cdot\,,\cdot)$.

$$\mathbf{P}_{s_i}(t) = \frac{\displaystyle\sum_{j \neq i} \mathbf{P}_{s_j}(t) \cdot \gamma_{ji}}{\displaystyle\sum_{j \neq i} \gamma_{ij}} \tag{3.9}$$

$$d([\mathbf{P}_{s_i}(t)]_{s_i \in \mathcal{S}}, [\mathbf{P}_{s_i}(t + \Delta t)]_{s_i \in \mathcal{S}}) = \sum_{s_i \in \mathcal{S}} |\mathbf{P}_{s_i}(t) - \mathbf{P}_{s_i}(t + \Delta t)| \tag{3.10}$$

We utilize metric $d(\cdot\,,\cdot)$ to analyze the convergence of the state probability vector. While solving the system numerically, iteration is stopped when $d(\cdot\,,\cdot)$ evaluated between successive iterations is less than a threshold. In Equation 3.10, $d(\cdot\,,\cdot)$ is the metric derived from ℓ_1-norm. Here, we have two probability vectors, $[\mathbf{P}_{s_i}(t)]_{s_i \in \mathcal{S}}$ and $[\mathbf{P}_{s_i}(t + \Delta t)]_{s_i \in \mathcal{S}}$. We sum the absolute probability difference of all states in these probability vectors. Calculating $d(\cdot\,,\cdot)$ between identical vectors gives zero due to nondegeneracy of the metric. The final probability vector in the last iteration is close to the probability vector in equilibrium situation according to the metric in Equation 3.10.

The analytical model presented above provides a tool to calculate state probabilities using the power method. However, the size of the state space constitutes a major challenge. Any combination of values for the tuples in the state definition constitutes a different state. For each component value we have three possibilities; empty, primary, and secondary. For the example topology with 32 frequencies in each of the four Cog-BSs, we have $3^{128} \approx 1.28 \times 10^{61}$ states. Hence, we present a method to solve the state probabilities analytically. Then, we calculate the state probabilities using simulations since the state space quickly explodes. Hence the model is verified with small topology consisting of two neighbor cells with each having five frequencies in Section 5.2.

4. CAPACITY PLANNING PROBLEM IN CRN

The fundamental idea behind the capacity assignment problem is to find an assignment of capacities to the base stations that meets the requirements of the operator over a given area. When there is a cell with bursty traffic in a cellular network, performance metrics related to bursty cell and its one hop neighbors are affected substantially and there becomes a huge difference between affected cell and other cells in terms of performance. Effect of bursty traffic has an exponential decreasing behavior when we investigate neighbor cells as they become more distant. We run simulations with a topology that has concentric cells and a bursty traffic at the center. Resources are distributed equally and the effect of bursty traffic is summarized in Table 4.1.

Table 4.1. Effect of bursty traffic on performance metrics

	Hop #0	Hop #1	Hop #2
Probability of dropping (secondary)	0.2248	0.1694	0.0151
Probability of blocking (secondary)	0.2095	0.1355	0.0171

Assigning higher capacity for the bursty cell may solve the performance degradation. If the system designers know the system parameters, then they can assign higher capacity for bursty cells considering the effect on the neighbor cells simultaneously. Our multi-cell model is capable of analyzing the effect of a bursty cell on neighbor cells. Therefore, more knowledge about the performance metrics can be gained and the capacity assignment problem can be solved more correctly.

Main goal of the capacity assignment method is to eliminate the huge gaps between different cells in terms of performance metrics considered. While achieving this goal, methods must take into account the load of the cell and the hop count to the loaded cell since the effect of the bursty traffic diffuses to other cells as seen in Table 4.1. Hence cells with more offered traffic need more frequency bands for lower blocking and dropping rates.

4.1. Problem Definition

For defining the capacity assignment problem we need to introduce new terminology and the respective notation. We denote the total number of frequencies with C_{tot} and the number of frequencies for b_i with C_i. Therefore, we have the relation between C_{tot} and C_i:

$$\sum_{b_i \in \mathbb{B}} C_i = C_{tot} \tag{4.1}$$

So we have limited number of frequencies and we want to minimize the gap in terms of performance metrics for different cells. In other words, we would like to achieve even performance across different cells. We define Δ to represent cumulative difference of metric used (let's say M). Formula for Δ is given in Equation 4.2,

$$\Delta = \sum_{i \in H} \Delta_i = \sum_{i \in H} |M_i - \overline{M}| \tag{4.2}$$

where H represents the set of hop counts, M_i is the performance metric value for i^{th} hop cells, and $\overline{M}$ is the mean value of the performance metric. Different capacity assignment methods results in different Δ values, where we want to minimize Δ by finding optimum C_i values for each b_i.

4.2. Proposed Solution

CR networks are inherently preemptive, which makes the system more complicated than legacy cellular networks. Simulator for IbCRN with multiple cells is developed in *OPNET (Optimized Network Evaluation Tool)*. The system model is adopted in the simulations explained in the following subsections.

There are various works in the literature addressing the capacity assignment problem. In [50], channel assignment problem is solved via a neural network algorithm by considering channel demand and heterogeneous interference conditions. In [51] simulated annealing algorithm is similarly used. Channel demand can be considered as offered load in our model. Hence, considering load is a known technique in the literature. In [52], required number of channels is evaluated by considering offered load and retrial and redial model for enhancing Erlang-B formula. In our model we assume that traffic parameters are not including retrials and redials. Also, CR systems are inherently preemptive which makes using Erlang formula improper.

4.2.1. Elementary events

There are various elementary events that cause the system to switch from one state to another. Main elementary events of the system are:

- Connection establishment
- Connection handoff
- Connection release

There are distinctive subevents particular to CR networks due to preemption of primary users. For example, a primary user starts a new connection request in the area of b_i by using primary infrastructure (not via b_i since b_i is an infrastructure of secondary system), while the frequency f_j is occupied by a secondary user, and there is no other free frequency. This new connection event causes the primary user to use f_j and the secondary connection to be forcefully terminated. Also, handoffs cause system to switch from one state to another. Handoff behavior for single cell is studied in [45, 46]. In our model, if there are no available frequencies in the new cell, this event is called a *connection drop*. Connection drop can be due to mobility and primary user preemption, where latter is called *forced termination.* If a secondary user is preempted by a primary user and the secondary user finds new frequency to hop, we call this *forced frequency handoff.*

4.2.2. Capacity planning

Each cell in the IbCRN has frequency bands for secondary usage. Mobile secondary users start using a frequency band that is available in their current cell. If a primary user starts a connection by using a frequency that is used by a secondary user, then primary user preempts the secondary user. Hence cells with more offered traffic need more frequency for lower blocking and dropping rates. Assigning more frequency bands for cells having higher offered traffic is straight forward solution for achieving QoS.

We denote the total number of frequencies with C_{tot} and the number of frequencies for b_i with C_i. Planning the C_i values for all the cells affect the system performance in terms of $P_d^{sec}(forced)$, P_b^{sec}, and $P_d^{sec}(mobility)$, where the first one is the probability of secondary forced termination (due to primary preemption), the second one is the probability of secondary blocking, and the third one is the probability of secondary dropping (due to mobility).

4.2.2.1. Capacity Planning Algorithms.

EqA Equal Assignment method assigns equal number of frequencies to all CogBSs.

LHA Load and Hop based Assignment method assigns frequencies to b_i directly proportional to κ_i (Equation 4.3).

ALHA Averaged Load and Hop based Assignment method assigns frequencies to b_i directly proportional to φ_i (Equation 4.4).

$$\kappa_i = \frac{\left(\dfrac{\rho_i^{pri} + \rho_i^{sec}}{\rho_{max}^{pri} + \rho_{max}^{sec}}\right)^{n_i}}{\sum_{j=0}^{n}\left(\dfrac{\rho_j^{pri} + \rho_j^{sec}}{\rho_{max}^{pri} + \rho_{max}^{sec}}\right)^{n_j}} \tag{4.3}$$

In Equation 4.3, load and the hop distance to the maximum loaded cell are integrated to the capacity assignment factor. n_i denotes the hop distance to the most loaded cell and ρ_i^{pri} denotes the expected number of primary connection request arrivals in cell of b_i within $1/\mu_{hold}$ seconds.

$$\varphi_i = \alpha\overline{\kappa}(n_i) + (1-\alpha)\overline{\kappa}(0) \tag{4.4}$$

In Equation 4.4, $\overline{\kappa}(n_i)$ denotes the mean κ_i for cells with n_i hop distance to most loaded cell. Coefficients of ALHA method are evaluated by weighted sum of LHA method and α depends on the velocity of mobile users.

5. SIMULATION RESULTS

We implement a simulator and the analytical solver for the CR system according to the model described. In this section, first parameters and metrics are described, then evaluation of analytical model is presented for system validation. Finally, evaluation of simulation results and capacity assignment methods are considered.

5.1. Parameters, Assumptions, and Metrics

We use the following system parameters in our simulations:

- Topology
- r: Cell radius
- C_i: Number of available frequencies in each cell
- U_i: Number of primary and secondary users in each cell
- v: User speed (m/s).
- λ: Primary and secondary connection request rate (conn/s)
- T_{hold}: Connection holding time (s/conn)
- ϵ: Sensing error probability

We make the following assumptions for simulations:

- Frequency reuse is possible but not between neighboring cognitive radio cells.
- We model a closed simulation environment, i.e., the total number of users during simulation does not change.
- We assume traffic arrivals are from a Poisson process as proposed in [46].
- We assume cell dwell times are exponentially distributed as proposed in [48].
- When a primary user makes a connection request she selects a frequency from a frequency set such that there exist frequencies available to primary users in that cell and not used by another primary at that moment. We assume that the available frequency set is known by primary users via primary BS broadcasting

periodically.

- Same assumption is valid for secondary users. Secondary users select frequency from a set such that there exist frequencies available to secondary users in that cell and not used by primary (since primary users have priority) or another secondary at that moment. We assume that the available frequency set is known by secondary users via secondary CogBS broadcasting periodically.

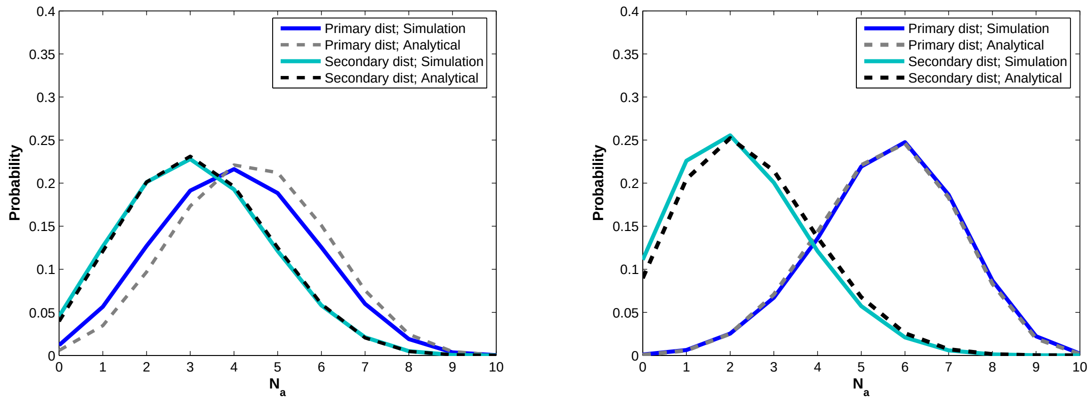
We evaluate the following metrics in our studies:

- Primary system utilization: Percentage of the spectrum that is used by primary users.
- Secondary system utilization: Percentage of the spectrum that is used by primary users.
- Primary blocking: Situation that primary connection request can not be granted.
- Secondary blocking: Situation that primary connection request can not be granted.
- Primary dropping: When a primary is making a call handoff and if there exists no available frequency in the destination cell, primary is dropped and connection is terminated.
- Primary dropping due to sensing error: When a primary is making a handoff requesting a frequency in the destined cell that is used by a secondary and if secondary can not sense the appearance of the primary, primary is dropped due to sensing error. Both secondary and primary connection is terminated.
- Secondary dropping due to mobility: When a secondary is making a call handoff and if there exists no available frequency in the destination cell, secondary is dropped due to mobility and connection is terminated.
- Forced handoff: If a secondary user is preempted by a primary user and the secondary user finds a new frequency to hop, we call this event forced handoff.
- Forced termination: If a secondary user is preempted by a primary user and the secondary user can not find a new frequency to hop secondary connection is terminated, this event is called forced termination.
- Active primary connection: Primary that is served by a primary BS has an active secondary connection.

- Active secondary connection: Secondary that is served by a CogBS has an active secondary connection.

5.2. Evaluation of Analytical Model

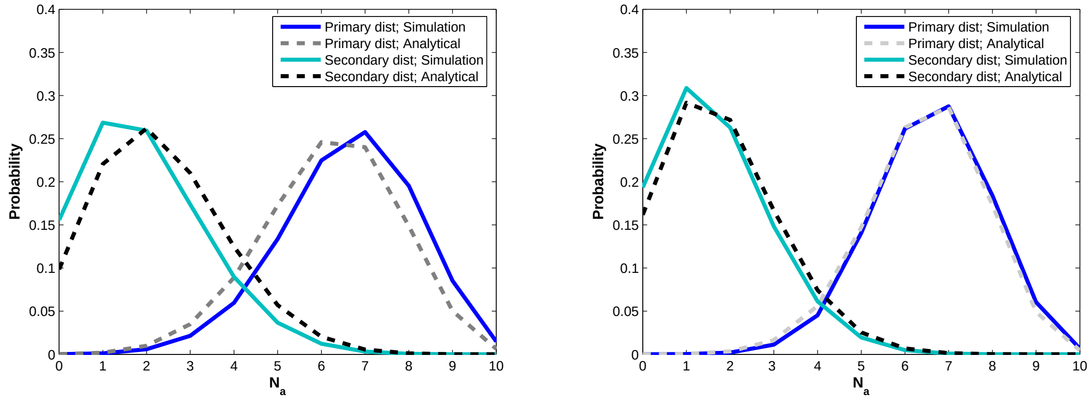
Analytical model described in Section 3.2 is solved by the method described in Subsection 3.2.6. Since the state space explodes model is verified with small topology consisting of two neighbor cells with each having five frequencies. The following results are representing the analytical solution results and the simulation results.



(a) $T_{hold} = 1000\,s/conn$ (b) $T_{hold} = 2000\,s/conn$

Figure 5.1. Comparison of simulator results and analytical results ($r = 250\,m$, $v = 0.5\,m/s$, $\lambda_i^{pri} = 0.002\ conn/s$, $\lambda_i^{sec} = 0.004\ conn/s$)

In Figures 5.1(a) and 5.1(b), x-axis corresponds to N_a (the number of active connections) and the y-axis corresponds to the probability of having that many active connections. The probability distribution of N_a is a good indicator of the system dynamics. For both figures analytical results and the simulation results are close, which implies in both cases analytical solution is in accordance with the simulation results. In Figure 5.1(b), T_{hold} value is doubled and the system dynamics are affected by this parameter change. The detailed analysis of the parameter analysis are done in the following subsections. Here we mainly focus on the verification of the model. Having similar distributions in both figures verifies the model under changing T_{hold} values.



(a) $v = 0.5\,m/s$ (b) $v = 1.0\,m/s$

Figure 5.2. Comparison of simulator results and analytical results ($r = 250\,m$, $T_{hold} = 2000\,s/conn$, $\lambda_i^{pri} = 0.004\ conn/s$, $\lambda_i^{sec} = 0.008\ conn/s$)

In Figure 5.2, connection generation rate for both primary and secondary connections are doubled with respect to Figure 5.1 and velocity value in Figure 5.2(a) is doubled in Figure 5.2(b). Having similar distributions shows the model is verified under changing velocity and connection generation rate.

5.3. Effect of System Parameters on CRN System Performance

We implement the CR system according to described model in OPNET. In our simulations, we use the topology shown in Figure 5.3 with cell radius of 250 m. We run our simulations with 30 different seeds in OPNET and trim 0.15 of the minimum and maximum values. We evaluate 95 per cent confidence intervals for trimmed means. And we assume that there exists an obstacle between Ω_{b_1} and Ω_{b_2}, so that they are not considered as neighbors.

The topology depicted in Figure 5.3 is used for the test scenarios. We set number of frequencies available in each cell as 32 initial number of primary and secondary users is 64 each in every cell for all test cases. Various values for v, λ_i^{pri}, λ_i^{sec}, and T_{hold} are considered. Primary systems sublease their under utilized frequencies. We set $\lambda_i^{sec} = 2 \times \lambda_i^{pri}$ since we assume higher load for the secondary system.

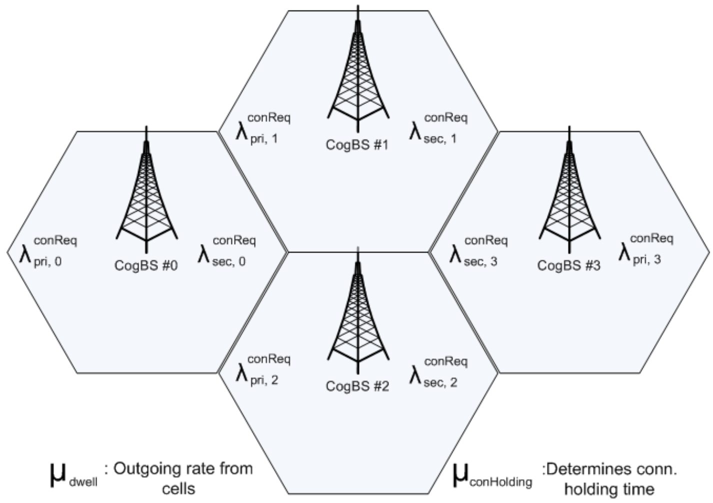


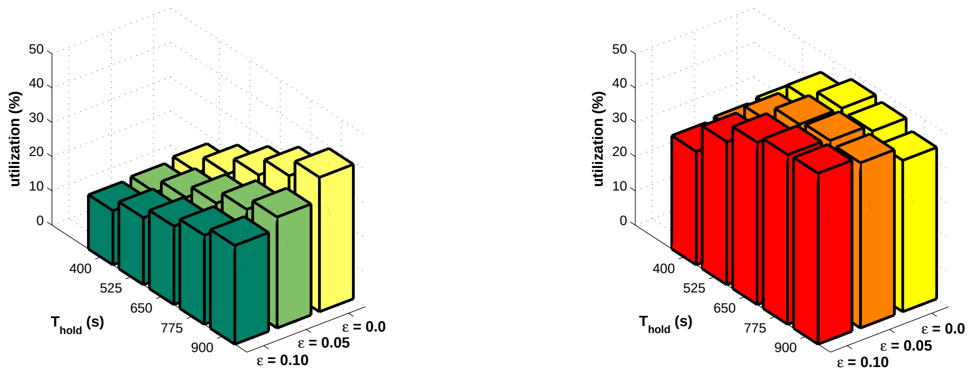
Figure 5.3. System topology for the tests

We analyze the probability of secondary forced termination (due to primary preemption), $P_d^{sec}(forced)$, the probability of secondary blocking, P_b^{sec}, and the probability of secondary dropping (due to mobility), $P_d^{sec}(mobility)$. We also investigate the probability of primary dropping (due to sensing error), which is denoted by $P_d^{pri}(sensing)$. Not only probabilities but also the number of events N_b^{sec}, $N_d^{sec}(forced)$, and $N_d^{sec}(mobility)$, are analyzed.

5.3.1. Effect of Sensing Error

Tests in this subsection focus on the effect of sensing error on the whole system. We investigate the effect of sensing error while we change the holding time, connection request rate, and velocity. First we start with holding time analysis.

5.3.1.1. Holding Time Analysis. Figure 5.4 shows the effect of sensing error on resource allocation for different connection holding times. As expected, the system with cognitive radio technology makes a significant improvement in spectrum utilization with respect to having only the primary system. In Table 5.1, in the last two columns for total utilization, a significant improvement in spectrum utilization with respect to having only the primary system is observed.



(a) Primary utilization

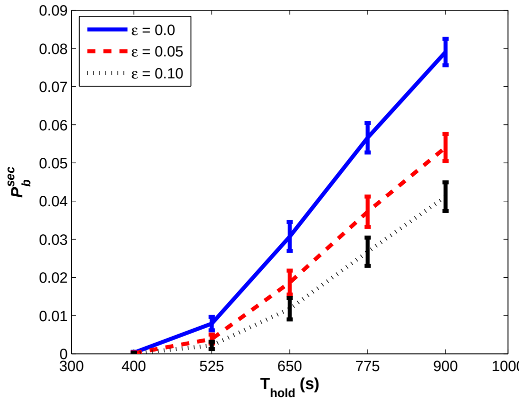
(b) Secondary utilization

Figure 5.4. Effect of connection holding time on utilization ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$)

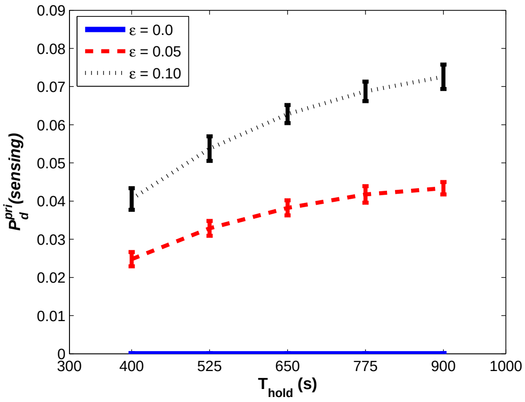
Table 5.1. Primary, secondary, and total utilization values with different T_{hold} values

	Primary		Secondary		Total	
T_{hold}	$\epsilon = 0.0$	$\epsilon = 0.10$	$\epsilon = 0.0$	$\epsilon = 0.10$	$\epsilon = 0.0$	$\epsilon = 0.10$
400	17.43	15.79	34.77	33.04	52.21	48.84
525	22.88	19.51	44.09	41.68	66.97	61.19
650	28.29	22.82	47.81	47.28	76.10	70.10
775	33.87	25.98	46.89	49.48	80.76	75.47
900	39.20	28.78	44.15	49.85	83.35	78.63

When we increase the connection holding time, primary utilization increases for $\epsilon = 0.0$, 0.05, 0.10. However, for secondary utilization we have decreasing behavior in perfect sensing case for connection holding time greater than 650 seconds. Decreasing behavior is due to the fact that longer connections of primary users are not affected in case of perfect sensing, and the system is utilized more by primary users. Having higher connection holding times results in fewer white spaces in the spectrum. Some of the new secondary connection requests cannot be handled if T_{hold} is increased. Therefore, secondary utilization decreases but the total utilization always increases. In Table 5.1, we observe that $T_{hold} = 650s$ is a turning point for secondary utilization when $\epsilon = 0.0$.



(a) P_b^{sec}



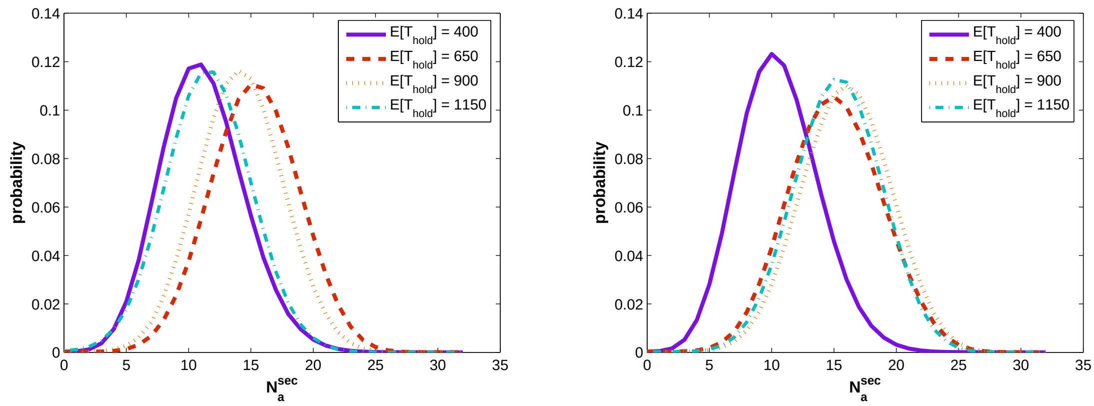
(b) $P_d^{pri}(sensing)$

Figure 5.5. Effect of connection holding time on P_b^{sec} and $P_d^{pri}(sensing)$ ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$)

After this point, secondary utilization starts to decrease. However, secondary utilization continues to increase for $\epsilon = 0.10$ case, which is due to new available frequencies dropped by primary users because of sensing error.

In Figure 5.5, the x-axis represents T_{hold} and the y-axis in Figure 5.5(a) and 5.5(b) represents P_b^{sec} and $P_d^{pri}(sensing)$ respectively. Each curve in the figures corresponds to different sensing error means. As observed in Figure 5.5(a), increasing T_{hold} results in increase in P_b^{sec} for $\epsilon = 0.0$, 0.05, and 0.10. Higher sensing error mean leads to a decrease in P_b^{sec}, but in this case we have less primary and total utilization as well as higher $P_d^{pri}(sensing)$ (See Table 5.1 and Figure 5.5(b), respectively).

Rate of increase in Figure 5.5(a) and Figure 5.5(b) decreases for both $\epsilon = 0.05, 0.10$ as connection holding time increases. This behavior can be explained by considering extreme values. Assuming connection holding time going to infinity results in frequencies being occupied with primary users and no white space for secondary users. Therefore, $P_d^{pri}(sensing)$ approaches zero. We recall that $P_d^{pri}(sensing)$ occurs when a secondary user has active connection. Then, a primary user starts using the actively used frequency, and secondary user fails to detect primary user activity. Therefore, very high connection holding times results in very low $P_d^{pri}(sensing)$ since



(a) $\epsilon = 0.0$ (b) $\epsilon = 0.10$

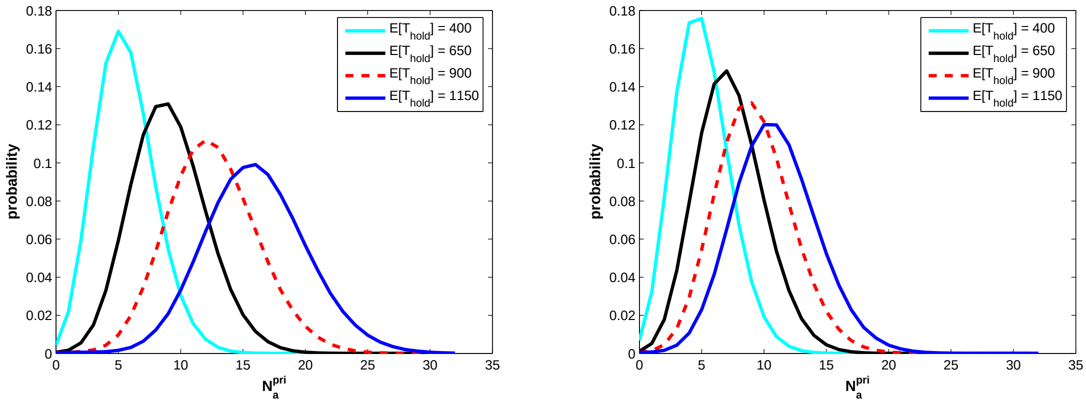
Figure 5.6. Effect of connection holding time on N_a^{sec} ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$)

number of active secondary users decreases. This behavior can be verified with the help of Figures 5.6(a) and 5.6(b).

As observed in Figure 5.5(a), increasing T_{hold} results in increase in P_b^{sec} for $\epsilon = 0.0$, 0.05, and 0.10. Higher sensing error mean leads to a decrease in P_b^{sec} due to new white spaces caused by dropping events related to sensing error. In this case we have lower primary and total utilization as well as higher $P_d^{pri}(sensing)$ (See Table 5.1 and Figure 5.5(b), respectively). By the help of Figure 5.6, expected number of active secondary connections can be evaluated.

$$E[N_a^{sec}] = \sum n_a^{sec} \times p(n_a^{sec})$$

Increasing connection holding time results in shifting the distribution of the frequency in use to right up to a point since primary users have higher priority and preempt secondary users. Distribution of secondary users for the case $\epsilon = 0.0$ shifts left after $T_{hold} = 650s$. For the case $\epsilon = 0.10$, the distribution shifts left after $T_{hold} = 900s$. Hence, $E[N_a^{sec}]$ decreases after a point due to primary user domination that can be seen from Figure 5.7. In Figure 5.7, as we increase the connection holding time then the number of primary active users in the system increases. Therefore, the number of active secondary users in the system decreases. For the $\epsilon = 0.10$ case, the probability distribution of N_a^{pri} shifts right, but the curves with the same parameters are tending to start from more smaller values and their variance gets smaller. This behavior can be explained by the dropping events that are caused by sensing error.



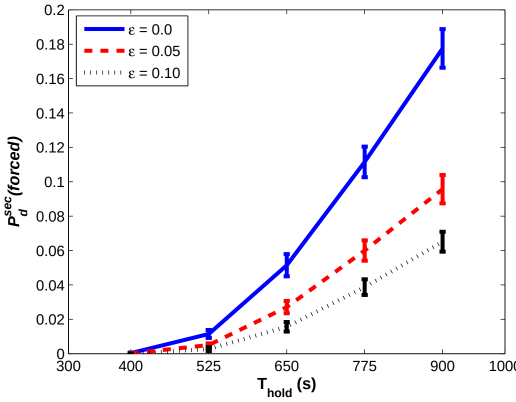
(a) $\epsilon = 0.0$ (b) $\epsilon = 0.10$

Figure 5.7. Effect of connection holding time on N_a^{pri} ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\ conn/s$, $\lambda_i^{sec} = 0.028\ conn/s$)

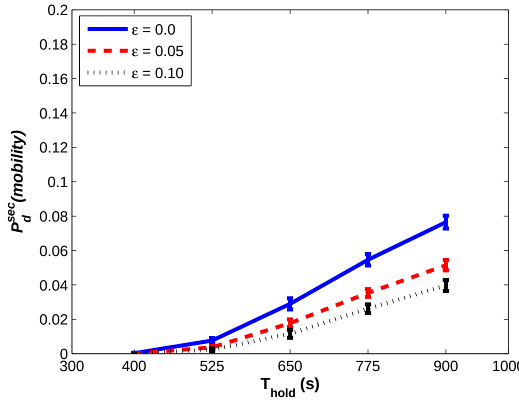
Table 5.2. Dropping probability values for secondary users

	$P_d^{sec}(forced)$		$P_d^{sec}(mobility)$		P_d^{sec}	
T_{hold}	$\epsilon = 0.0$	$\epsilon = 0.10$	$\epsilon = 0.0$	$\epsilon = 0.10$	$\epsilon = 0.0$	$\epsilon = 0.10$
400	0.0	0.0	0.0	0.0	0.0	0.0
525	0.011	0.002	0.007	0.002	0.018	0.004
650	0.051	0.015	0.028	0.011	0.079	0.026
775	0.111	0.038	0.054	0.026	0.165	0.064
900	0.177	0.065	0.076	0.039	0.253	0.104

In Table 5.2, we have forced termination probabilities, secondary dropping probabilities due to mobility, and secondary total dropping probabilities for different T_{hold} values. We plot the curves corresponding to different ϵ values for $P_d^{sec}(forced)$ and $P_d^{sec}(mobility)$ in Figure 5.8(a) and Figure 5.8(b). Increasing connection holding time results in an increase for both types of dropping events for secondary users. For the



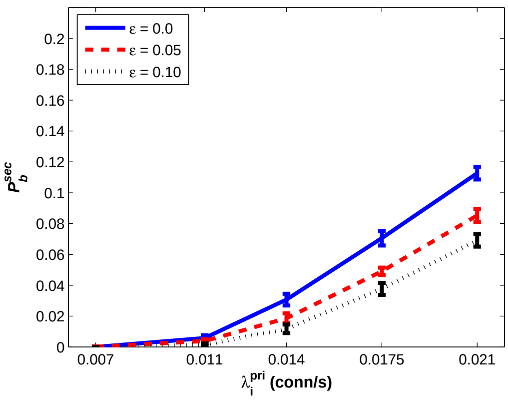
(a) $P_d^{sec}(forced)$



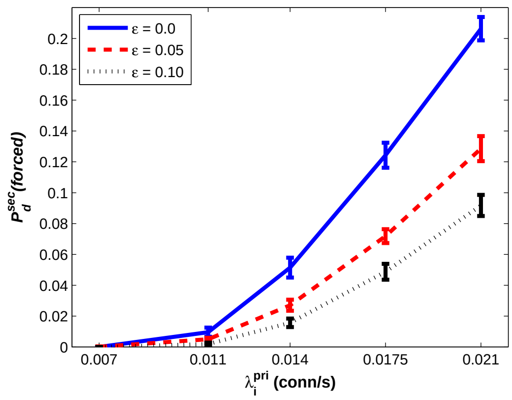
(b) $P_d^{sec}(mobility)$

Figure 5.8. Effect of connection holding time on $P_d^{sec}(forced)$ and $P_d^{sec}(mobility)$ $(r = 250\,m,\ v = 1.2\,m/s,\ \lambda_i^{pri} = 0.014\,conn/s,\ \lambda_i^{sec} = 0.028\,conn/s)$

$\epsilon = 0.10$ case, we have lower $P_d^{sec}(forced)$ and $P_d^{sec}(mobility)$ since sensing error causes dropping events and results in releasing actively used frequencies.



(a) $P_b^{sec}(\lambda_i^{sec} = 2 \times \lambda_i^{pri})$

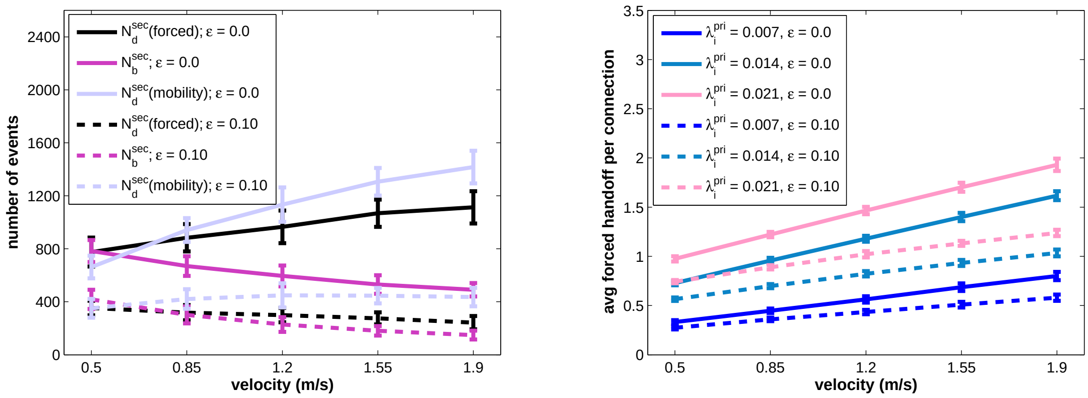


(b) $P_d^{sec}(forced)(\lambda_i^{sec} = 2 \times \lambda_i^{pri})$

Figure 5.9. Effect of connection request rate on P_b^{sec} and $P_d^{sec}(forced)$ $(r = 250\,m,\ v = 1.2\,m/s,\ T_{hold} = 650s)$

5.3.1.2. Connection Request Rate Analysis. In Figure 5.9(a) and Figure 5.9(b), the blocking and forced termination probabilities of secondary users are depicted for varying the connection request rate. When we increase connection request rate, more users (both primary and secondary) make connection attempts. As a result, P_b^{sec} increases with the increasing connection request rate. In this situation there exists a competition between secondary users, but obsolescent frequencies are fewer at higher connection request rate due to priority of primary users. Primary users generating new requests and trying to make handoff causes forced terminations if there is no white space. This leads to a sharp increase in $P_d^{sec}(forced)$. If we increase the ϵ value, then we have more dropping events for primary and secondary users resulting in more obsolescent frequencies. Therefore, P_b^{sec} and $P_d^{sec}(forced)$ decrease.

<u>5.3.1.3. Velocity Analysis.</u> We further examine the effect of user speed on $N_d^{sec}(forced)$, N_b^{sec}, and $N_d^{sec}(mobility)$ in Figure 5.10(a). The results for $\epsilon = 0.0$ and $\epsilon = 0.10$ are plotted. When the user speed increases, N_b^{sec} decreases because of the dynamic behavior of users. With the increased speed, users are allocated frequencies in a cell for shorter durations. Hence, the opportunity that a secondary user finds an available frequency increases with increasing user speed. Having dropping events due to sensing error causes decrease in N_b^{sec}, $N_d^{sec}(mobility)$, and $N_d^{sec}(forced)$ since opportunity to find free resources increases.



(a) number of events

(b) average forced handoff

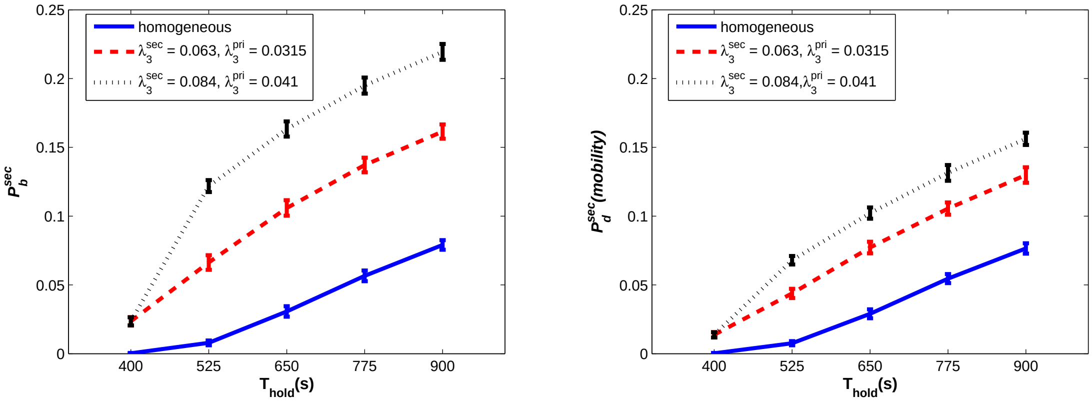
Figure 5.10. Effect of velocity on (a)number of events ($r = 250\,m$, $T_{hold} = 650s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$) (b)average forced handoff ($r = 250\,m$, $T_{hold} = 650s$, $\lambda_i^{sec} = 2 \times \lambda_i^{pri}$)

5.3.2. Effect of Heterogeneity

Tests in this subsection focus on the effect of heterogeneity on the whole system. Having a neighbor that has bursty traffic affects other cells. We investigate the behavior of the system while changing the holding time and velocity.

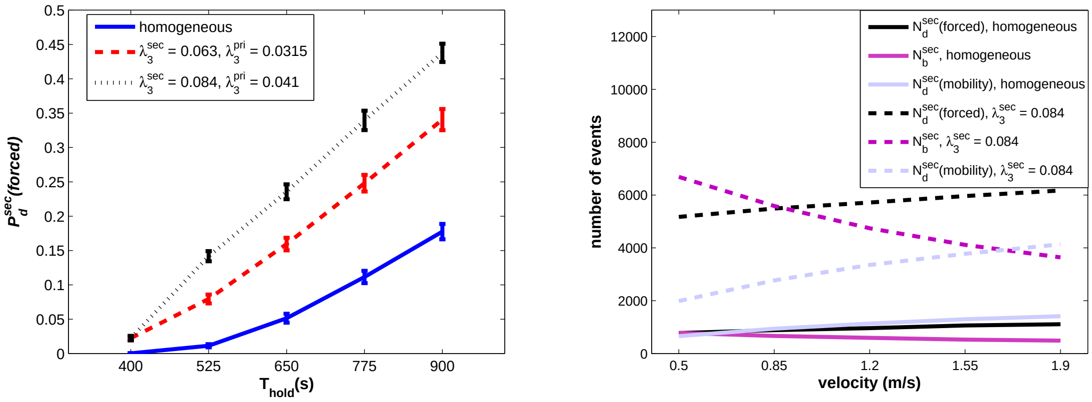
The effect of heterogeneous traffic on probability of blocking for secondary users is examined by comparing homogeneous traffic and two different heterogeneous traffics with increasing connection holding times. When users hold frequencies longer, probability that a secondary user finds an available channel is decreased. So, the probability of blocking for secondary users increases with increasing connection holding times for all three scenarios as shown in Figure 5.11(a). We observe that more heterogeneity leads to more the probability of blocking for secondary users. The more heterogeneous traffic we have, more secondary connection requests are generated. Hence, probability of blocking of secondary users is increased. In Figure 5.11(b), dropping probabilities for three cases are shown. With the increasing connection holding time, both secondary and primary users make more handoffs on average. More handoff attempts lead to an increase on probability of dropping for secondary users. Like dropping, forced termination is increased with the increasing number of primary handoffs. Since primary users have priority, more handoffs leads to more forced handoff or forced termination for secondary users. In addition, probability of dropping and forced termination for secondary users gets larger with increasing heterogeneity. Much more primary connection requests are generated because of heterogeneity, which increases the expected number of primary in the system. Since there are more primary users in the system, a much larger number of primary handoffs occur. Hence, secondary users experience more forced termination. Also, because of the increased primary users, probability of a secondary user to find an available frequency after a handoff is decreased since more channels are occupied with primary users. So, the probability of dropping for secondary users is increased with increasing heterogeneity.

The effect of user speed on number of secondary blocks, drops, and forced termination for homogeneous and heterogeneous traffic scenarios are shown in Figure 5.12(b).



(a) P_b^{sec} (b) $P_d^{sec}(mobility)$

Figure 5.11. Effect of heterogeneity on P_b^{sec} and $P_d^{sec}(mobility)$ ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$ for $i \neq 3$)



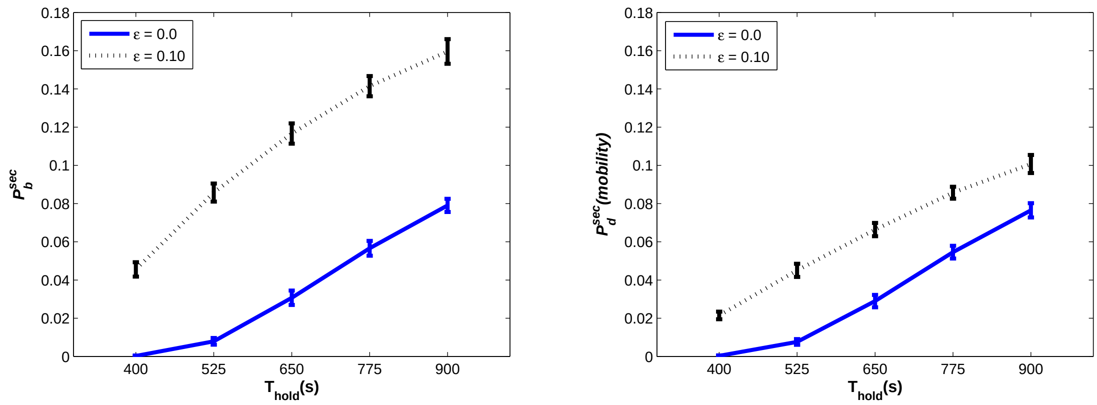
(a) $P_d^{sec}(forced)$ ($v = 1.2\,m/s$) (b) Number of events ($T_{hold} = 650$)

Figure 5.12. Effect of heterogeneity on $P_d^{sec}(forced)$ and number of events ($r = 250\,m$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$ for $i \neq 3$)

As expected, the number of secondary drops and forced termination gets larger when user speed increases. That is because more handoffs occur on average when the user speed is increased. More handoffs lead to more dropping events and forced termination for secondary users since primary users have priority. As the number of dropping events increases, more frequencies are released so that opportunity to find an available frequency for a secondary is increased. So, the number of blocking for secondary is decreased with increasing user speed. The curves for number of secondary blocks, drops, and forced termination for homogeneous and heterogeneous traffic scenarios show parallel behaviors. The number of secondary blocks, drops, and forced termination with heterogeneous traffic is greater than that for homogeneous traffic scenario. With heterogeneous traffic, more connection requests are generated compared to homogeneous traffic, so the number of blocks, drops, and forced termination for secondary users are increased.

5.3.3. Effect of Heterogeneity with Sensing Error

Tests in this subsection focus on a more realistic scenario to demonstrate the effects of heterogeneity including error in sensing. We study the case where $\epsilon = 0.10$, $\lambda_{sec,\,3}^{conReq} = 0.084$, and $\lambda_i^{sec} = 0.028$ for $i \neq 3$. We investigate the behavior of the system while altering the holding time.

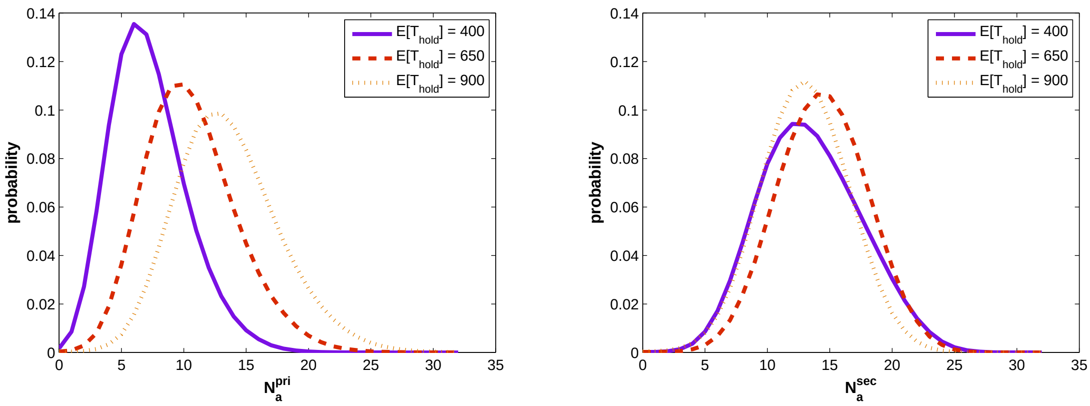


(a) P_b^{sec} (b) $P_d^{sec}(mobility)$

Figure 5.13. Effect of connection holding time on P_b^{sec} and $P_d^{sec}(mobility)$ ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$ for $i \neq 3$)

Considering the probability of blocking for secondary users in Figure 5.13(a) and Figure 5.13(b), it is observed that secondary users suffer more with increasing holding time for both homogeneous with perfect sensing scenario and heterogeneous with sensing error scenario. However, secondary users are exposed blocking more frequently in the heterogeneous traffic and sensing error scenario. Since some frequencies are released as a result of dropping due to sensing error, secondary users find an opportunity to seize a channel. However, as a result of bursty traffic more secondary connection requests are generated, which suppresses the impact of sensing error on probability of blocking of secondary users.

Similar behavior is observed for probability of dropping for secondary users. Probability of dropping for secondary users increases with the increasing connection holding time since secondary users encounter more handoffs on average. More handoff attempts lead to more dropping events for secondary users. While frequency release occurs due to sensing error, secondary connection requests are also generated because of bursty traffic. The effect of bursty traffic compensates the effect of sensing error and secondary users experience more drops.



(a) Primary active connection

(b) Secondary active connection

Figure 5.14. Effect of connection holding time on N_a^{pri} and N_a^{sec} ($r = 250\,m$, $v = 1.2\,m/s$, $\lambda_i^{pri} = 0.014\,conn/s$, $\lambda_i^{sec} = 0.028\,conn/s$ for $i \neq 3$)

We study the effect of heterogeneous traffic over sensing error in Figure 5.14(a) and Figure 5.14(b). The dropping events due to sensing error make more channels available. However, more connection requests are generated by both primary and secondary users due to the heterogeneous traffic. Primary users seize the available channels. Up to a point, secondary users occupy more frequencies with increasing holding time. Further increase in holding time causes primary users to dominate the system and secondary users to suffer. Hence, the distribution of number of frequencies used by secondary users tends to shift left with increasing holding time while the distribution of number of frequencies used by primary users shifts right.

5.4. Effect of Capacity Planning on CRN System Performance

In Figure 5.15, example system has 19 CogBSs, hence $\mathbb{B} = \{b_0, b_1, b_2, ..., b_{18}\}$. For a given b_i, the set of assigned frequencies are symbolized by $\mathbb{F}_{b_i}$. System traffic parameters, λ_i^{pri} and λ_i^{sec} represent the connection request arrival rate of primary users and secondary users in b_i, respectively. We can safely assume that the connection request arrival is a Poisson process. If there are enough mobile users in one cell, then the call arrival is a Poisson process even if the request arrival for an individual mobile user is not.

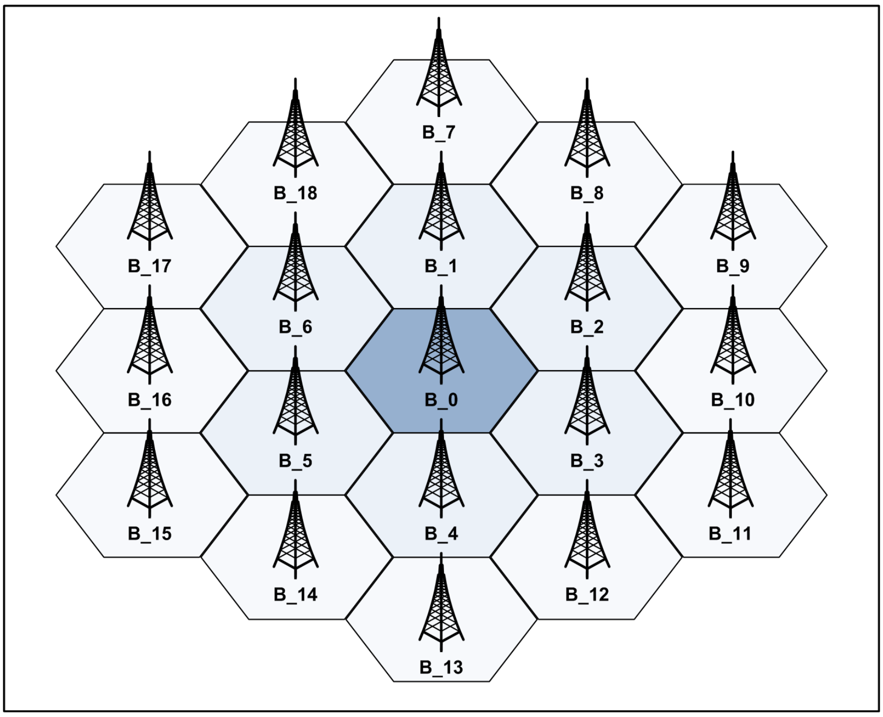


Figure 5.15. System topology for the tests

In our tests, we use the topology shown in Figure 5.15 with cell radius of 250 m. Mean connection holding time is 750 seconds, number of primary and secondary users per cell is 64 each, $\lambda_i^{pri} = 0.014$, $\lambda_i^{sec} = 0.028$ for $i = 1, 2, ..., 18$. For bursty traffic, b_0 is selected and traffic parameters are set to $\lambda_{pri,\,0}^{conReq} = 0.028$ and $\lambda_{sec,\,0}^{conReq} = 0.056$. We assume a sensing error probability of two per cent in our tests. We run the simulations 15 times and maintain a confidence intervals of 95 per cent for the simulations shown in the figures. Figures on probability of dropping and forced termination (Figures 5.17(a) and 5.17(b)) and figures on probability of blocking (Figures 5.18(a) and 5.18(b)) are drawn to scale for fair analysis.

Table 5.3. Capacity assignment values for different algorithms

	Hop #0	Hop #1	Hop #2	Total # of frequency
EqA	32	32	32	608
LHA	86	43	22+1	608
ALHA with $\alpha = 0.6$	51	36	29+1	608
ALHA with $\alpha = 0.7$	56	37	28+1	608

We have implemented three different frequency capacity planning algorithms, namely EqA, LHA, ALHA. The capacity assignments for the cells are summarized in Table 5.3. EqA assigns equal number of frequency for each cell regardless of traffic load. Hence, EqA performs worse for systems with different load. To improve the performance of EqA defined by the equal capacity assignment approach, we consider hop count, secondary frequency request rate, and primary request rate in LHA. We add α parameter to provide more stable capacity assignment with ALHA algorithm.

The first performance metric we study is system utilization according to closeness to heavy loaded cell. In Figure 5.16, each group corresponds to different capacity assignment algorithm and x-axis represents different hop numbers. With EqA, system utilization is very high especially in the bursty cell and its neighbors. LHA assigns more capacity to cells with bursty traffic but this time utilization is low even if secondary users exist. With ALHA method capacity assignment is more appropriate in order to provide similar QoS for all cells. System utilization of ALHA method with two different α values is considered. Probability of dropping of secondary connections is analyzed in Figure 5.17(a). One can observe that EqA works with higher dropping rates, especially in cells with bursty traffic, and also cannot provide similar dropping

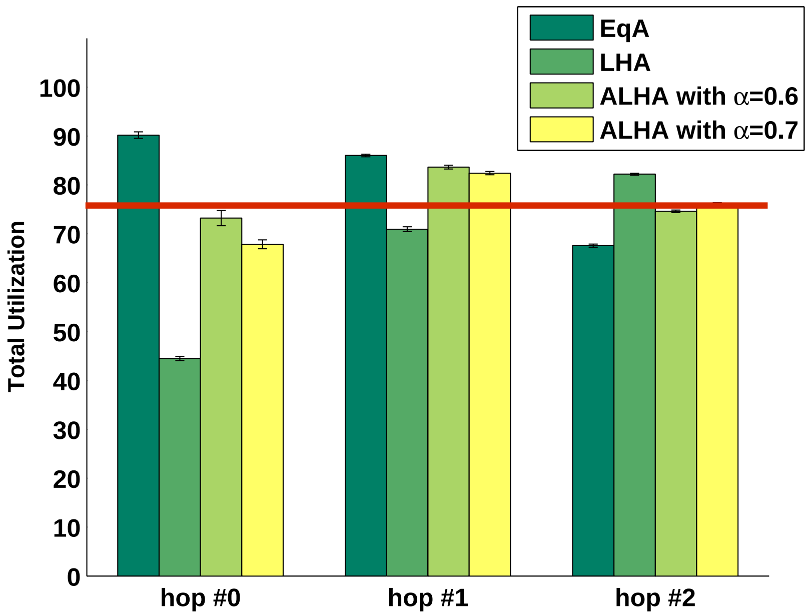
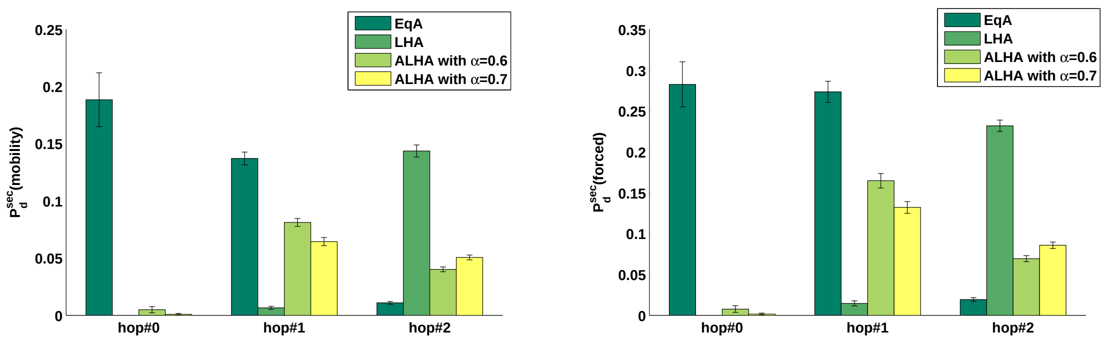


Figure 5.16. Total utilization for different hop numbers $v = 1.2\ m/s$



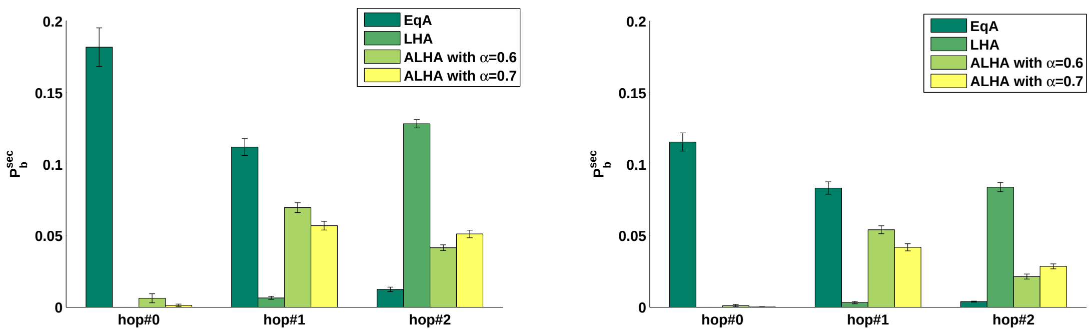
(a) $P_d^{sec}(mobility)$

(b) $P_d^{sec}(forced)$

Figure 5.17. $P_d^{sec}(forced)$ and $P_d^{sec}(mobility)$ for different hop numbers ($v = 1.2\,m/s$)

rate for all cells. LHA assigns very large capacities to cells with bursty traffic so that dropping probabilities of secondary users in these cells are very low. However since LHA assigns more capacity to bursty cells, their two hop neighbors lack sufficient resources. Hence, probability of dropping for secondary connections in two hop neighbors is very high. ALHA method performs better with both α values since it provides lower dropping probability as well as reducing fluctuations from cell to cell. Therefore, Δ value is smaller for ALHA method which is desired for a balanced system. System performance can be adjusted with α parameter.

Similar behavior is observed in Figure 5.17(b) for probability of forced termination. With EqA, higher probability of forced termination is experienced by secondary users in cells with bursty traffic and their one hop neighbors since EqA assigns same capacity without considering traffic load of individual cells. LHA performs better, but secondary users in two hop neighbor suffer from high forced termination due to lack of capacity. With ALHA method, less fluctuation in probability of forced termination is observed since ALHA method assigns capacities according to request rates and closeness to the bursty cell. Hence, ALHA method provides a sustainable probability of forced termination across cells.



(a) P_b^{sec} $(v = 1.2\, m/s)$ (b) P_b^{sec} $(v = 2.4\, m/s)$

Figure 5.18. Effect of velocity on P_b^{sec} for different hop numbers

Lastly, we analyze P_b^{sec} in Figure 5.18. As expected, similar behavior is observed with probability of dropping for secondary users. ALHA method achieves lower probability of blocking and provides similar probability of blocking across cells which lowers the Δ value. Also, we study the effect of velocity on P_b^{sec}. We work with two different user speeds $v = 1.2\ m/s$ and $v = 2.4\ m/s$. When we increase user speed, users make more handoffs on average. With more handoffs, more frequency bands are released in the originating cell meaning more opportunities. Therefore, P_b^{sec} significantly decreases for all methods.

The effect of proposed capacity planning algorithms on performance metrics like dropping, blocking, forced termination is evaluated. Proposed methods especially ALHA performs better than fixed equal assignment strategy EqA. In order to implement ALHA you need to have cell statistics like user speed, request rates etc. In order to implement such a flexible system, you need to have a centralized frequency usage monitoring scheme.

6. CONCLUSIONS

In this study, a model for a CR system with multiple cells is considered and performance metrics such as probability of dropping and probability of blocking for primary and secondary users, forced termination and forced frequency handoff for secondary users are evaluated via simulations after verifying the model with analytical solution. The proposed model for the IbCRN architecture defines the states of the system in a multi-cell environment. Our model allows multiple cells with different parameters, hence permits neighbors with bursty traffic.

First, we verify the model and then evaluate performance with different levels of sensing error and investigate the effect of sensing error on the performance metrics. Since the effect of neighbor with bursty traffic degrades the system performance, we finally evaluate performance of the system under different capacity assignment methods to improve system performance. Proposed capacity assignment method ALHA diffuses the performance degradation and results in more balanced performance metric values throughout the whole system. ALHA method can be further improved and adapted to different systems by using appropriate alpha values. With ALHA capacity assignment method, similar QoS can be achieved throughout the network as traffic load varies.

For future directions, effect of neighbor cells will be investigated in detail and we plan to develop a dynamic capacity assignment algorithm for adjusting capacities while the system operates. Also, we plan to develop a practical method to find a numerical solution of the analytical model.

REFERENCES

1. Akyildiz, I., W. Lee, M. Vuran, and S. Mohanty, “Next Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey”, *Computer Networks*, Vol. 50, No. 13, pp. 2127–2159, 2006.

2. Mitola, J. and J. Maguire, G.Q., “Cognitive Radio: Making Software Radios More Personal”, *IEEE Personal Communications*, Vol. 6, No. 4, pp. 13–18, 1999.

3. Mitola, J., *Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio*, Ph.D. thesis, Royal institute of Technology (KTH), 2000.

4. FCC, “Notice of Inquiry, in the Matter of Additional Spectrum for Unlicensed Below 900Mhz and in the 3Ghz Band”, Technical Report 17 FCC Rcd 25632, ET Docket No. 02-380, 2002.

5. IEEE, *Funtional Requirements for 802.22 WRAN Standard*, IEEE 802.22-05/0007/R48, Nov. 2006.

6. Attar, A., S. Ghorashi, M. Sooriyabandara, and A. Aghvami, “Challenges of Real-time Secondary Usage of Spectrum”, *Computer Networks*, 2007.

7. Dimou, K., R. Agero, M. Bortnik, R. Karimi, G. Koudouridis, S. Kaminski, H. Lederer, and J. Sachs, “Generic Link Layer: A Solution for Multi-Radio Transmission Diversity in Communication Networks Beyond 3G”, *IEEE 62nd Vehicular Technology Conference*, Vol. 3, pp. 1672–1676, Sept. 2005.

8. Leaves, P., K. Moessner, R. Tafazolli, D. Grandblaise, D. Bourse, R. Tonjes, and M. Breveglieri, “Dynamic Spectrum Allocation in Composite Reconfigurable Wireless Networks”, *IEEE Communications Magazine*, Vol. 42, No. 5, pp. 72–81, 2004.

9. Grandblaise, D. *et al.*, “Techno-economic of Collaborative Based Secondary Spec-

trum Usage-E2R Research Project Outcomes Overview", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 8–11, 2005.

10. "Ambient Networks Project", http://www.ambient-networks.org/, 2008.

11. Isler, D., H. B. Yilmaz, A. Zumbul, and T. Tugcu, "An Entire Architecture for Cognitive Radio Networks", *IEEE 16th Signal Processing, Communication and Applications Conference (SIU 2008)*, Didim, April 2008.

12. Haykin, S., "Cognitive Radio: Brain-Empowered Wireless Communications", *IEEE Journal on Selected Areas in Communications*, Vol. 23, No. 2, pp. 201–220, 2005.

13. Akyildiz, I., W. Lee, M. Vuran, and S. Mohanty, "A Survey on Spectrum Management in Cognitive Radio Networks", *IEEE Communications Magazine*, Vol. 46, No. 4, pp. 40–48, 2008.

14. Wild, B. and K. Ramchandran, "Detecting Primary Receivers for Cognitive Radio Applications", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 124–130, Nov. 2005.

15. Cabric, D., S. Mishra, and R. Brodersen, "Implementation Issues in Spectrum Sensing for Cognitive Radios", *Conference Record of the 38th Asilomar Conference on Signals, Systems and Computers, 2004*, Vol. 1, pp. 772–776, Nov. 2004.

16. Sahai, A., N. Hoven, and R. Tandra, "Some Fundamental Limits in Cognitive Radio", *Proceedings of the Allerton Conference on Communication, Control and Computing*, 2004.

17. Tang, H., "Some Physical Layer Issues of Wide-band Cognitive Radio Systems", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 151–159, Nov. 2005.

18. Ghasemi, A. and E. Sousa, "Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 131–136, Nov. 2005.

19. Fehske, A., J. Gaeddert, and J. Reed, "A New Approach to Signal Classification Using Spectral Correlation and Neural Networks", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 144–150, Nov. 2005.

20. Oner, M. and F. Jondral, "On the Extraction of the Channel Allocation Information in Spectrum Pooling Systems", *IEEE Journal on Selected Areas in Communications*, Vol. 25, No. 3, pp. 558–565, April 2007.

21. Ganesan, G. and Y. Li, "Cooperative Spectrum Sensing in Cognitive Radio Networks", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 137–143, Nov. 2005.

22. Yang, L., L. Cao, and H. Zheng, "Proactive Channel Access in Dynamic Spectrum Networks", *Second International Conference on Cognitive Radio Oriented Wireless Networks and Communications (Crowncom 2007)*, pp. 487–491, Aug. 2007.

23. Yarkan, S. and H. Arslan, "Binary Time Series Approach to Spectrum Prediction for Cognitive Radio", *IEEE 66th Vehicular Technology Conference*, pp. 1563–1567, 2007.

24. Zheng, H. and L. Cao, "Device-Centric Spectrum Management", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 56–65, Nov. 2005.

25. Brik, V., E. Rozner, S. Banerjee, and P. Bahl, "DSAP: A Protocol for Coordinated Spectrum Access", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 611–614, Nov. 2005.

26. Zhao, J., H. Zheng, and G.-H. Yang, "Distributed Coordination in Dynamic Spectrum Allocation Networks", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 259–268, Nov. 2005.

27. Zhao, Q., L. Tong, and A. Swami, "Decentralized Cognitive MAC for Dynamic Spectrum Access", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 224–232, Nov. 2005.

28. Huang, J., R. Berry, and M. Honig, "Spectrum Sharing with Distributed interference Compensation", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 88–93, Nov. 2005.

29. Ma, L., X. Han, and C.-C. Shen, "Dynamic Open Spectrum Sharing MAC Protocol for Wireless Ad Hoc Networks", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 203–213, Nov. 2005.

30. Bertsekas, D. and R. Galleger, *Data Networks*, Prentice Hall, Englewood Cliffs, NJ, 1992.

31. Kleinrock, L., *Queueing Systems, Volume 1: Theory*, John Wiley & Sons, 1975.

32. Fette, B., *Cognitive Radio Technology*, Communications Engineering Series: Elsevier, Burlington, USA, Aug. 2006.

33. Shankar, N., C. Cordeiro, and K. Challapali, "Spectrum Agile Radios: Utilization and Sensing Architectures", *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, pp. 160–169, Nov. 2005.

34. Xing, Y., R. Chandramouli, S. Mangold, and S. Shankar, "Dynamic Spectrum Access in Open Spectrum Wireless Networks", *IEEE Journal on Selected Areas in*

Communications, Vol. 24, No. 3, pp. 626–637, 2006.

35. Mangold, S. and K. Challapali, "Coexistence of Wireless Networks in Unlicensed Frequency Bands", *Proceedings of the WWRF9*, Vol. 0, Zurich, Switzerland, July 2003.

36. Zhu, X., L. Shen, and T. Yum, "Analysis of Cognitive Radio Spectrum Access with Optimal Channel Reservation", *IEEE Communications Letters*, Vol. 11, No. 4, pp. 304–306, April 2007.

37. Srinivasa, S. and S. Jafar, "How Much Spectrum Sharing is Optimal in Cognitive Radio Networks?", *IEEE Transactions on Wireless Communications*, Vol. 7, No. 10, pp. 4010–4018, October 2008.

38. Watanabe, K., K. Ishibashi, and R. Kohno, "Performance of Cognitive Radio Technologies in the Presence of Primary Radio Systems", *IEEE 18th International Symposium on Personal, indoor and Mobile Radio Communications (PIMRC 2007)*, pp. 1–5, Sept. 2007.

39. Haddad, M., A. Hayar, and M. Debbah, "Spectral Efficiency of Cognitive Radio Systems", *IEEE Global Telecommunications Conference (GLOBECOM 2007)*, pp. 4165–4169, Nov. 2007.

40. Kahwa, T. and N. Georganas, "A Hybrid Channel Assignment Scheme in Large-scale, Cellular-structured Mobile Communication Systems", *IEEE Transactions on Communications*, Vol. 26, No. 4, pp. 432–438, April 1978.

41. Elnoubi, S., R. Singh, and S. Gupta, "A New Frequency Channel Assignment Algorithm in High Capacity Mobile Communication Systems", *IEEE Transactions on Vehicular Technology*, Vol. 31, No. 3, pp. 125–131, Aug. 1982.

42. Raymond, P., "Performance Analysis of Cellular Networks", *IEEE Transactions on Communications*, Vol. 39, No. 12, pp. 1787–1793, Dec. 1991.

43. Tutschku, K., “Demand-Based Radio Network Planning of Cellular Mobile Communication Systems”, *Proceedings of 17th Annual Joint Conference of the IEEE Computer and Communications Societies(inFOCOM 1998)*, Vol. 3, pp. 1054–1061 Vol.3, Apr. 1998.

44. Hurley, S., “Planning Effective Cellular Mobile Radio Networks”, *IEEE Transactions on Vehicular Technology*, Vol. 51, No. 2, pp. 243–253, March 2002.

45. Feng, W. and M. Kowada, “Performance Analysis of Wireless Mobile Networks with Queueing Priority and Guard Channels”, *International Transactions in Operational Research*, Vol. 15, No. 4, pp. 481–508, 2008.

46. Li, W., H. Chen, and D. Agrawal, “Performance Analysis of Handoff Schemes with Preemptive and Nonpreemptive Channel Borrowing in Integrated Wireless Cellular Networks”, *IEEE Transactions on Wireless Communications*, Vol. 4, No. 3, pp. 1222–1233, 2005.

47. Liu, X., E. Chong, and N. Shroff, “Efficient Network Utilization for Multimedia Wireless Networks”, *Lecture Notes in Computer Science*, pp. 108–122, 2000.

48. Xie, H. and S. Kuek, “Priority Handoff Analysis”, *International Journal of Wireless Information Networks*, Vol. 1, No. 2, pp. 141–148, 1994.

49. Shen, W., H. Liu, and Q. Zeng, “Traffic Modeling and Analysis of Wireless and Mobile Cellular Systems Using Smart Antennas”, *Proceedings of International Conference on Mobile Computing and Ubiquitous Networking (ICMU 2005)*, Vol. 2, 2005.

50. Kunz, D., “Channel Assignment for Cellular Radio Using Neural Networks”, *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 1 Part 2, pp. 188–193, 1991.

51. Duque-Anton, M., D. Kunz, and B. Ruber, “Channel Assignment for Cellular Radio Using Simulated Annealing”, *IEEE Transactions on Vehicular Technology*,

Vol. 42, No. 1, pp. 14–21, Feb. 1993.

52. Onur, E., H. Delic, C. Ersoy, and M. Caglayan, “Measurement-Based Replanning of Cell Capacities in GSM Networks”, *Computer Networks*, Vol. 39, No. 6, pp. 749–767, 2002.