COGNITIVE RADIO NETWORKS:
SYSTEM OPTIMIZATION AND SMART GRID APPLICATIONS

APPROVED BY SUPERVISING COMMITTEE:

________________________________________
Mo Jamshidi, Ph.D., Chair

________________________________________
Brian Kelley, Ph.D.

________________________________________
David Akopian, Ph.D.

Accepted: _________________________________________
Dean, Graduate School
DEDICATION

This thesis is dedicated to my mother and father who have supported me all the way since the beginning of my studies and have been a great source of motivation and inspiration.
COGNITIVE RADIO NETWORKS:
SYSTEM OPTIMIZATION AND SMART GRID APPLICATIONS

by

AMIR RAJAEE, B.Sc.

THESIS
Presented to the Graduate Faculty of
The University of Texas at San Antonio
In partial Fulfillment
Of the Requirements
For the Degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT SAN ANTONIO
College of Engineering
Department of Electrical Engineering
August 2012
ACKNOWLEDGEMENTS

I am extremely thankful to my supervisor Dr. Mo Jamshidi for his outstanding pedagogy, valuable advice and consistent support during preparation of this research project. I hope he will be proud of me throughout future successful challenges in my career.

I also express my gratitude and special thanks to my supervisor Dr. Brian Kelley for his support, patience, and encouragement throughout my graduate studies. It is not often that one finds an advisor and colleague that always finds the time for listening to the little problems and roadblocks that unavoidably crop up in the course of performing research. His technical and editorial advice was essential to the completion of this dissertation and has taught me innumerable lessons and insights on the workings of academic research in general.

Besides my advisors, I would like to thank Dr. David Akopian for his encouragement, insightful comments, and hard questions.

Special thanks also to all my friends and colleagues especially Mahdy Saedy, Kranthi Manoj Nagothu, and Yashar Sahraei Manjili for sharing the literature and invaluable assistance.

August 2012
This thesis presents the Cognitive Radio framework for wireless networks. The proposed Cognitive Radio framework is a complete model for Cognitive Radio that describes the decision and sharing procedures in wireless networks by introducing Queued Markov Chain method.

Queued Markov Chain method is capable of considering waiting time and is very well generalized for unlimited number of secondary users. It includes the sharing aspect of Cognitive Radio.

The proposed approach in this thesis uses pervasive smart grid systems (i.e. cloud data centers) as the central communication and optimization infrastructure supporting metropolitan area based smart meter infrastructure. In this thesis, we investigate the performance of various scheduling algorithms in context with CR units to provide a satisfactory tradeoff between maximizing the system capacity, achieving fairness among cognitive users.

This thesis also addresses improvements in the multiuser capacity in unplanned networks with high levels of co-channel interference. For this, a novel opportunistic interference aware scheduling protocol ideally suited for maximum channel reuse in unplanned networks. In this thesis, we analyze the application of SISO and MIMO interference aware scheduling to maximize the capacity and number of scheduled smart meters.
Moreover, a Fuzzy Logic-based framework and Particle Swarm Optimization are proposed for control of Battery Storage Unit in Micro-Grid Systems to achieve Efficient Energy Management. Typically, a Micro-Grid system operates synchronously with the main grid and also has the ability to operate independently from the main power grid in an islanded mode. The goal here is to control the amount of power delivered to/taken from the storage unit in order to improve a cost function, defined based on summation of payment required for purchasing power from main grid or profit obtained by selling power to the main grid and distribution power loss.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS .............................................................................................................. IV

TABLE OF CONTENTS .................................................................................................................. VII

LIST OF TABLES .......................................................................................................................... X

LIST OF FIGURES ......................................................................................................................... XI

CHAPTER ONE: INTRODUCTION ............................................................................................... 1

CHAPTER TWO: COGNITIVE RADIO .......................................................................................... 4

APPLICATIONS OF COGNITIVE RADIO ................................................................................... 4

TV WHITE SPACES ...................................................................................................................... 4

CELLULAR NETWORKS .................................................................................................................. 4

MILITARY USAGE .......................................................................................................................... 5

COGNITIVE RADIO NETWORK ARCHITECTURE ....................................................................... 5

NETWORK COMPONENTS ............................................................................................................. 6

SPECTRUM MANAGEMENT FRAMEWORK ................................................................................. 8

SPECTRUM SENSING ..................................................................................................................... 8

SPECTRUM SENSING CHALLENGES .......................................................................................... 10

SPECTRUM DECISION .................................................................................................................. 12

CHANNEL CHARACTERISTICS IN COGNITIVE RADIO NETWORKS ........................................ 13

DECISION PROCEDURE ............................................................................................................... 14

SPECTRUM DECISION CHALLENGES ....................................................................................... 14

SPECTRUM SHARING ................................................................................................................... 15

SPECTRUM SHARING CHALLENGES ......................................................................................... 17

SPECTRUM MOBILITY ................................................................................................................... 18

SPECTRUM MOBILITY CHALLENGES ......................................................................................... 19

CHAPTER THREE: PROPOSED SPECTRUM DECISION AND SPECTRUM SHARING ALGORITHM

INTRODUCTION ............................................................................................................................ 20
CHAPTER FOUR: COGNITIVE RADIO IN SMART GRID THROUGHPUT ANALYSIS ON COGNITIVE RADIO NETWORKS FOR AMI METERS IN SMART GRID

INTRODUCTION.........................................................................................46

4G COGNITIVE RADIO FRAMEWORK.......................................................48

4G COGNITIVE RADIO SYSTEM ARCHITECTURE.......................................48

PERVASIVE SMART GRID SYSTEMS.......................................................49

CR SYSTEM MODEL................................................................................50

PRIMARY USER ACTIVITY MODEL..............................................................51

OPTIMUM SENSING TIME........................................................................52

SCHEDULING ALGORITHMS FOR CR USERS...........................................53

ANALYSIS AND SIMULATION RESULTS................................................55

CONCLUSION............................................................................................58
CHAPTER FIVE: INTERFERENCE AWARE SCHEDULING FOR MAXIMUM CHANNEL REUSE AND MAX-CAPACITY IN SMART METER NETWORKS ................................................................. 59

CONTRIBUTIONS OF THIS CHAPTER ON INTERFERENCE AWARE SCHEDULING................................. 59

SYSTEM MODEL ....................................................................................................................... 59

INTERFERENCE – AWARE SCHEDULING ALGORITHM .............................................................. 62

INTERFERENCE MODEL FOR SISO ......................................................................................... 65

INTERFERENCE MODEL FOR BEAMFORMING ......................................................................... 67

SIMULATIONS AND RESULTS ................................................................................................. 68

CONCLUSION .......................................................................................................................... 72

CHAPTER SIX: SMART GRID AND OPTIMIZATION................................................................. 75

FUZZY CONTROL OF ELECTRICITY STORAGE UNIT FOR ENERGY MANAGEMENT OF MICRO-GRIDS... 75

SYSTEM MODEL ....................................................................................................................... 76

CHARACTERISTICS OF BUSES IN SCENARIO 1 ................................................................. 78

CHARACTERISTICS OF BUSES IN SCENARIO 2 ................................................................. 78

CHARACTERISTICS OF BUSES IN SCENARIO 3 ................................................................. 78

PROBLEM STATEMENT ............................................................................................................ 79

SCENARIO 1 ............................................................................................................................. 80

SCENARIO 2 ............................................................................................................................. 81

SCENARIO 3 ............................................................................................................................. 81

FUZZY CONTROL APPROACH .............................................................................................. 82

SIMULATION RESULTS AND DISCUSSIONS ......................................................................... 84

CONCLUSION .......................................................................................................................... 93

PARTICLE SWARM OPTIMIZATION ...................................................................................... 94

SIMULATIONS FOR PSO .......................................................................................................... 95

CHAPTER SEVEN: CONCLUSION ......................................................................................... 101

REFERENCES ......................................................................................................................... 104

VITA
LIST OF TABLES

Table 1  Simulation traffic parameters .................................................................30
Table 2  The OFDM parameters for IEEE802.22 WRAN .................................41
Table 3  Parameters for simulation analysis ..........................................................44
Table 4  Simulation results for Loss, Cost, and Balance .................................67
LIST OF FIGURES

Figure 1 Available chunks of spectrum (white squares) are detected in frequency and time and can be aggregated for opportunistic use.........................................................2
Figure 2 Cognitive operations needed for an optimal decision ........................................2
Figure 3 Cognitive radio network architecture.................................................................6
Figure 4 Scale-free network formation with power-law degree distribution..................22
Figure 5 a) Timing model, b) resource block & dynamic resource management.........25
Figure 6 Wide spectrum sensing model.........................................................................28
Figure 7 Queued Markov Chain state machine without sharing....................................29
Figure 8 Scale free infrastructure and its ul and dl spectrum resource model............34
Figure 9 Queued markov chain state machine with sharing...........................................39
Figure 10 State probabilities using competitive sharing for different number of users.....41
Figure 11 State probabilities using competitive and uniform sharing n=3......................41
Figure 12 Load and net request in cluster a.....................................................................42
Figure 13 Load with different traffic in cluster a.............................................................43
Figure 14 Capacity improvement in cluster a....................................................................44
Figure 15 Capacity improvement in cluster a....................................................................44
Figure 16 Capacity improvement for scale-free network.................................................45
Figure 17 4G cr network system architecture: scenario of multiple ami meters serviced by cognitive radio network infrastructure enabled by cloud center coexisting with private cellular network ..............................................................................................................49
Figure 18 Markov chains model; optimum sensing time.................................................51
Figure 19 Average capacity over time............................................................................56
Figure 20 Max-rate average capacity.............................................................................57
Figure 21 Average no. of scheduled sus .................................................................57
Figure 22 SISO system model depicted with coordinated and uncoordinated interference ...60
Figure 23 Mechanism of our reuse model .............................................................61
Figure 24 Interference-aware scheduler (ias) algorithm for pre reuse ....................62
Figure 25 MIMO system model with coordinated and uncoordinated interference ....67
Figure 26 Total capacity of a-su in the cases of no ias, ias-siso and ias-bf ................70
Figure 27 Total capacity of a-su in the cases of no ias, ias-siso and ias-bf ...............70
Figure 28 Relation between interference generated by reuse and total capacity of scheduled a-su in the cases of ias-siso and ias-bf .................................................................73
Figure 29 Number of reuse for every scheduled a-sus in one instance ..................73
Figure 30 Total number of reuses over entire bw in cases of ias-siso and ias-bf ..........74
Figure 31 Basic grid system model .....................................................................77
Figure 32 Three bus model for micro-grid ..........................................................80
Figure 33 Fuzzy membership functions for input and output variables of the fuzzy controller; .................................................................83
Figure 34 Profiles of price, renewable generation, and the load ............................85
Figure 35 Power flow of bus 1 connected to solar panels; scenario 1 .....................85
Figure 36 Power flow of bus 2 connected to utility; scenario 1 .............................86
Figure 37 Power flow of bus 3 connected to load; scenario 1 ...............................86
Figure 38 Output of the fuzzy controller, i.e. measure of the amount of power given to/taken from storage unit; scenario 2; .................................................................87
Figure 39 Power flow of bus 2 connected to utility; scenario 2 ............................88
Figure 40 Output of the fuzzy controller; scenario 3; ........................................89
Figure 41 Measure of energy stored in battery; scenario 3 .................................90
Figure 42 Power flow of bus 2 connected to utility; scenario 3 ............................90
Figure 43 Micro grid control by pso with load, re, and price profile ..........................96

Figure 44 Power from battery ..................................................................................96

Figure 45 All profiles and battery behavior through pso utilization ..........................97

Figure 46 The re power, price, and load profile when re power is not sufficient for given load
......................................................................................................................................98

Figure 47 Battery charging and discharging states ..................................................98

Figure 48 Grid power, price, cost function, and power from re ...............................99

Figure 49 Battery power, input profiles and grid power ..........................................100
CHAPTER ONE: INTRODUCTION

Current wireless networks are identified by an inactive spectrum allocation policy, where governmental agencies assign wireless spectrum to licensed users on a long-term basis for large geographical regions. Recently, because of the increase in spectrum demand, this policy faces spectrum scarcity in particular spectrum bands [1].

Most of the spectrum that is interesting to operators has already been exclusively assigned. This means that it is difficult for new operators to get access to spectrum and for existing operators to get access to more spectrums to meet an ever increasing demand for capacity [2]. This combination of a large unsatisfied demand for spectrum and the current poor spectrum utilization is unacceptable from a regulatory and political point of view. It indicates that there is a potential for offering the public better and cheaper wireless telecommunication services. Not utilized spectrum can be used by a new operator to offer services competing with existing services to enhance the competition in the market and hence reduce prices. Or it can be used by new operators to offer new types of services or by existing operators to enhance their existing services [2].

In contrast, a large portion of the assigned spectrum is used periodically, leading to underutilization of a significant amount of spectrum[1].

One of the ways to achieve a more efficient utilization of spectrum is Cognitive Radio (CR), which relies on the opportunistic use of frequency holes [2].
Figure 1 Available chunks of spectrum (white squares) are detected in frequency and time and can be aggregated for opportunistic use.

Figure 2 Cognitive operations needed for an optimal decision

Cognitive Radio (CR) has been proposed as a way to increase the availability of spectrum resources. It is a system utilizing spectrum holes in licensed bands in an opportunistic manner.
illustrated in figure 1. In order to implement this feature, a CR system functions along three basic steps: 1. Detection of available spectrum from primary, licensed users; 2. Usage of this spectrum as secondary user; 3. Exit as quickly as possible if primary usage resumes [2].

A Cognitive Radio system is an ‘intelligent’ radio system that takes into account its knowledge about its environment and its communication needs and adapts its wireless transmissions in an optimal manner as illustrated in Figure 2[2].

CR networks, however, impose unique challenges due to the high fluctuation in the available spectrum, as well as the diverse quality of service (QoS) requirements of various applications. In order to address these challenges, each CR user in the CR network must[1]:

• Determine which portions of the spectrum are available
• Select the best available channel
• Coordinate access to this channel with other users
• Vacate the channel when a licensed user is detected [3]

These capabilities can be realized through spectrum management functions that address four main challenges: *spectrum sensing*, *spectrum decision*, *spectrum sharing*, and *spectrum mobility*. This article presents a definition, the functions, and the current research challenges of spectrum management in CR networks. [1].
APPLICATIONS OF COGNITIVE RADIO

Applications of Cognitive Radio

The development of spectrum sensing and spectrum sharing techniques enable the applications of CR in many areas. In this section, we introduce some of them.

TV WHITE SPACES

The main regulatory agencies for the unlicensed use of TV white spaces are the FCC in the United States, the Office of Communications in the United Kingdom, and the Electronic Communications Committee (ECC) of the conference of European Post and Telecommunications in Europe. After many years of effort in this area, FCC released the final rules for using the TV white space in September 2010 [4], which led to the culmination of this field. Meanwhile, other agencies have been also getting progress [5]. This is based on the idea of having an accessible database (centralize-fasion) of free TV bands, otherwise called TV white space, or to sense and obtain SHs (distributed-fasion) within TV bands to utilize for SUs communication.

CELLULAR NETWORKS

The applications of CR in cellular networks are emerging in recent years. To overcome the indoor coverage problem and adapt to traffic growth, the concept of small cells, such as femtocells, has been proposed in 3GPP LTE-Advanced (LTE-A)[6] and IEEE 802.16m [7], and companies like PicoChip driving femtocell revolution.. The femtocell unit has the function of the
typical BS (eNodeB in LTE). However, the self-deployment property of the femtocells makes the centralized interference management impractical.

MILITARY USAGE

CR is a must-have technique for military usage. With CR, the users can recognize the enemies’ communications and protect their own. Moreover, the users can search for more transmission opportunities. The US department of defense (DoD) has already established programs such as SPEAK easy radio system and next Generation (XG) to exploit the benefits of CR techniques [3].

Cognitive Radio Network Architecture

A comprehensive description of the CR network architecture is essential for the development of communication protocols that address the dynamic spectrum challenges. The CR network architecture is presented in this section.
Network Components

The components of the CR network architecture can be classified as shown in Fig. 3 as two groups: the primary network and the CR network. The primary network (or licensed network) is referred to as an existing network, where the primary users have a license to operate in a certain spectrum band. If primary networks have an infrastructure, primary user activities are controlled through primary base stations. Due to their priority in spectrum access, the operations of primary users should not be affected by unlicensed users. The CR network (also called the dynamic spectrum access network, secondary network, or unlicensed network) does not have a license to operate in a desired band. Hence, additional functionality is required for CR users to share the licensed spectrum band. CR networks also can be equipped with CR base stations that

![Figure 3 Cognitive radio network architecture.](image-url)
provide single-hop connection to CR users. Finally, CR networks may include *spectrum brokers* that play a role in distributing the spectrum resources among different CR networks [1].

CR users are capable of accessing both the licensed portions of the spectrum used by primary users and the unlicensed portions of the spectrum through wideband access technology. Consequently, the operation types for CR networks can be classified as *licensed band operation* and *unlicensed band operation*.

- **Licensed band operation**: The licensed band is primarily used by the primary network. Hence, CR networks are focused mainly on the detection of primary users in this case. The channel capacity depends on the interference at nearby primary users. Furthermore, if primary users appear in the spectrum band occupied by CR users, CR users should vacate that spectrum band and move to available spectrum immediately [1].

- **Unlicensed band operation**: In the absence of primary users, CR users have the same right to access the spectrum. Hence, sophisticated spectrum sharing methods are required for CR users to compete for the unlicensed band [1].

As shown in Fig. 3, the CR users have the opportunity to perform three different access types:

- **CR network access**: CR users can access their own CR base station, on both licensed and unlicensed spectrum bands. Because all interactions occur inside the CR network, their spectrum sharing policy can be independent of that of the primary network.

- **CR ad hoc access**: CR users can communicate with other CR users through an ad hoc connection on both licensed and unlicensed spectrum bands.

- **Primary network access**: CR users can also access the primary base station through the licensed band. Unlike for other access types, CR users require an adaptive medium access
control (MAC) protocol, which enables roaming over multiple primary networks with different access technologies. According to the CR architecture shown in Fig. 3, various functionalities are required to support spectrum management in CR networks. An overview of the spectrum management framework and its components is provided next[1].

Spectrum Management Framework

CR networks impose unique challenges due to their coexistence with primary networks as well as diverse QoS requirements. Thus, new spectrum management functions are required for CR networks with the following critical design challenges:

*Interference avoidance; QoS awareness; Seamless communication; Spectrum sensing; Spectrum decision; Spectrum sharing; Spectrum mobility.*

In the following sections we discuss the four main spectrum management functions [1].

Spectrum Sensing

In practice, the unlicensed users, also called secondary users (SUs), need to continuously monitor the activities of the licensed users, also called primary users (PUs), to find the spectrum holes (SHs), which is defined as the spectrum bands that can be used by the SUs without interfering with the PUs. This procedure is called spectrum sensing [8], [9].

Generally, spectrum sensing techniques can be classified into three groups: primary transmitter detection, primary receiver detection, and interference temperature management as described in the following [1].
Transmitter detection is based on the detection of a weak signal from a primary transmitter through the local observations of CR users. Three schemes are generally used for transmitter detection: matched filter detection, energy detection, and feature detection[10]:

• **Matched filter detection**: When the information of the primary user signal is known to the CR user, the optimal detector in stationary Gaussian noise is the matched filter. However, the matched filter requires a priori knowledge of the characteristics of the primary user signal.

• **Energy detection**: If the receiver cannot gather sufficient information about the primary user signal, the optimal detector is an energy detector. However, the performance of the energy detector is susceptible to uncertainty in noise power. Also, energy detectors often generate false alarms triggered by unintended signals because they cannot differentiate signal types.

• **Feature detection**: In general, modulated signals are characterized by built-in periodicity or cyclostationarity. This feature can be detected by analyzing a spectral correlation function. The main advantage of feature detection is its robustness to uncertainty in noise power. However, it is computationally complex and requires significantly long observation times. Due to the lack of interactions between primary users and CR users, transmitter detection techniques rely only on weak signals from the primary transmitters. Transmitter detection models cannot prevent the hidden terminal problem. A CR user (transmitter) can have a good line of sight to a CR receiver but may not be able to detect the primary transmitter due to shadowing. Therefore, sensing information from other users is required for more accurate primary transmitter detection — referred to as cooperative detection.

Cooperative detection is theoretically more accurate because the uncertainty in a single user’s detection can be minimized through collaboration. Moreover, multipath fading and shadowing effects can be mitigated so that the detection probability is improved in a heavily...
shadowed environment. However, cooperative approaches cause adverse effects on resource constrained networks due to the overhead traffic required for cooperation [1].

There are several other spectrum sensing techniques, such as eigenvalue-based and moment-based detectors.

*Eigenvalue-based detector:* In the multiple-antenna system, eigenvalue-based detection can be used for spectrum sensing [11],[12]. In [11], maximum-minimum eigenvalue (MME) and energy with minimum eigenvalue detectors have been proposed, which can simultaneously achieve both high probability of detection and low probability of false-alarm without requiring information of the PU transmitter signals and noise power. In most of the existing eigenvalue-based methods, the expression for the decision threshold and the probabilities of detection and false-alarm are calculated based on the asymptotical distributions of eigenvalues. To address this issue, the exact decision threshold for the probability of false-alarm for the MME detector with finite numbers of cooperative SUs and samples has been derived in [12], which leads to our next section on cooperative spectrum sensing (CSS). *Moment-based detector:* When accurate noise variance and PU transmitter signal power are unknown, blind moment-based spectrum sensing algorithms can be applied[13]. Unknown parameters are first estimated by exploiting the constellation of the PU transmitter signal. When the SU does not know the PU transmitter signal constellation, a robust approach that approximates a finite quadrature amplitude modulation (QAM) constellation by a continuous uniform distribution has been developed [13].

**SPECTRUM SENSING CHALLENGES**

There exist several open research challenges that must be investigated for the development of spectrum sensing techniques:
• **Interference temperature measurement:** Due to the lack of interactions between primary networks and CR networks, generally a CR user cannot be aware of the precise locations of the primary receivers. Thus, new techniques are required to measure or estimate the interference temperature at nearby primary receivers.

• **Spectrum sensing in multi-user networks:** The multi-user environment, consisting of multiple CR users and primary users, makes it more difficult to sense spectrum holes and estimate interference. Hence, spectrum sensing functions should be developed considering the multi-user environment.

• **Spectrum-efficient sensing:** Sensing cannot be performed while transmitting packets. Hence, CR users should stop transmitting while sensing, which decreases spectrum efficiency. For this reason, balancing spectrum efficiency and sensing accuracy is an important issue. Moreover, because sensing time directly affects transmission performance, novel spectrum sensing algorithms must be developed such that the sensing time is minimized within a given sensing accuracy [1].

• **Wideband sensing:** Wideband sensing faces technique challenges and there is limited work on it. The main challenge stems from the high data rate radio-front (RF) end requirement to sense the whole band, with the additional constraint that deployed CR systems (like mobile phones) will be limited in data processing rates. To achieve reliable results, the sample rate should be above the Nyquist rate if conventional estimation methods are used, which is a challenging task. Alternatively, the RF end can use a sequence of narrowband bandpass filters to sense one narrow frequency band at a time [14]. However, a large number of RF components are needed for the whole band. For more effective SU network, a multiband sensing-time-adaptive joint detection framework has been proposed in [15], [16], which adaptively senses multiple
narrowband channels jointly to maximize the achievable opportunistic throughput of the SU network while keeping the interference with the PU network bounded to a reasonably low level. Based on energy detector for narrowband sensing, the sensing time and detection thresholds for each narrowband detector are optimized jointly, which is different from the previous multiband joint detection framework in [17].

- **Synchronization**: Besides the synchronization problem for quiet sensing period, spectrum synchronization before the data transmission for non-contiguous OFDM based systems is also a challenge. To address this challenge, a scheme has been proposed in [18] to use the received training symbols to calculate a posterior probability of each subband’s being active without the information of out-of-band spectrum synchronization. The proposed hard-decision-based detection (HDD) utilizes a set of adjacent subbands while the soft-decision-based detection (SDD) uses all the subbands for detection. Both HDD and SDD schemes provide satisfactory performance while SDD performs better.

### Spectrum Decision

CR networks require the capability to decide which spectrum is the best spectrum band among the available bands according to the QoS requirements of the applications. This notion is called *spectrum decision*. Spectrum decision usually consists of two steps: first, each spectrum band is characterized, based on not only local observations of CR users but also statistical information of primary networks. Then, based on this characterization, the most appropriate spectrum band can be chosen [1].
Because available spectrum holes show different characteristics that vary over time, each spectrum hole should be characterized considering both the time-varying radio environment and spectrum parameters, such as operating frequency and bandwidth. Hence, it is essential to define parameters that can represent a particular spectrum band as follows:

• **Interference**: From the amount of interference at the primary receiver, the permissible power of a CR user can be derived, which is used for the estimation of channel capacity.

• **Path loss**: The path loss is closely related to distance and frequency. As the operating frequency increases, the path loss increases, which results in a decrease in the transmission range. If transmission power is increased to compensate for the increased path loss, interference at other users may increase.

• **Wireless link errors**: Depending on the modulation scheme and the interference level of the spectrum band, the error rate of the channel changes.

• **Link layer delay**: To address different path loss, wireless link error, and interference, different types of link layer protocols are required at different spectrum bands. This results in different link layer delays. It is desirable to identify the spectrum bands that combine all the characterization parameters described previously for accurate spectrum decision. However, a complete analysis and modeling of spectrum in CR networks has not been developed yet [1].
DECISION PROCEDURE

After the available spectrum bands are characterized, the most appropriate spectrum band should be selected, considering the QoS requirements and spectrum characteristics. Accordingly, the transmission mode and bandwidth for the transmission can be reconfigured. To describe the dynamic nature of CR networks, a new metric — primary user activity — is proposed [19], which is defined as the probability of a primary user appearance during CR user transmission. Because there is no guarantee that a spectrum band will be available during the entire communication of a CR user, it is important to consider how often the primary user appears on the spectrum band [1].

SPECTRUM DECISION CHALLENGES

In the development of the spectrum decision function, several challenges still remain unsolved:

- **Decision model**: Spectrum capacity estimation using signal-to-noise ratio (SNR) is not sufficient to characterize the spectrum band in CR networks. Also, applications require different QoS requirements. Thus, design of application- and spectrum-adaptive spectrum decision models is still an open issue.

- **Cooperation with reconfiguration**: CR techniques enable transmission parameters to be reconfigured for optimal operation in a certain spectrum band. For example, even if SNR is changed, bit rate and bit error rate (BER) can be maintained by exploiting adaptive modulation instead of spectrum decision. Hence, a cooperative framework with reconfiguration is required in spectrum decision.
• **Spectrum decision over heterogeneous spectrum bands**: Currently, certain spectrum bands are assigned to different purposes, whereas some bands remain unlicensed. Thus, a CR network should support spectrum decision operations on both the licensed and unlicensed bands[1].

**Spectrum Sharing**

The shared nature of the wireless channel requires the coordination of transmission attempts between CR users. In this respect, spectrum sharing should include much of the functionality of a MAC protocol. Moreover, the unique characteristics of CRs, such as the coexistence of CR users with licensed users and the wide range of available spectrum, incur substantially different challenges for spectrum sharing in CR networks. The existing work in spectrum sharing aims to address these challenges and can be classified by four aspects: the architecture, spectrum allocation behavior, spectrum access technique, and scope.

The first classification is based on the architecture, which can be *centralized* or *distributed*:

• **Centralized spectrum sharing**: The spectrum allocation and access procedures are controlled by a central entity. Moreover, a distributed sensing procedure can be used such that measurements of the spectrum allocation are forwarded to the central entity, and a spectrum allocation map is constructed. Furthermore, the central entity can lease spectrum to users in a limited geographical region for a specific amount of time. In addition to competition for the spectrum, competition for users can also be considered through a central spectrum policy server [20].
• **Distributed spectrum sharing:** Spectrum allocation and access are based on local (or possibly global) policies that are performed by each node distributively [21]. Distributed solutions also are used between different networks such that a base station (BS) competes with its interferer BSs according to the QoS requirements of its users to allocate a portion of the spectrum. The recent work on comparison of centralized and distributed solutions reveals that distributed solutions generally closely follow the centralized solutions, but at the cost of message exchanges between nodes. The second classification is based on allocation behavior, where spectrum access can be cooperative or noncooperative.

• **Cooperative spectrum sharing:** Cooperative (or collaborative) solutions exploit the interference measurements of each node such that the effect of the communication of one node on other nodes is considered. A common technique used in these schemes is forming clusters to share interference information locally. This localized operation provides an effective balance between a fully centralized and a distributed scheme.

• **Non-cooperative spectrum sharing:** Only a single node is considered in non-cooperative (or non-collaborative, selfish) solutions [22]. Because interference in other CR nodes is not considered, non-cooperative solutions may result in reduced spectrum utilization. However, these solutions do not require frequent message exchanges between neighbors as in cooperative solutions. Cooperative approaches generally outperform noncooperative approaches, as well as closely approximating the global optimum. Moreover, cooperative techniques result in a certain degree of fairness, as well as improved throughput. On the other hand, the performance degradation of non-cooperative approaches are generally offset by the significantly low information exchange and hence, energy consumption. The third classification for spectrum sharing in CR networks is based on the access technology [23]:
• **Overlay spectrum sharing**: Nodes access the network using a portion of the spectrum that has not been used by licensed users. This minimizes interference to the primary network.

• **Underlay spectrum sharing**: The spread spectrum techniques are exploited such that the transmission of a CR node is regarded as noise by licensed users. Underlay techniques can utilize higher bandwidth at the cost of a slight increase in complexity. Considering this trade-off, hybrid techniques can be considered for the spectrum access technology for CR networks. Finally, spectrum sharing techniques are generally focused on two types of solutions: spectrum sharing inside a CR network (*intracranet spectrum sharing*) and among multiple coexisting CR networks (*intercranet spectrum sharing*), as explained in the following:

• **Intracranet spectrum sharing**: These solutions focus on spectrum allocation between the entities of a CR network. Accordingly, the users of a CR network try to access the available spectrum without causing interference to the primary users. Intracranet spectrum sharing poses unique challenges that have not been considered previously in wireless communication systems.

• **Intercranet spectrum sharing**: The CR architecture enables multiple systems to be deployed in overlapping locations and spectrum.

**SPECTRUM SHARING CHALLENGES**

There are many open research issues for the realization of efficient and seamless open spectrum operation in CR networks, such as:

• **Common control channel**: A common control channel (CCC) facilitates many spectrum sharing functionalities. However, because a channel must be vacated when a primary user chooses a channel, implementation of a fixed CCC is infeasible. Moreover, in CR networks a channel common to all users is highly dependent on topology and varies over time[24].
Consequently, either CCC mitigation techniques must be devised or local CCCs must be exploited for clusters of nodes.

- **Dynamic radio range**: Due to the interdependency between radio range and operating frequency, the neighbors of a node may change as the operating frequency changes. So far, there is no work addressing this important challenge in CR networks, and we advocate frequency-aware spectrum sharing techniques.

- **Spectrum unit**: Almost all spectrum decision and sharing techniques consider a channel as the basic spectrum unit. Hence, the definition of a channel as a spectrum unit is crucial in developing algorithms.

- **Location information**: An important assumption in the existing work is that secondary users know the location and transmit power of primary users so that interference calculations can be performed easily. However, such an assumption may not always be valid in CR networks.

### Spectrum Mobility

The fourth step of spectrum management, as explained earlier, is *spectrum mobility* management. After a CR captures the best available spectrum, primary user activity on the selected spectrum may necessitate that the user change its operating spectrum band(s), which is referred to as spectrum mobility. Spectrum mobility gives rise to a new type of handoff in CR networks, *spectrum handoff*. An important requirement of mobility management protocols is information about the duration of a spectrum handoff. This information can be provided by the sensing algorithm [1].
SPECTRUM MOBILITY CHALLENGES

The following are the open research issues for efficient spectrum mobility in CR networks:

- **Spectrum mobility in the time domain**: CR networks adapt to the wireless spectrum based on the available bands. Because these available channels change over time, enabling QoS in this environment is challenging.

- **Spectrum mobility in space**: The available bands also change as a user moves from one place to another. Hence, continuous allocation of spectrum is a major challenge [1].
CHAPTER THREE: PROPOSED SPECTRUM DECISION AND SPECTRUM SHARING ALGORITHM

Introduction

In current communication networks, the average spectrum utilization is between 15% to 85%. Cognitive Radio (CR) is a solution to increase the spectrum utilization and ultimately the network capacity leading to generating new revenue streams with higher quality of service. With increasing demand for higher capacity in wireless networks due to the rapid growth of new applications such as multimedia, the network resources such as spectrum should be used more efficiently to fulfill the need for both quantity and quality of service. This implies an optimum resource management [25],[26]. Spectrum is one of the most challenging network resources which needs to be carefully consumed. Cognitive Radio Networks (CRN) are supposed to efficiently use idle portions of the spectrum (resource grid). There are many techniques to sense the idle spectrum channels and manage them to increase the networks efficiency.

The works done in spectrum sharing has faced some challenges and can be categorized as centralized spectrum sharing vs. distributed spectrum sharing, and cooperative spectrum sharing vs. non-cooperative spectrum sharing. Spectrum sharing can also be considered from inter or intra network perspective as either one or two operators share the resources. On the other hand, the network topology and the user distribution are determining factors that directly affect the network state of being either overloaded or underloaded. CRs can be employed in many applications. CR using dynamic spectrum access can alleviate the spectrum congestion through efficient allocation of bandwidth and flexible spectrum access. It provides additional bandwidth and versatility for rapidly growing data applications. Moreover, a CR network can also be
implemented to enhance public safety and homeland security. A natural disaster or terrorist attack can destroy existing communication infrastructure, so an emergency network becomes indispensable to aid the search and rescue. CR can also improve the quality of service when frequency changes are needed due to conflict or interference, the CR frequency management software will change the operating frequency automatically even without human intervention. Additionally, the radio software can change the service bandwidth remotely to accommodate new applications. As communication networks tend to become more social-like networks, Ad hoc networks and in particular power-law distributed networks i.e. scale-free networks are proposed in this thesis to be considered for developing spectrum sharing technique then a new method for sharing the spectrum is proposed and proved to have the optimum performance in increasing the network capacity. At the end the results are presented and compared.

**Network Topology**

The network topology is one of the main factors in considering the traffic flow and resource management in telecommunication networks. There are different ad hoc topologies like random and scale-free discussed in network theories each presenting certain characteristics.

**RANDOM TOPOLOGY**

There are classes of networks where the nodes are attached to the network in a random way meaning that the number of connections of nodes has a normal distribution. The degree (number of links to the node) distribution of nodes in such networks is a Gaussian type distribution.
SCALE-FREE TOPOLOGY

In 1999, A. L. Barabasi, and R. Albert (BA) proposed a scale-free network model based on a mechanism of growth with preferential attachment characterized with power-law distribution of the nodes degree [27]. Scale-free networks are robust to random attacks (node removal) and very well describe the nature of real world networks where there are always few nodes with much higher degree called hubs. Each new node enters the network initially with ability to have \( m \) links to existing nodes. The probability to connect to an existing node is dependent on the degree of that node meaning that the new node gets connected most probably to nodes with higher degree. The degree distribution for this model is a power-law distribution. The probability of a node to have a degree \( d_i \) is given by

\[
P(d_i) = d_i^{-\alpha}
\]

where \( 2 < \alpha < +\infty \).

Figure 4 scale-free network formation with power-law degree distribution

The distribution tail shows the nodes with highest degree called hubs. Here we use scale-free properties to better sense network traffic and manage the resources. Since hubs have the highest degrees amongst the nodes and because of their many connections, they have big impact on overall behavior of the network [27]. Consider a cluster of having \( N_0 \) nodes and some
newcomers tends to attach to this network. The newcomer starts to scan its neighborhood in a radius of $r_x$ which is determined by minimum satisfactory bitrate. There will be some existing nodes within $r_x$ from which only one node is selected to be connected based on scale-free algorithm and that is the node with highest degree and of course the one with the best link quality as in Figure 4.

**Spectrum Sensing**

The spectrum sensing is one of the main layer tasks for CR system to obtain the spectrum usage information and the presence of PUs. Spectrum detection is based on the detection of the signal from PU through the observation of cognitive radio network.

The sensing methods can be categorized in three methods: i) Energy Detection, ii) Matched Filter, and iii) Feature Detection. The spectrum sensing method considered for this thesis is Energy Detection. Since, it is particularly suitable for multiband sensing because of its low computational and implementation complexities. We presume using OFDM modulation with $M$ sub carriers with bandwidth $W$. In this thesis we premised the IEEE 802.22 as it has developed air interface for opportunistic SU access to the TV spectrum in which PUs change slowly [28].

The timing model for spectrum sensing is shown in Fig. 2.a and spectrum mobility model for SUs is depicted in Fig. 2.b. The required time for channel estimation, spectrum sensing and sharing is indicated by $\tau$. According to the [29] the given channel estimation delay is for WCDMA/HSDPA, so the scaled delay for a shorter sub-frame length in UTRAN LTE is considered for this thesis. For each Resource Block (RB), there are 7 frames in time frame and 12 subcarriers and each square in Fig. 5.b is called Resource Element (RE In Fig. 5.a. T is time
length of each frame and K is number of frames. Supposed that received signal at SUs sampled at \( f_s \) over \( i^{th} \) sub channel where values of discretized samples at \( t = v \cdot T_s \) where \( T_s \) is 0.1\( \mu \)s in our framework. In discrete form, when the primary user is active, we define two hypotheses as follow:

\[
\begin{align*}
\begin{cases}
y_i(n) = h_i x_i(n) + u_i(n) & , H_{1,i} \\
y_i(n) = u_i(n) & , H_{0,i}
\end{cases}
\end{align*}
\]

That \( h_i \) is the subchannel gain between PU transmitter and SU receiver with variance \( E(|h_i|^2) = \sigma_{h,i}^2 \). The signal transmitted, \( x_i \), by PU is assumed to be independent and identically distributed (\( i.i.d. \), \( \mathcal{CN}(0, \sigma_x^2) \)), and \( u_i \), the noise, is circularly symmetric complex Gaussian (CSCG) noise.

**ENERGY DETECTION**

In order to detect the RF energy in the certain subcarrier for a given PU, the CR service residing in the WCD samples on-the-air signal constructs the following test statistics as the observed energy summation within N samples to decide on the presence of the active users in targeted subcarrier \([30]\).
is number of samples transmitted on duration \( \tau \) which is equal to \( N_i \). The PDF of \( U_i \) is Central Chi Square distribution with \( 2N_i \) degrees of freedom, \( \chi^2_{2N_i} \), for when no PU exists and on Central Chi Square distribution with \( 2N_i \) degrees of freedom and non-centrality parameter \( 2\gamma_i, \chi^2_{2N_i}(2\gamma_i) \), for the state that PU exists. So:

\[
U_i = \begin{cases} 
\frac{1}{N_i} \sum_{n=1}^{N_i} |h_i x_i(n) + u_i(n)|^2, & H_{1,i} \\
\frac{1}{N_i} \sum_{n=1}^{N_i} |u_i(n)|^2, & H_{0,i}
\end{cases}
\] (3)
where the signal to noise ratio (SNR) is depicted by \( \gamma_i = \frac{\sigma_x^2}{\sigma_n^2}, \) \( \Gamma(.) \) denotes the gamma function, \( I_{\alpha}(.) \) is the first kind modified Bessel function of degree \( \alpha \).

Two performance parameters for spectrum sensing are probability of detection, \( P_d \), and probability of false alarm, \( P_f \), which is probability of when the frequency is unoccupied but we get alarm that the frequency is used. Hence, Higher \( P_d \) protects PU from interfering with SUs and smaller \( P_f \) causes better band usage efficiency. To calculate probability of detection [31]:

\[
P_{d,i}(\hat{o}_i, \tau_i, \gamma_i) = Pr(U_i > \hat{o}_i \mid H_i) = \int_{\hat{o}_i}^{\infty} p_i(x)dx
\]

where \( \hat{o}_i \) is threshold and \( \tau_i \) is denoted sensing time for \( i \)th subchannel.

Now the probability of missed detection can be defined as:

\[
P_{m,i}(\hat{o}_i, \tau_i, \gamma_i) = Q\left(\frac{\hat{o}_i - \gamma_i}{\sigma_n} \mid h_i \mid^2 - 1\right) = \left(\frac{\tau_i f_s}{2 \gamma_i} \mid h_i \mid^2 + 1\right)
\]
\[ P_{m,i} (\hat{\varphi}, \tau_i, \gamma_i) = 1 - P_{d,i} (\hat{\varphi}, \tau_i, \gamma_i) \tag{7} \]

We have following equations for probability of false alarm,

\[ P_{f,i} (\hat{\varphi}, \tau_i) = Pr(U_i > \hat{\varphi} \mid H_0) = \int_{\hat{\varphi}}^{\infty} p_0(x)dx \tag{8} \]

\[ P_{f,i} (\hat{\varphi}, \tau_i) = Q\left(\frac{\hat{\varphi} - \mu_i}{\sigma_{\mu_i}} - 1\right) \sqrt{\tau_i f_x} \tag{9} \]

Usually to evaluate the performance of energy detection, the goal is to minimize \( P_f \) for a target \( P_0 \) or to maximize \( P_d \) for a target \( P_f \). At first we assume \( P_{d,i,target} \) is our target probability of detection,

\[ \hat{\varphi} (P_{d,i,target}, \tau_i) = \frac{Q^{-1}(P_{d,i,target})}{\sqrt{\tau_i f_x}} + \gamma_i \left| h_i \right|^2 + 1 \sigma_{h_i}^2 \tag{10} \]

\[ P_{f,i}(\epsilon(P_{d,i,target}), \tau_i) = Q\left(Q^{-1}(P_{d,i,target}) \sqrt{2\gamma_i \left| h_i \right|^2 + 1 + \gamma_i \left| h_i \right|^2 \sqrt{\tau_i f_x}} \right) \tag{11} \]

\( P_{f,i,target} \) is the probability of false alarm regard to target \( P_{d,i} \), and \( Q^{-1} \) is the inverse of complementary error function. For a target \( P_{f,i,target} \) we have:


\[
\hat{\varrho}_i(P_{d,i,\text{target}}) = \frac{Q^{-1}(P_{d,i,\text{target}}) + 1}{\sqrt{\tau_f s}} \sigma^2_h
\]

\[
P_{d,i}(\hat{\varrho}_i(P_{d,i,\text{target}}), \tau_i) = Q\left(\frac{Q^{-1}(P_{d,i,\text{target}}) - \gamma_i \sqrt{2\gamma_i |h_i|^2 + 1}}{\sqrt{2\gamma_i |h_i|^2}}\right)
\]

\[P_{d,i}(\epsilon(P_{d,i,\text{target}}), \tau_i)\]

is the probability of detection when \(P_{f,i}\) is targeted. As a result, in this part, probability of false alarm and detection based on \(P_{d,i,\text{target}}\) and \(P_{f,i,\text{target}}\), respectively, are calculated. The proposed wide spectrum sensing by energy detection can be shown in figure 6.

### Queued Markov Chain Model For Spectrum Analysis-Access

In this section, we consider group of secondary users that tend to access idle licensed spectrum portions in an opportunistic way. The process of sensing and decision making on the spectrum allocation is analyzed with a Markov Chain Process with a queue state in which, primary user has the spectrum and secondary users are waiting to access once it is released by
primary user. This model is for one subcarrier and can be generalized for a resource block with multiple subcarriers.

The primary user PU is licensed to operate in the spectrum. The PU traffic is modeled as Poisson random process with arrival rate $\lambda_p$ and departure rate $\mu_p$. The secondary users are indexed by $i$ ($i=1,2,\ldots,N$) and modeled with Poisson random process as well; the arrival rate of SU is $\lambda_i$ and departure rate is $\mu_i$. All users are connected to Cognitive Radio (CR) Control Unit (CU) that controls CR network. To avoid interference with Primary Users (PU), once the PU starts using the subchannel, CU forces the Secondary Users (SU) to leave and if SUs still need to access the subchannel, CU puts them in Queue State (Sq) to find another band or wait for PU to release the subchannel. Here we assume that spectrum band is not allowed to be shared with two or more users concurrently [32], [33], [34].

$$\begin{align*}
S_0 & \xrightarrow{\lambda_1} S_1 \\
& \quad \xrightarrow{\mu_1} S_0 \\
& \quad \xrightarrow{\lambda_2} S_2 \\
& \quad \quad \vdots \\
& \quad \xrightarrow{\mu_N} S_N \\
& \quad \xrightarrow{\lambda_p} S_{PU} \\
& \quad \quad \vdots \\
& \quad \xrightarrow{\mu_p} S_0 \\
& \quad \xrightarrow{\lambda_1 + \lambda_2 + \cdots + \lambda_N} Sq
\end{align*}$$

Figure 7 Queued Markov Chain State Machine without sharing

$$(N+3)$-state Markov Chain State Machine$ is illustrated in Figure 2, where state $S_0$ means that the spectrum band is idle. Without the loss of generality, the probability of transition from $S_0$ to $S_i$ ($i=1,2,\ldots,N$) is proportional to $\lambda_i$’s. $S_0$ is the state when the subchannel is idle. Inversely, the
transition probability from \( S_i \) to \( S_0 \) is \( \mu_i \). If SU’s are operating in subchannel, and PU shows up, SU’s have to leave the subchannel. The probability of \( S_i \) to \( S_{PU} \) is proportional to arrival rate of primary user. If PU is active in the subchannel by itself i.e. \( S_{PU} \), the transition probability from \( S_{PU} \) to \( S_q \) is proportional to summation of SU’s arrival rates, \( \lambda_1 + \lambda_2 + \ldots + \lambda_N \), because when they request to access, due to PU’s priority, they will be forced to be put in queue. In \( S_q \) state, as soon as PU leaves the subchannel, the user state changes to either of \( S_i \) whose total probabilities are proportional to departure rate of PU that are considered \( a_i \).

The set of equations based on above Markov Chain Model is as follow:

\[
\Pi H = 0 \tag{14}
\]

\[
\Pi_0 + \Pi_1 + \Pi_2 + \ldots + \Pi_N + \Pi_Q + \Pi_P = I \tag{15}
\]

where \( H \) is the matrix that characterizes the transition state of the Markov chain, and \( \Pi = [\Pi_0, \Pi_1, \Pi_2, \ldots, \Pi_N, \Pi_Q, \Pi_P] \) is the state probability vector for \( S_0, S_1, S_2, \ldots, S_N, S_Q, S_{PU} \) respectively.

The H matrix of our model is as follow:

\[
\begin{bmatrix}
-\left(\lambda_1 + \lambda_2 + \ldots + \lambda_N + \lambda_p\right) & \lambda_1 & \ldots & \lambda_N & 0 & \lambda_p \\
\mu_i & -(\mu_i + \lambda_p) & \ldots & 0 & 0 & \lambda_p \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
\mu_N & 0 & \ldots & -(\mu_N + \lambda_p) & 0 & \lambda_p \\
0 & a_i & \ldots & a_N & -(a_i + \ldots + a_N) & 0 \\
\mu_p & 0 & \ldots & 0 & \lambda_1 + \lambda_2 + \ldots + \lambda_N & -(\lambda_1 + \lambda_2 + \ldots + \lambda_N + \mu_p)
\end{bmatrix} = 0
\tag{16}
\]
So the set of equations from (16) will be:

\[ -\Pi_0(\sum_{i=1}^{N} \lambda_i + \lambda_p) + \sum_{i=1}^{N} (\Pi_i \mu_p) + \Pi_p \mu_p = 0 \]

\[ \Pi_0 \lambda_i - \Pi_i(\mu_i + \lambda_p) + \Pi_Q a_i = 0 \]

\[ -\Pi_Q(\sum_{i=1}^{N} a_i) + \Pi_P(\sum_{i=1}^{N} \lambda_i) - 0 \]

\[ \lambda_p(\sum_{i=1}^{N}) - \Pi_P(\sum_{i=1}^{N} \lambda_i + \mu_p) = 0 \]

With which all \( \Pi \) entries will be calculated with known entries of \( H \). With more complex systems, computer aided solution is required to above set of equations. This has been done for specific \( H \) in simulation section.

**Max-Rate Spectrum Sharing**

In communication networks, there are always unused resources due to mismanagement or the traffic usage pattern. However, it is possible to share the inactive resources between different portions of the network and in some cases share them with other service providers. Therefore, implementing spectrum sharing would highly improve the spectrum utilization efficiency and reduce the request blocking rate (Grade of Service). We assume that the network topology is mainly scale free which has ad hoc properties plus that nodes are preferentially distributed mostly around hubs; different portions of the network are then categorized as clusters which have access to certain part of the resources. In this thesis we deal with a case where clusters are overloaded and needs extra resources for providing acceptable quality of service. Figure 8 shows
the infrastructure of scale free inter-network interaction. Each cluster is defined with a cluster hub and a range of operation. Clusters A, B, and C each of NA, NB, and NC active users are initially planned to operate in separate allocated resource blocks (AU, AD), (BU, BD), and (CU, CD), respectively as in Figure 8. Index U represents the uplink and D is for downlink communications. If a new user attaches to cluster A and all of the resources in resource block A are busy, the hub node in cluster A i.e. HA, tries to see if there is available idle resources in neighboring clusters. The resource elements in this portion are in the form of REU and RED. For instance, REU(i,j) represents the resource element for uplink at ith subcarrier and jth time slot. Now consider a new user willing to attach to cluster A by sending a request to the cluster hub, HA. We presume at the time of request all of the resources of cluster A are occupied. The new user is not blocked at this stage like conventional communication networks. Instead, HA starts to sense and search for potential available resources in neighboring clusters like B, and C. if the resource is available in either neighboring clusters for more than a limited period of time, it will be granted to cluster A and finally allocated to the new user. There is a process to consider associated criteria for releasing and granting the resources from other clusters to requesting clusters. In real world applications the hubs in clusters are distinguished mainly with their degree which is the number of active links either terminated to or originated from these hub nodes. Hubs are basically supposed to have access to as many resources as the number of active links connected to them. This leads to initially interrogating the more populated clusters as opposed to handshaking with less important (lower degree) nodes. The degree of the nodes is then considered in evaluating the merit for a specific hub. The Merit function determines the merit value for each requesting node given a certain set of available resources in granting cluster. One of the main factors in merit function is that the idle resources in neighboring clusters are not idle
for unlimited time. As opposed, based on the number of active users in granting clusters, there is an average number of requests coming from user side which leads to always updating a request queue. This queue will be monitored at the time of releasing the idle resource to make sure that there is no potential demand from local cluster for the idle resource.

COGNITIVE PARAMETERS

The hubs are presumed to be Cognitive Enabled in order to be able to sense unoccupied channels. A channel is said to be unoccupied if the instantaneous radio frequency (RF) energy (plus noise) in this channel, is less than the certain interference limit. The probability that the channel is available for a period of time is greater than a threshold \( p_{th} \). These measures can be evaluated by the CR node through monitoring the traffic pattern. The Interference is measured using Carrier to Interference ratio \( \left( \frac{C}{I} \right) \) for each subcarrier. The probability of a channel to be available for a certain period of time is predicted by looking up the traffic profiles both in real time and the traffic history. Because the network has a scale-free topology, the requesting users/nodes are characterized with their degree. \( d_i \) is the degree of \( i \)th node in a cluster. The degree information of the nodes is also communicated along with the request or obtained from network statistics. Nodes with higher degree have higher priority. This information is known in the local cluster and there is no need for global information broadcast [35],[36].
Another criterion for granting the network resources to requesting users is the Customer Classification (Qi). Each of these new users has a specific service profile with different QoS like gold, silver and bronze. When a resource is reported to be available, it’s now time to see which users of what level of quality (priority) have requested the resource. There are users with different subscription profiles which enables the decision making process directed based on the required QoS from user side. Another level of priority is also defined for emergency and security cases which dominate all incoming requests.

Signal to Noise Ratio (SNR) is important parameter that is considered for the users. Finally, the interrogated CR node from neighboring cluster reports the available channels with a
set of information \((C,T)\), p to the overloaded cluster. At the requesting cluster, \(d_i, Q_i\) are used to classify the users for granting borrowed resources.

**MERIT FUNCTION**

For the reported available resources to be granted to requesting users/nodes in a fairly optimum way there needs to be a function that considers the Cognitive Parameters to calculate the merit for users/nodes.

**CHANNEL INDEXING FUNCTION**

Let \(R\) denote the set of available resources reported by the CR node. (Hub node in neighboring cluster(s)). The Channel Indexing Function (CIF) is meant for indexing the elements in \(R\) based on received Cognitive Parameters \(R = \{r_1, r_2, \ldots, r_L\}\) Where \(r_i = \phi_i((C,T)_i, p_i)\) for every available channel. Then CIF operates on \(R\) to generate \(\chi\)

\[
\Phi(R) = \chi
\]

\(\chi = \{x_1, x_2, \ldots, x_L\}\) is the output of Channel Indexing Function, \(\Phi\), which consists of sorted performance indices for all available channels. \(U\) is the list of cognitive parameters collected from requesting users/nodes from requesting clusters. \(U = \{u_1, u_2, \ldots, u_L\}\) where \(u_i = \psi_i(SNR_i, Q_i, d_i)\). Then the Merit Function is applied to calculate the merit value for requesting users.

\[
\Psi(U) = M
\]
where $M$ is the set of merit values for all requesting users i.e. $M = \{m_1, m_2, ..., m_\ell\}$.

$\phi_i$ and $\psi_i$ are CIF and Merit functions operating on each resource and user respectively and can be defined as:

$$\phi_i = \omega_p p_i + \omega_I \left( \frac{C}{I} \right)_i$$

$$\psi_i = \omega_d d_i + \omega_Q Q_i + \omega_{SNR} SNR_i$$

All $\omega$ parameters are set according to technical and commercial constraints. We define the SNR for target node $i$ as the summation of uplink (UL) and downlink (DL) SNRs.

$$SNR_i = SNR_i^{UL} + SNR_i^{DL} = \frac{P_x / N_i}{r_x^2} + \frac{P_i / N_x}{r_x^2}$$

$P_x$ and $P_i$ represent the transmit power of the newcomer node $x$ and target node $i$, respectively. $N_x$ and $N_i$ are the noise power at newcomer and target node receivers.

**COMPETITIVE INDEXING ALGORITHM**

$M$ and $\chi$ are matched against each other to grant the best performing channel to the users/nodes with highest merit values because the users with higher value are those who require better quality of service and are in urgent need of resources to either use them or distribute them amongst their neighbors. Then the second best resource is granted to the second user with highest merit. This process goes on until either there is no request from overloaded cluster or comes a
new request from the local cluster which leads to filling up the request queue in the local cluster[37].

Cluster A sends its request to the neighboring clusters. Matrix $\chi$ is a set of performance indices for all available resources (channels) in neighboring clusters where $x_i$ is the performance index for $i$th available resource element which is a function of cognitive parameters for $i$th subcarrier like interference and availability probability and other potential cognitive parameters that can be defined/measured as well.

$\Phi$ and $\Psi$ are determined based on network statistics, measurements, topology and operators commercial strategies. Based on the proposed competitive algorithm for granting available resources, $\chi$ and $M$ are sorted in descendingly and the winning channel which is the top indexed one in $\chi$ is granted to the user with highest merit value at the top of $M$. This process goes on until all the demands from cluster A(or all requesting clusters) are supplied. This algorithm gives optimum performance in terms of the increased capacity in the network compared to uniform allocation of resources (without indexing) in response to incoming request.

To evaluate the performance for different algorithms, we define a resource sharing performance index, $\Upsilon = M\chi^T$, which is maximized based on rearrangement inequality for proposed competitive indexing algorithm. Since $\chi$ and $M$ are sorted, we can write:

\[
x_1 \geq x_2 \geq \ldots \geq x_L, m_1 \geq m_2 \geq \ldots \geq m_L\quad (22)
\]

Let $\sigma_k(\chi)$ and $\sigma_l(M)$ be any arbitrary permutation of $\chi$ and $M$. The rearrangement inequality states that for sorted matrices $\chi$ and $M$:

\[
x_1 \geq x_2 \geq \ldots \geq x_L, m_1 \geq m_2 \geq \ldots \geq m_L\quad (22)
\]
\[
\sum_{i=1}^{L} x_i m_i \geq \sum_{i=1}^{L} \sigma_k (x_i) \sigma_l (m_i)
\]

(23)

\[
Y_{opt} = \sum_{i=1}^{L} x_i m_i \geq \sum_{i=1}^{L} \sigma_k (x_i) \sigma_l (m_i) = Y_{rand}
\]

(24)

\(Y_{opt}\) is the performance index of the proposed competitive algorithm. \(Y_{rand}\) can be defined as different known parameters like total increased capacity if \(X\) and \(M\) are defined appropriately.

**Sharing Incorporated in Markov Chain Model**

Now, we put sharing part in our Markov Chain Model as shown in Figure 7. Because of each futures the SU’s have, their chance to get spectrum from S_q is different based on our specific sharing policy shown by \(a_i\)’s. Based on different policies we considered for allocating the spectrum with SU’s, the \(a_i\)’s will be different. For example, in Scale-Free Ad Hoc networks, degree is an important feature we can consider for SU that user with greater degree has more priority to get access. In our simulation, we assumed different traffic for each SU. The arrival rates is the same and departure rates are different. The first user has more priority than others in our simulation and the departure rates descending from first to last SU. So, the chance of first user is more than others, because of its less departure rate and its higher priority, and for second user is more than third user, only because of its less departure rate, and so on. As we see, if we increase the number of users, \(P_q\) (probability of being in queue) is decreasing and \(P_{PU}\) (the probability that only the primary user requested to access) decreasing. At the End, we compared
the probability of SU’s when number of users is 3. The only difference will be in $P_i$’s that in sharing method, the chance of user with priority is more (user 1) and the difference between other users is because of their different traffics.

In this model, imperfect spectrum sensing consisting of false alarm, $P_f$ and miss-detection, $P_m$ is also considered. If the idle channel is reported as busy, the current state does not change. So $(1 - P_f)$ is multiplied by arrival rates. In addition, when a channel is busy but reported as idle, the state $S_q$ will not be allowed to go to $S_i$’s. As a result, $\alpha_i \times (1 - P_m)$ is considered as a transition probability.

**Simulations**

**SIMULATION RESULTS FOR SENSING**

SU with greater degree has more priority to get access to subchannel. In our simulation, we assumed different traffic models i.e. $\lambda_i$ for each SU. We simulated a scenario with 2, 3, 4 and 5 secondary users and one primary user over one subchannel. $\lambda_p = 2, \mu_p = 4$ and $\lambda_i = 3$. The rest of parameters are assigned as in Table 1.
Table 1 Simulation traffic parameters

<table>
<thead>
<tr>
<th>No.</th>
<th>$\mu_i$</th>
<th>$\alpha_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The first user is assumed to have higher degree in our scale-free model resulting in having greater parameter $\alpha_1$, which means it will have better chance than other users in the queue. The departure rates are assigned to SU’s descendingly. Therefore, the probability of $S_1, \Pi_1$ will be greater than other secondary users because of its less departure rate and higher priority. Also $\Pi_2$, the probability of $S_2$ is more that others’ since its departure rate is smaller than others’ and so on. As we see in Figure 10, if we increase the number of secondary users, $\Pi_Q$ (probability of $S_Q$) is increasing and $\Pi_P$ (the probability of $S_P$) is decreasing. At the End, we compared the probability of SU’s when number of SU’s is 3. The only difference between results with uniform sharing (all users have equal allocation chance) and competitive sharing (users are prioritized) will be in $\Pi_j$ ($j=1,2,\ldots,N$). in our simulation we assumed only first SU has higher priority in competitive sharing. As shown in Figure 11, $\Pi_1$ in competitive sharing is greater than $\Pi_1$ in uniform sharing.
Figure 10 state probabilities using competitive sharing for different number of users

Figure 11 state probabilities using competitive and uniform sharing N=3
SIMULATION RESULTS FOR SHARING

The network structure used in the simulation is a scale-free topology with \( N = 100 \) nodes and three hubs each of 19, 17, and 15 links. The average degree of nodes in this network is 3.7 meaning that each user is in average connected to about 4 nodes. There are 3 clusters centered around aforementioned hubs called cluster A, B, and C respectively. Each cluster uses a typical OFDM (3GPP compliant) resource block of 12 subcarriers in 7 time slots for Uplink and another 7 time slots for Downlinks resulting total 84 resource elements. At each time instance, there are \( K_i \) incoming nodes to cluster A and \( K_o \) nodes leave this cluster drawn from Poisson distribution. Without spectrum sharing based on the distribution of the requests coming from the users side, cluster A may get overloaded. The capacity and load measures are simulated for cluster A without having the chance to borrow resources from neighboring clusters; Figure 9 demonstrates the performance of Uniform Indexing and Competitive Indexing. Our method in Spectrum Sharing outperforms the Uniform Indexing.

![Figure 12 Load and Net Request in cluster A](image-url)
As we can see in Figure 12, the network gets saturated after a certain time and all resource elements will be occupied and the capacity tends to zero. Figure 13 shows the cluster load and net request for two different incoming and outgoing traffic. To avoid user blocking, CR nodes start to search to find idle resources in neighboring clusters. If the found resources are allocated uniformly to requesting nodes, the Capacity will increase to some extent like purple line in Figure 14, but the optimum algorithm i.e. competitive indexing will outperform any uniformly random allocation scheme as green curve in Figure 14. Depending on the distribution of incoming request from users, the capacity increase will be different. Figure 9 shows a case where $K_i=10$ and $K_o=4$. 

![Figure 13 Load with different traffic in cluster A](image)
Because the degree is directly proportional to the indexing performance, and in Scale-Free networks, the difference between users degree is prominent as a key factor, the outperformance of CIF compared to UI algorithm is much higher than when we apply CIF in Random Network shown in Figure 15 and Figure 16.
Conclusion

In this thesis, we presented the Cognitive Radio framework for wireless Ad Hoc networks. The complete model describes the sensing and sharing procedures in wireless networks in general but the simulation results are for random and scale-free topologies. We introduced Queued Markov Chain method in spectrum sensing and Competitive Indexing Algorithm in spectrum sharing part. We demonstrate that our proposed Competitive Indexing Algorithm outperforms the Uniform Indexing Algorithm.

Figure 16 Capacity improvement for Scale-Free Network
CHAPTER FOUR: COGNITIVE RADIO IN SMART GRID THROUGHPUT ANALYSIS
ON COGNITIVE RADIO NETWORKS FOR AMI METERS IN SMART GRID

Introduction

We consider the future smart grid as leveraging Information and Communications Technology (ICT) facilitated by the smart meter (also named as Advance Infrastructure Metering (AMI)) information networks. The smart meter enables the flow of real-time information within the power utility, between the power utility and its customers. It is essential for AMI to be networked since it enables system wide sensing, utility and customer linkages, and future self healing capability.

Communication network infrastructures represent a very large capital expense. Research on CR has evolved from SDR (see [38],[39] ) with an objective of efficient utilization of radio spectrum. In this thesis, we analyze CR in the context of smart energy systems. Although there have been significant advances and improvements in CR hardware, algorithms, and protocols, less attention has been given to developing ubiquitous and pervasive metropolitan scale CR networks, particularly with respect to smart grid information networking [3]. A metropolitan infrastructure based CR networks is shown in Fig. 1. In this context, there are major challenges to overcome such as Secondary Users (SU) should sense the spectrum and timely model the behavior of the Primary Users (PU). The other issue is how the SUs manage the available spectrum resources and share the resources among the SUs to satisfy the smart grid protocol requirements and meeting the interference constraints suggested by the FCC Spectrum Policy Task.
In such a system, our objective for SUs (i.e. AMI) is to efficiently transmit their delay sensitive traffic over the network and meet the QoS requirements of the smart grid protocol. In this thesis, we investigate different scheduling polices that maximize the downlink sum throughput in the given area and achieving fairness among the SUs. We present an opportunistic scheduling policy that exploits both maximizing the downlink sum throughput and fairness under time-varying channel conditions for multi-user CR network in a metropolitan based environment.

Several authors have defined aspects of AMI networking in smart grids. Mesh, Ethernet and cellular AMI network topology for smart grid has been proposed. In [40] the authors propose mesh networks of Zigbee based transmission architecture. In [41], the authors discuss communication infrastructure based on Ethernet (LAN and WAN). The approach will support automated meter readings and customer home appliance connections. However, wireline systems are not always available. Customer subscription to service must occur and wired system can be challenging to rapidly redeploy, particularly in swiftly enveloping emergencies.

The authors in [42] describe a framework for RF mesh networking interfaced with high speed WiMAX access networks. In [43], overview of architecture, hardware platform, is reported to enable CR for smart grid communications. Our work discusses the CR network infrastructure architecture from 4G perspective. We also present multi-user performance analysis of various scheduling algorithms in context with AMI units considering the delay occurred due to offloading the processes to cloud in our architecture.
4G Cognitive Radio Framework

4G COGNITIVE RADIO SYSTEM ARCHITECTURE

We presume a LTE network as a CR LTE network (4G CR), if the LTE work is adopted the CR techniques. We consider a cloud data center infrastructure based CR network coexisting with PU network shown in Fig.17. The coverage of both the CR base station and PU network base station are similar. As depicted in the Fig. 1 at the center of the each cell, there is base-station which is shared as e Node-B for PUs and as antenna for SUs. The PU base-station only serves to PUs as it lacks the CR protocols capabilities to support SUs. However, it may consider supporting certain features in order to communicate with SUs.

Placement of a Cognitive Radio Antenna on the BTS tower may occur in tandem with deployment of the cellular provider antenna. The CR senses the spectral environment over a wide frequency band, particularly the spectrum in the cell region. It identifies the unused bands in the spectrum. These bands could be owned by cellular companies or license television band owners, but are not limited to these bands or to licensed bands. Sensed information using the CR is relayed to cloud data center. In principle, eNode-B which terminates the air interface protocol and first point of contact for PU is located at the primary user base-station. However, in proposed architecture all the cognitive radio service, waveform service, protocols service, security service, scheduling and control services are displaced into cloud data center. The CR services indentify unused frequency bands, the relevant cognitive services residing in the cloud data center generates a clear to send (CTS) signal.
The CTS is sent back to the AMI meters through the feedback channel via base station. Eventually, the CR antenna relays CTS signals to every AMI in the cell region for uplink transmission.

PERVASIVE SMART GRID SYSTEMS

The energy services of the future can be privately contracted services or public services. The cloud center enables convenient, on-demand network access to a shared pool of configurable, computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort. There are different cloud computing platform classifications. Standard architectures includes Abi (or Abiquo), Nimbus Open Nebula, Azure (Microsoft), Google (App Engine), Blue (IBM) and Mosso (Rackspace). Fig.17. depicts the model for a cloud data center architecture optimized for based smart grids. Our Wireless Cloud Data (WCD) model is organized into four principle
layers: application layer, platform layer, CR communication and networking layer and infrastructure layer. The first two layers are akin to existing cloud architectures. However, the lower two layers are augmented to enable the CR networking and wireless services. CR communication and networking layer provides services such as cognitive radio services, waveform services, Radio Link Control (RLC), and Medium Access Control (MAC) services. CR services, which provide spectrum management and spectrum sensing, are discussed in detail in section III. The infrastructure layer facilitates the effective integration of computing resources, storage, networks to deploy applications and operating systems. We augment our cloud infrastructure microprocessor racks with FPGA boards targeted to processing high computation rate processes typically associate with CR services, communication waveform signal processing and coding.

**CR System Model**

In the thesis system model 4G cellular network is considered with $N_{su}$ secondary users sharing the spectrum simultaneously with $N_{pu}$ primary users. It is presumed in the context that the secondary users (i.e. AMI meters) are fixed in sense of geographical location and yields to fixed first and second statistical moments of SINR.
In this section, we present a model for primary users’ activities which is directly proportional to CR network performance. In our Markov chains model, we consider two states (Busy by PU and Idle) for each subcarrier. The Poisson distribution is considered in the modeling with arrival rate, $\alpha$, and departure rate, $\beta$:

$$N_{tot}(nT_s) = N_{tot}(n(T_s - 1)) + \alpha(nT_s) - \beta(nT_s)$$  \hspace{1cm} (25)

as a result, the existing users in a cell is equivalent to total existing users on previous time period added to arrival rate at current time and subtracted by current departure time as mentioned in equation (25). The transition probabilities are $p^T$ and $q^T$ as illustrated in Fig. 18 and the calculated steady probabilities are depicted below [34]:

$$P_{i,BUSY} = \frac{p^T}{p^T + q^T}, \quad P_{i,Idle} = \frac{q^T}{p^T + q^T}$$ \hspace{1cm} (26)
Eq. (26) is applied to analyze the model for identifying subcarriers states (i.e. busy or idle).

**OPTIMUM SENSING TIME**

The throughput of SU is calculated as follows [17],

\[
C_i = W \log_2(1 + \frac{P_{i,SU}}{\sqrt{h_{i,SU}^2 N_0}})
\]

where \( W \) is bandwidth, \( P_{i,SU} \) is the power of transmitter SU and \( N_0 \) is the noise power and \( h_{i,SU} \) is the gain channel between \( i \)th SU’s transmitter and receiver with variance \( E(|h_{i,SU}|^2) = \sigma_{h_{i,SU}}^2 \).

Considering probabilities for different states gives us achievable throughput, \( R_i(\tau_i) \), calculated by,

\[
R_i(\tau_i) = (1 - \frac{\tau_i}{T})(1 - P_{f,i}) P_{i,Idle} C_i
\]

where \( (1 - P_{f,i}(\epsilon_i, \tau_i)) \) is the probability of absence of PU when we detect correctly. \((1 - \frac{\tau_i}{T})\) is the entire data transmission. Following equations can be derived,

\[
\lim_{\tau_i \to 0^+} \frac{d}{d \tau_i} R_i(\tau_i) \to +\infty > 0
\]

\[
\lim_{\tau_i \to \tau} \frac{d}{d \tau_i} R_i(\tau_i) < 0
\]
Thus, there is a $\tau_1$ between 0 and T that gives us maximum $R_t(\tau_1)$. The Fig. 1 shows the optimum sensing time based on equation (28). By Fig. 18, it can be denoted that the optimum sensing time in regard to technology limits and optimum sensing time is approximated between 3ns and 1µs.

**Scheduling Algorithms for CR Users**

We consider the downlink of $N_{su}$ secondary users are serviced by a base station within a cell. The base station allocates $RE(i,j)$ among the $N_{su}$ SUs. At each frame multiple REs can be assigned to a single user, although each RE can be allocated to only one SU.

We assume that channel conditions vary across the subcarriers as well as secondary users. The channel conditions typically depend on the channel frequency, so they may be different for different channels. We presume typical urban area model. Moreover, scheduling of SUs also depend on the user location and the time frame. However, in our context the AMI meters are geographical stationary leading to constant SINR values. We also define capacity of secondary user in presence of loss,

$$\rho = \int \sum_{SNR} (1-\rho)(1-\delta)\beta W_{eff} \eta \log_2 (1 + \frac{SNR_{eff}}{\rho}) dt$$

(31)

$\rho$ is detection probability parameter and calculated by addition of false alarm detection probability ($P_f$) and detection probability ($P_d$). $\delta$ is primary user spectrum usage and we presume a average of 80% loading. $\beta$ is a correction factor which nominally should be equal to one and it is
discussed more detailed in. $\eta$ is the spectrum sensing efficiency. The scheduler decides which SU to transmit the information at each time frames, based on the request rates the base station.

Scheduling the user with the instantaneously best link conditions is often referred as max rate scheduling. The max rate can be expressed as $k = \arg \max_i R_i$ for $i^{th}$ user.

Proportional fair (PF) scheduler is designed to meet the challenges of delay and fairness constraints while harnessing multi user diversity. PF scheduler tracks the average throughput, $T_k[nT_s]$, for each SU delivered in the past over sliding window of size $t_c$. In the time frame $[\tau]$, the base station receives rates $R_k[nT_s]$, $k=1...N_{su}$ from all the active SUs and scheduler basically schedules the SU with highest PF metric value, $\gamma$ that is defined as $\gamma = \frac{R_k[nT_s]}{T_k[nT_s]}$.

The average throughputs $T_k[nT_s]$ are updated using an exponentially weighted low pass-filter:

$$T_k[nT_s + 1] = \begin{cases} (1 - \frac{1}{t_c})T_k[nT_s] + \frac{1}{t_c}R_k[nT_s] & k = \gamma \\ (1 - \frac{1}{t_c})T_k[nT_s] & k \neq \gamma \end{cases}$$

(32)

Based on the Eq. (31) and (32) we can write as the following

$$C = \int \sum_{SNR} (1 - \rho)(1 - \delta)\beta W_{eff}. \eta \log_2(1 + \frac{N + 1}{\text{SNR}_{eff}})dt$$

$$\gamma = \frac{\log \left| S \right|}{T_k[nT_s]}$$

(33)

As a result, unlike PF scheduling, the users having low throughput but high PF metric, $\gamma$, that had been chosen to access frequency will have lower priority than users with enough PF metric and higher throughput.
Algorithm: Opportunistic scheduling

1) for \( n=1 \) to \( N_T \) (simulation time)

2) Update SU profile, Update \( \gamma \)

3) Let \( S \) be the set of secondary users

4) Let \( RE(i,j) \) where \( i=1 \) to \( M \) subcarriers and \( j=1 \) to \( K \) be the total time frames.

5) for \( i=1 \) to \( M \), for \( j=1 \) to \( K \)

6) Select the secondary user \( l \in S \) with highest \( \gamma(l) \)

7) If \( R_l[nT_s] \geq \bar{R}_l[nT_s] \)

8) Update the SU profile with \( S=S-\{l\} \)

9) Allocate \( RE(i,j) \) to \( l \)th secondary user from \( S \)

10) Else

11) Update the SU profile with \( S=S-\{l\} \)

12) End if, End for \( j \), \( i \), \( n \)

Analysis and Simulation Results

To evaluate the performance of CR system model, system level simulations have been conducted based on 3GPP LTE system model. Table (see [44]) shows the simulation parameters used for the simulations. We analyze the performance of the scheduling in terms of throughput and fairness. We first evaluate the system throughput for algorithms with varying the primary user loading within a cell. In this case, the primary user average loading is around 80% and total number of users is 500 in a cell. Over the period of time that spectrum sensing reports the
number of idle resource blocks, scheduler allocates the idle REs with SUs. The Fig. 19 illustrates average capacity for three aforementioned algorithms.

Max-rate results in highest average capacity among three algorithms are followed by opportunistic and fairness algorithms. In proportional fair algorithm the users compete for resources not directly based on the requested rates but based on the rates normalized by their respective average throughputs, PF metrics. In OS the users having low request rate but high PF metric, $\gamma$, will have less chance to be scheduled. OS objective is to achieve higher average capacity compared to PF, while achieving decent fairness among the SUs.

![Figure 19 Average Capacity over Time](image)

In Fig. 20, we analyze the scheduled SUs average capacity of each algorithm in each scenario when number of active PUs varies. Based on goals of each algorithm they indicate respective positions in the results. It can be seen that the solution obtained using the proposed algorithm (OS) is quite close to the PF specifically when the active PUs are less.
We note that the less PUs scheduled yields to high availability of idle REs. Therefore, higher number of SUs scheduled results in larger average capacity in the CR network. When the numbers of PUs are increased, the advantage of the OS algorithm over PF is more obvious (i.e. Fig.20) due to more sparse SUs. Sparse implies large variability in SUs profile (i.e. SINR, fading channel, physical location).
In Fig. 21, we analyze the average number of scheduled SUs in each scenario when number of active PUs varies. We note that the more PUs scheduled yields to less availability of idle REs and therefore less number of SU scheduled.

In Fig. 21 the Max-Rate average capacity is much higher than average capacity of PF; on the contrary, Fig. 22 shows the more scheduled SUs by PF algorithm compared to Max-Rate algorithm. As a result, the OS algorithm can balance both the performance of the cognitive radio networks in terms of achieving acceptable average capacity of secondary users and the fairness.

**Conclusion**

In this thesis, we have analyzed the potential 4G CR network framework in context of smart grid information systems. Our system level simulation results show that the 4G CR network can achieve an average capacity of 3.5Mbs in a 3Km cell radius under the constraint of an average primary user network usage of 80%. Finally, we present that the CR capacity of a 20% usage model meets the smart grid protocols requirements for a multi-user CR network of smart meters.
CHAPTER FIVE: INTERFERENCE AWARE SCHEDULING FOR MAXIMUM CHANNEL REUSE AND MAX-CAPACITY IN SMART METER NETWORKS

Contributions of This Chapter On Interference Aware Scheduling

In this thesis, we develop a novel opportunistic interference–aware scheme based on maximum channel reuse in unplanned networks. The framework adopts the IEEE 802.22 for CR. Our model of channel reuse implies simultaneous use of intra cell physical resource elements (PRE) leading to dynamic co-channel interference on a per-PRE basis. We analyze the application of SISO and MIMO interference aware scheduling. The proposed scheduling scheme eliminates idle time-slots under the joint constraint of maximum interference and maximum capacity. We demonstrate that this approach substantially increases capacity gains for MIMO systems in multi-cell environments compared to conventional scheduling schemes discussed previously. Another distinguishing aspect of this thesis is that we analyze the smart meter network in a manner that jointly satisfies both the DOE smart grid communication protocol in terms of capacity [45] and the IEEE 802.22 protocol satisfying the FCC CR requirements.

System Model

Fig. 22 illustrates the system model under consideration in this thesis. As shown in Fig. 22, the system utilizes the CR scheme of IEEE802.22 WRAN. The TV antenna indicates service for PUs in the CR protocol. In addition, AMI is denoted as SU. The SU electronic component is alternatively named as consumer premise equipment (CPE) indicates in the CR protocol [46]. Since the 802.22 WRAN specifies a fixed point-to-multipoint wireless air interface, CR base
station (BS) can manage its own cell and all associated AMIs as shown in Fig. 22. In IEEE802.22 WRAN, multiple cells are overlapped which results in uncoordinated interference from other cells as shown in Fig. 22.

Radio resource management in our IEEE 802.22 based CR network model involves three dimensions: frequency, time and space. Physical resource element (PRE) spans in both frequency and time dimensions. We presume a scheduler coordinating the usage of PREs in adjacent cells by opportunistically leveraging multi-user AMI frequency, time and spatial diversity. It also ensures that PRE may be simultaneously assigned to more than one A-SU within each cell. By further assuming that orthogonally among sub-carriers can be adequately maintained, then intra-cell interference can be ignored between PU and SU. However, as previously mentioned if a PRE is simultaneously assigned to more than one A-SU meter it results in coordinated interference between A-SUs within the cell as illustrated in Fig. 22.
Fig. 23 shows the methodology for scheduling the PREs allocated to A-SUs. When PREs are reused, increased co-channel interference is traded off versus the allocation of additional frequency channels to unscheduled A-SUs. In Fig. 23, PU transmits over frequency $f_3$; scheduled A-SU1 transmits over frequency $f_1$; the scheduled A-SU2 transmits over frequency $f_2$. We note that PU communication is disrupted if any user transmits data using frequency $f_3$ respectively.

The system controls the interference power of the PUs to insure it remains below the maximum tolerable interference power. The diagram in Fig. 23 depicts that PUs that are unaffected. This is due to the fact that the A-SUs operate on orthogonal frequencies. However, it is possible that A-SU1 increases the co-channel interference to A-SU3 since they operate on same frequency $f_1$.

The main objective in this method is to determine the dynamic scheduling of PREs that maximizes channel reuse among A-SUs and maximized multi-user capacity considering both interference and noise of existing A-SU in that particular PRE.
Interference–Aware Scheduling Algorithm

We presume the initial scheduling is performed on secondary users based on max rate algorithm (MRA) [47]. \( \overline{SU} \) is showing set of indices of all A-SUs within the cell as follow,

\[
\overline{SU} = [su_1, su_2, ..., su_N, ]
\]

(34)

where \( N \) is total number of A-SUs. \( \overline{SU} \) is defined as the initial scheduled users through max–rate and \( \overline{SU}_w \) are unscheduled users. \( \overline{SU}_s \) and \( \overline{SU}_u \) are sub set of \( \overline{SU} \).
\[ SU = SU_s \cup SU_u \]  

Furthermore, the vector of fading coefficients for the channels between the SUs and CBS is

\[ H^c_{SU}(nT) = [h_1(nT), \ldots, h_N(nT)] \]  

Fig. 3 depicts the proposed interference aware scheduling (IAS) algorithm. The scheduler selects active unscheduled users with data to send. We sort the \( SU_u \) by SINR and channel coefficients in ascending order represented as \( SU_u^{sort} \). The ascending order ensures that A-SUs with high SINR are available for exploiting interference introduced by reusing the PRE. We choose unscheduled A-SU \( SU_u^{sort}(i), i = 1..N_u \) from \( SU_u^{sort} \) with maximum SINR and higher channel coefficients as represented in step 4 in Fig. 24. We calculate the co-channel interference between \( SU_u^{sort}(i) \) and \( SU_s(j), j = 1..N_s \). Where \( N_s \) and \( N_u \) are total number of scheduled and unscheduled A-SUs respectively. Choose the \( SU_s(j) \) with minimum co-channel interference with respect to \( SU_u^{sort}(i) \). Co-channel interference \( I' = I_{SU_s(j),SU_u^{sort}(i)} \) is evaluated in the later part of the section. In step 7, we recalculate the capacity of \( SU_s(j) \) and \( SU_u^{sort} \) based on updated interference \( I' \) in step 5.

If each A-SU, \( i \), is serviced on a channel, the multiuser capacity for orthogonal OFDM signaling is given below and notes that it cannot exceed the Shannon capacity given in [47].

\[ C_i = W \log_2 \left( 1 + h_i^2(nT) \text{SINR}_i \right) \]  

\[ (37) \]
In real-world deployments, we can develop a modified Shannon capacity formula, by replacing the cell bandwidth, $W_{cell}$ with an effective bandwidth and $\beta W_{eff}$ [47] which accounts for G-factor dependencies and protocol control, pilot, and cyclic prefix overheads. Closely related to the SINR is the G-factor, which accounts for the geometric dependencies of cell layouts and dictates the statistics of the downlink capacity. The G-factor is the average own cell power to the other cell-power plus noise ratio when considering uniform spatial distributions of transceivers within a cell.

In addition, we can define a normalized effective signal to noise ratio, $SINR_{eff}$ adjust SNR for both interference, G-factor and statistics. Defining the modified Shannon spectral efficiency for PU, as we therefore define the modified A-SU capacity in

$$C_i = \beta W_{eff} \cdot \log_2 \left(1 + \frac{N + I}{SINR_{eff}}\right)$$

where $SINR_i$ is the signal to interference plus noise power ratio for $i^{th}$ A-SU. Therefore $SINR_i$ can be expresses as

$$SINR_i = \frac{P_r}{\sigma_N^2 + \sigma_i^2}$$

where $P_r$, $\sigma_N^2$, and $\sigma_i^2$ denote the received signal power from $i^{th}$ A-SU, the noise power, and the self-interference power at the CBS in the cell.

Using equation 5 we calculate capacity of $SU_j(i)$ and $SU_{sort}(i)$ as labeled as $C_{SU_j(i)}$ and $C_{SU_{sort}(i)}$. 

$$C_{SU_j(i)}$$
\[
C'_{SU_i(j)} < C_{SU_i(j)}, \text{ is due to effect of increase in interference caused due to PRE reuse. The}
\]
objective of the IAS algorithm is to reuse the PRE and improve the capacity while optimally
exploiting the interference variations occurred. This necessity to verify,

\[
C' = C'_{SU_i^\text{nom}}(i) + C'_{SU_j}(j)
\]

(40)

\[
C' > C_{SU_j}(j)
\]

(41)

However, the other critical factor to be taken in consideration is maximum tolerable
interference \( I_{th} \). We need to check the co-channel interference \( I' = I_{SU_i(j),SU_j^\text{nom}}(i) \) observed should be
always less than \( I_{th} \) in order satisfy QoS factor and FCC requirements.

\[
I' < I_{th}
\]

(42)

In step 9, we check the conditions stated in (41) and (42). If conditions are satisfied
scheduler allows \( SU_i^\text{nom}(i) \) reusing the same PREs of \( SU_j(i) \) and updates the \( SU_i \) and \( SU_j \) shown
in step 11 and iterates the process until all \( SU_i \) are empty. If the conditions are not satisfies, we
updated the \( SU_i \) as seen in step 12 and we iterates the process to step 3.

**Interference Model for SISO**

The OFDM transmission system with MIMO model for an A-SU as a function of sub
carrier \( K \) is given by,
\[ Y(k) = H_{n_T \times n_R}(k)X(k) + N(k) + I(K) \]  

(43)

In (43), \( Y(k) = [Y_{1}[k],...,Y_{n_T}[k]] \) is the received signal on the \( k^{th} \) subcarrier in CR base station. \( H_{n_T \times n_R}(k) = [H_{1}[k],...,H_{n_R}[k]] \) is the channel coefficients. In SISO, \( n_T = 1 \) and \( n_R = 1 \); \( X(k) = [X_{1}[k],...,X_{n_T}[k]] \) denotes vector of transmit data at \( k^{th} \) subcarrier in CRBS from the transmitted OFDM signal in uplink model.

Our attention in this thesis is focused on smart meter equipped with multi-antenna systems. Performance can be enhanced and capacity maximized when perfect or partial channel state information (CSI) is made available at the transmitter [21]. This presumption applies well to AMI networks with fixed spatial location and wireless channels with zero Doppler. Though many MIMO approaches can be applied in multi-antenna systems, we focus on beamforming due to our focus on spatial interference.

\[
I_j(k) = \sum_{i=1}^{N_{us}} \sum_{l=1}^{n_s} H_{n_T \times n_R}^{i-j} x_{\psi_{us},i} \psi_{k} \cdot \zeta(k) + \sum_{i=1}^{N_{us}} \sum_{l=1}^{n_s} H_{n_T \times n_R}^{i-j} x_{\psi_{us}} \psi_{k} \cdot \zeta(k)
\]

(44)

The desired the received signal at CRBS is distorted by coordinated interference aggregated in \( \zeta_{\psi_{us}} \) and uncoordinated interference in \( \psi_{k} \). In (44), \( N_{us} \) is the total number of scheduled users from \( SU_{us} \) based on IAS algorithm.
The multi-antenna system offers well-known motivations compared to conventional wireless communication systems. Our attention in this thesis is focused on smart meter equipped with multi-antenna systems. Performance can be enhanced and capacity maximized when perfect or partial channel state information (CSI) is made available at the transmitter [21]. This presumption applies well to AMI networks with fixed spatial location and wireless channels with zero Doppler. Though many MIMO approaches can be applied in multi-antenna systems, we focus on beamforming due to our focus on spatial interference.
**Simulations and Results**

Numerical results exhibit the effectiveness of the proposed interference-aware scheduler for the SSIO and beamforming approach to smart meters. In this simulation, we follow the IEEE WRAN standard [46] as OFDM parameters.

In the simulation, we follow IEEE 802.22 for smart grid systems as given in Table 2. It is assumed to operate at 599 MHz which belongs to the VHF/UHF TV broadcast bands. In addition, the profile-A frequency selective fading channel [48] is considered for the simulation. The parameters in Table 3 also show the parameters used for simulation.

Fig. 26 exhibits total capacity of all the scheduled A-SUs in the case of conventional max–rate, IAS- SISO, IAS-BF. As shown in Fig. 26, the achieved capacity in IAS-BF and IAS-SISO in average is about five times and two times, respectively, larger than that for the case of max rate at received SINR.

As shown in figure, the capacity for the case of IAS-SISO and IAS-MIMO increases with the increase in A-SUs reusing PREs. However, capacity of the IAS-SISO and IAS-BF saturates at 15 and 70 A-SUs respectively, due to the effect of coordinated interference. Moreover, Fig. 26 shows that the average capacity for each scheduled A-SU satisfies the DOE smart grid communication protocol average capacity requirements [45].
### Table 2 THE OFDM PARAMETERS FOR IEEE 802.22 WRAN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel bandwidth (MHz)</td>
<td>6</td>
</tr>
<tr>
<td>Number ((N)) of subcarriers for FFT</td>
<td>2048</td>
</tr>
<tr>
<td>Number of data subcarriers for FFT</td>
<td>1440</td>
</tr>
<tr>
<td>Number of pilot subcarriers for FFT</td>
<td>240</td>
</tr>
<tr>
<td>Subcarrier spacing (KHz): PRE BW</td>
<td>3.348</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK</td>
</tr>
</tbody>
</table>

### Table 3 PARAMETERS FOR SIMULATION ANALYSIS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Radius (Km)</td>
<td>6</td>
</tr>
<tr>
<td>Carrier frequency (MHz)</td>
<td>599</td>
</tr>
<tr>
<td>Cell-level user distribution</td>
<td>Uniform</td>
</tr>
<tr>
<td>Cell layout</td>
<td>Hexagonal grid, 3 sector sites</td>
</tr>
<tr>
<td>Channel Estimation</td>
<td>Ideal</td>
</tr>
<tr>
<td>Antenna pattern ((\theta_{3dB}))</td>
<td>68</td>
</tr>
<tr>
<td>Average Primary user Loading</td>
<td>70%</td>
</tr>
<tr>
<td>Number of Total Users in cell</td>
<td>400</td>
</tr>
<tr>
<td>Number of SU in cell</td>
<td>100</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----</td>
</tr>
<tr>
<td>Thermal Noise(dBm/Hz)</td>
<td>-174</td>
</tr>
</tbody>
</table>

Figure 26 Total capacity of A-SU in the cases of no IAS, IAS-SISO and IAS-BF

Figure 27 Total capacity of A-SU in the cases of no IAS, IAS-SISO and IAS-BF
Fig. 27 illustrates the interference and number of reuses for one of A-SUs scheduled (with index 22). As it shown in figure, after third reuse for SISO, if we add one more unscheduled A-SU with minimum interference in order to reuse the PRE, interference exceeds the threshold. This is because of high interference caused by SISO. To satisfy the condition in step 9 in Fig. 24, the reusing is ended at 3. On the other hand, because of less interference due to side lobes in beamforming, we are able to reuse more unscheduled A-SUs till we have total interference close to $I_{th}$ in that PRE. As a result, in Fig. 26, we have greater interference for beamforming compared to SISO, because in beamforming, the interference is closer to $I_{th}$ than in SISO for all PREs. That is, we are taking advantage of all possible interference that can be tolerated by A-SUs.

Fig. 28 illustrates the comparison of total capacity for IAS-SISO and IAS-BF. As exhibited in Fig. 28, the proposed IAS-BF achieves greater capacity than IAS-SISO at the same interference. Moreover, capacity of the IAS-SISO and IAS-BF saturates due to the effect of coordinated interference. Although, the IAS-BF shows higher interference compared to IAS-SISO, the interference in all PREs caused by IAS-BF is still within $I_{th}$.

Fig. 29 illustrates the number of reuse for each scheduled A-SU. As depicted in Fig. 29a, 22 A-SUs have been scheduled by max rate algorithm. Regard to two conditions in step 9 in Fig. 24, PREs of A-SU with indices 2, 6, 7, 13, 15 and 22 are reused.

Based on Fig 29, reuse of each scheduled A-SU’s PREs in IAS-BF is always more than reuse in IAS-SISO. Since the interference in other A-SUs exceeds the threshold, no reuse occurred.
In Fig. 30, the total number of reuse in IAS-SISO and IAS-BF SUs bandwidth is depicted. The figure shows that the total number in IAS-BF is always more than IAS-SISO. This is due to less interference caused by IAS-BF.

**Conclusion**

In this thesis we presented a novel interference aware scheduling for CR network by maximizing channel reuse in SISO and MIMO. IAS is able to utilize the opportunistic interference aware scheduling to improve the system capacity significantly. With suggested scheduling approach, we can conclude following observations. For 4Tx-4Rx Antenna IAS-BF and 1Tx-1Rx IAS-SISO we observe an average capacity increase of 5x and 2x, respectively, larger than that for the case of max rate at received SINR. Much larger gains occur as the antenna array size increases. The comparison was done with max rate in a metropolitan area network system simulation. Our analysis has shown that the IEEE 802.22 protocol enabling FCC-CR can support future distributed smart grid communication network comprised of smart meters. Without loss of generality, our IAS also increases the number of scheduled A-SUs, which indirectly indicates the fairness among users. Developing an IAS based on fairness would be an interesting topic in future.
Figure 28 Relation between Interference generated by reuse and total capacity of scheduled A-SU in the cases of IAS-SISO and IAS-BF

Figure 29 Number of reuse for every scheduled A-SUs in one instance.
Figure 30 Total number of reuses over entire BW in cases of IAS-SISO and IAS-BF.
CHAPTER SIX: SMART GRID AND OPTIMIZATION

Fuzzy Control of Electricity Storage Unit for Energy Management of Micro-Grids

This work is partially funded by CPS Energy through Texas Sustainable Energy Research Institute at the University of Texas at San Antonio.

Micro-Grid is a small-scale grid that is designed to provide power for local communities. A Micro-Grid is an aggregation of multiple distributed generators (DGs) such as renewable energy sources, conventional generators, in association with energy storage units which work together as a power supply network in order to provide both electric power and thermal energy for small communities which may vary from one common building to a smart house or even a set of complicated loads consisting of a mixture of different structures such as buildings, factories, etc [49]. Typically, a Micro-Grid operates synchronously in parallel with the main grid. However, there are cases in which a Micro-Grid operates in islanded mode, or in a disconnected state [50]. In this article we assume that when the Micro-grid is connected to the main grid and is working synchronously with it, the flow of electric power can be either from the main grid to the Micro-grid or vice-versa. If the flow of electric power is from the main grid towards Micro-grid it means that the Micro-grid is consuming the main grid’s energy for each KiloWatt-Hour of which the consumer, here Micro-grid, must pay to the Grid. This borrowed power can be either sent to local load to be consumed or can be stored in battery for future use. But, in case the flow of power is from the Micro-Grid towards the main grid, this means that Micro-Grid is delivering power to the main grid. In other words, the excess power generated currently by the renewable electricity generators or stored previously in the batteries is being sold to the main grid, and the Micro-Grid, or in general the consumer, is making profit by selling energy to the main grid.
Without loss of generality, we have assumed that the price rate for buying energy from the main grid is equal to the electricity price rate which is sold to the grid. The excess power can be sold to the grid whenever the storage unit or load don’t need that power or whenever it is more beneficial to sell power to grid than to use it for supplying the load. However, in this article the main goal is to have the load completely supplied by the required power demand at all conditions. Authors have previously simulated the Micro-Grid assuming no maximum and minimum limit for the amount of energy stored in the battery unit [49].

**System Model**

The model used for simulation of the Micro-grid network is a three-bus system. One of the busses in the distributed generation model is assumed to serve the renewable generators which include either solar farm, wind farm, or any other renewable generation units either in association with battery storage unit or without storage. Another bus is assumed to be there as the grid (utility) bus which will provide the complement part of the power demanded by the local load that renewable electricity generation system cannot afford. The third bus will be the specific load to which the demanded power is to be provided. This load can be anything from a common building or a smart house, to even a group of plants and factories or a mixture of all of them. Figure 31 shows an overall Micro-Grid schematic including Renewable Electricity Generators and Storage Unit, Utility, and Local Load.
There are three scenarios defined for simulation in this article; scenario 1 deals with a Micro-Grid which includes the renewable electricity generators without any battery storage unit. Therefore there will not be any approaches required for controlling the battery storage system in this scenario. The second scenario deals with the same Micro-Grid system as mentioned in scenario one but after the battery storage unit is connected to the same bus with the renewable generators. Also, the fuzzy approach is applied in this scenario for energy management through battery unit control. The point in this scenario is that the battery storage is assumed to be an ideal battery without any maximum or minimum limits on stored energy, i.e. infinite battery capacity. In the third scenario which is the last one, the Micro-Grid is assumed to have everything mentioned in scenario two plus the fact that maximum and minimum limits of stored energy are taken into account for storage unit and are assumed to be 85% and 15% of the nominal maximum storable energy respectively.
CHARACTERISTICS OF BUSES IN SCENARIO 1

The three buses in the model of Micro-Grid Network simulated in this article have the following characteristics in the first scenario:

Bus 1 is of type PQ and is used as the renewable electricity generation unit's bus.

Bus 2 is of type Slack (reference) and is used as the Utility (grid) bus.

Bus 3 is of type PV and is used as the Local Load bus.

CHARACTERISTICS OF BUSES IN SCENARIO 2

The characteristics of the three buses in the Micro-Grid Network model simulated in this article are as follows in the second scenario:

Bus 1 is a PQ bus and is used as the bus for renewable generation unit and infinite-capacity battery storage.

Bus 2 will be the Slack (reference) bus and is used as the Utility (grid) bus.

Bus 3 is of type PV and is used as the Local Load bus.

CHARACTERISTICS OF BUSES IN SCENARIO 3

Bus characteristics of the three buses in the Micro-Grid Network model simulated in this article are as follows in the third, i.e. last, scenario:

Bus 1 is a PQ bus and is used as the bus for renewable generation unit and finite-capacity battery storage unit.

Bus 2 will be the Slack (reference) bus and is used as the Utility (grid) bus.

Bus 3 is of type PV and is used as the Local Load bus.
This must be noted that battery units are assumed to be ideal batteries, i.e. no dynamic transient of change in the amount of stored energy in batteries are assumed, i.e. the amount of stored energy in the batteries is assumed to be changing as a pure ramp by time in both ascending and descending direction.

**Problem Statement**

The important point which lies behind the idea of this article is that we have assumed the real-time pricing for electricity. The update duration of pricing is assumed to be 15 minutes, which means that the price per KiloWatt-Hour of electricity consumed by the customers of the load region is updated every 15 minutes. This means that the money consumers need to pay to the utility for the same amount of energy used during different time-intervals might be different. Therefore, a function is required to be defined which takes into account the difference between amount of power given to the utility by the Micro-Grid, and the amount of power taken from the utility by the Micro-Grid. The Equation 1 represents this cost function:

$$\text{Cost} = \sum_{t=1}^{T} \left( \text{Pr}(t) \cdot (S_{UL}(t) + S_{L}(t)) \right) \quad (45)$$

where the electricity price $\text{Pr}(t)$ is determined by the CPS energy every 15 minutes for the next 15 minute period. $S_{UL}(t)$ is the amount of power transferred to/from the Grid during each 15 minute period. If power is received from the Grid $S_{UL}(t)$ will be positive, and if power is delivered to the grid in case of excess power generation by the renewable generation system $S_{UL}(t)$ will appear in the equations with a negative sign. $S_{L}(t)$ is the amount of distribution loss which
will occur on the branches we have between these three buses in the Micro-Grid system during each 15 minute period. Depending on whether the load is getting how much of its demanded power from renewable generation system and how much from the Grid, and also depending on whether the renewable generation system is producing excess power and is selling the excess power to the Grid, this power Loss will vary.

![Figure 32 Three Bus Model for Micro-Grid](image)

Figure 32 represents the three-bus model used for simulation of the Micro-Grid in different scenarios along with the branch impedances and the types of buses. Simulation is done on the Micro-Grid system considering three scenarios. In the following the summary of these scenarios is given:

**SCENARIO 1**

Analysis of the Micro-Grid system profits and costs under real-time electricity pricing policy; in this scenario the simulation, analysis and study will be done on a Micro-Grid model
which includes the renewable generation unit without any battery storage unit. Therefore there will not be any approaches required for controlling the battery storage system.

SCENARIO 2

Fuzzy Control of the Micro-Grid system under real-time electricity pricing policy; the cost function assumed in this scenario is the same as the cost function used in the scenario 1. The main difference here is that the storage unit exists in the network and will appear to be on the same bus with the renewable electricity generation unit. The storage unit in this scenario is assumed to be ideal with infinite capacity.

SCENARIO 3

Fuzzy Control of the Micro-Grid system under real-time electricity pricing policy; the cost function assumed in this scenario is the same as the cost function described in the two scenarios 1 and 2. In this scenario also the storage unit exists in the network on the same bus with the renewable generation unit. The critical difference between this scenario and scenario 2 is that the storage unit in this scenario is assumed to be an ideal battery with finite capacity. Therefore, the maximum and minimum amounts of energy stored in the batteries are finite values and serve as boundaries which cannot be exceeded.

The power flow calculation and analysis in the Micro-Grid is the key to simulate the whole system. There are a number of well-known methods for calculation of power flow in the distributed generation network. There are four different types of busses considered in a
distributed generation network, the characteristics of which will be calculated in power flow algorithms. These four types include PQ, PV, Slack, and isolated.

**Fuzzy Control Approach**

The control strategy implemented in this thesis is to use Fuzzy Logic for controlling the power flow to/from the battery storage unit in order to improve the value of the cost function introduced in section III. The three input variables to the fuzzy inference engine are Electricity Price, Renewable Generation Rate, and Load Demand. The Fuzzy inference engine serves as the controller which determines a measure of the amount of power that must be sent to/taken from the battery unit during the next time interval, i.e. 15 minute period, based on the current values of its three inputs.

The fuzzy membership functions for the three inputs price, load demand, and renewable generation rate, and also for the output variable which determines the amount of power transaction with the storage unit are shown in figure 33.
The numerical values for these three input variables are normalized to the [0 1] interval, and then are Fuzzified using three fuzzy sets defined as Low (L), Medium (M), and High (H) as can be seen in figure 3a. The input variables after fuzzification will be fed to a fuzzy inference engine where the rule-base is applied to the input-output variables and the output will be determined by human reasoning. There is only one output variable from the fuzzy controller. This variable determines the amount of power to be stored in the battery, or to be drawn out from battery in each 15 minute interval. As represented in figure 3b, output variable fuzzy set is assumed to have five membership functions called Negative Large (NL), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Large (PL). The power drawn from the batteries can be used to complement the renewable electricity generation unit’s power for providing the load's demand, can be sold to the Grid, or can be partially used for both reasons. The role of fuzzy inference engine is critically important for obtaining satisfactory results. For example two of the rules can be as follows:
IF the Price is Low, AND the Renewable Generation rate is High, AND the Load Demand is Medium, THEN the amount of Power to Battery storage system should be Positive-Large.

IF the Price is High, AND the Renewable Generation rate is Low, AND the Load Demand is Medium, THEN the amount of Power to Battery storage system should be Negative-Large.

The primary goal in these simulations is to provide the local load with all the power it demands at any circumstances. Meanwhile, this must be noted that whenever the price is high or low, the secondary goal will be to sell the most power to the main grid, and to purchase the most power possible from the main grid respectively. Under low-price electricity conditions, the action required by the rules might even require the Micro-Grid network to purchase power from grid and store it in the battery storage unit because the main point here is that the Price is low.

This means by storing the energy in the batteries during low price times, the system will have enough stored energy in order to sell to the Grid during high-price periods. Even under cases of High local Load demand this will be a rational strategy. Therefore, having feasible rules predefined for the fuzzy system will help improve the cost function drastically. The proposed approach may even sometimes result in making the cost function value negative, which means that the system is making some profit instead of paying to the utility by the use of this control approach.

**Simulation Results And Discussions**

The simulation is done on the three bus system shown in figure 32. The Gauss-Seidel algorithm is implemented using Matlab for power flow calculation. Some typical data are
generated for electricity price rate, time-varying Load Demand and Renewable Generation Rate. The power demand of the Load on bus 3 (Smart House) is supplied by two generators on buses 1 and 2. Bus 1 includes solar panel and/or storage unit and bus 2 is slack which is connected to utility as shown in figure 2.

Figure 34 Profiles of Price, Renewable Generation, and the Load

Figure 35 Power Flow of Bus 1 connected to Solar Panels; scenario 1
The numerical values of the data profile for the three input variables which are fed to the fuzzy controller are shown in figure 34 during a typical day. These variables include electricity price which is assumed to be variable as time passes, renewable electricity generation rate, and local load demand. The data is generated arbitrarily for simulation purposes only with regard to the fact that the peak electricity consumption duration of the whole region of interest for the main grid is around 8:30 pm where the electricity price gets to its maximum value. The simulation results for scenario 1 are represented in figures 35 to 37.
As it can be inferred from figure 35, the value of reactive power for bus 1 is constantly zero which corresponds to the assumption that the renewable generators do not provide reactive energy. Figure 6 shows that the active power is taken from the Utility during first half of the day time, and during most of the second half of the day the active power is being delivered to the grid. Load is evidently consuming active power regarding the blue curve represented in figure 37.

Simulation results for scenario 2 which associates ideal storage with infinite capacity to the renewable electricity generators on bus 2 are represented in figures 38 and 39.

Figure 38 Output of the Fuzzy Controller, i.e. measure of the amount of power given to/taken from storage unit; scenario 2;
Figure 38 parts a and b are matched to each other and this clearly shows that any value decided by the Fuzzy Controller for the power to be given to Battery or to be taken from it can be practical since battery unit assumed in scenario 2 is of infinite capacity. Figure 39 shows that active power is taken from the utility during first half of the day, and in the second half of day the active power is mostly being sold to the grid which can be deduced by the negative value of the blue curve in figure 39. The point is that the first part of the active power diagram is raised dramatically due to fuzzy decision making which means that the system is absorbing more active power from the grid during low-price hours and stores the power in the storage unit. Also, the second part of the active power diagram has fallen more in comparison to the same section of figure 36 which denotes on increase in the amount of power drawn from storage unit and using this power for partially charging the load and also selling the excess power to the grid during high-price hours. This strategy results in reduction of cost function value or in other words increases the profit.

Remembering that the pricing periods are assumed to be 15 minute periods and one day is 24 hours overall there will be 96 periods of pricing during one day period. The summation of
payment/profit and the loss during each of the periods will give us the overall value of cost function for one day. The process can be extended to one week, one month, one year etc.

Output of the fuzzy inference engine which represents the power rate given to battery is shown in figure 41. Whenever the value of this variable is positive it means that power is delivered to the storage unit and if the power is drawn from the storage unit, the value will be negative.

Simulation results for scenario 3 in which ideal finite-capacity storage is added on bus 2 in Micro-Grid network are represented in figures 40 to 42.

Figure 40 Output of the Fuzzy Controller; scenario 3;

Figure 40 parts a and b are not matched to each other and this shows the fact that the values decided by the Fuzzy Controller for the power to be given to Battery or be taken from it might not be practical since battery unit assumed in scenario 3 is of finite capacity and the maximum and minimum limits of stored energy should be taken into account.
The Center of Gravity, i.e. Centroid, defuzzification method is used for computing the crisp values of the output variable from the union of the Fuzzy rules. The formula used for defuzzification is shown in Eq. 46

\[
y_{\text{crisp}} = \frac{\sum_{i=1}^{n} (\max_j (\mu_i) \times y_i)}{\sum_{i=1}^{n} \max_j (\mu_i)}
\]  

(46)

where \( y_{\text{crisp}} \) stands for crisp value of output variable. \( i \) changes between 1 and \( n \), and \( n \) refers to the number of discrete points at which the calculation is being done. \( j \) changes between 1 and the number of membership functions of output variable, which in this case is 5, and
represents the number of membership function curve for which we are getting the membership value of \(i\)th point in the universe of discourse of the output variable. Therefore, \(\max_i(\mu_i)\) represents the final membership value of the \(i\)th point in the universe of discourse of output, i.e. \(y_i\). Equation 47 shows the relation between Balance, Distribution Loss and the overall Cost of Electricity.

\[
Balance = Loss + Cost
\]  

(47)

In table 4, total values of distribution loss, cost, and balance on one typical day for the three scenarios mentioned in section III are summarized. It must be noted that the values in the table are unit-less, and they can be regarded as measures for payment that the end-user should make to the utility because of regular operation of Micro-Grid, or profits earned due to improved operation and control of the Micro-Grid.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Loss</th>
<th>Cost</th>
<th>Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>0.1339</td>
<td>1.2294</td>
<td>1.3632</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>6.6039</td>
<td>-17.6716</td>
<td>-11.0677</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>6.6039</td>
<td>-13.3021</td>
<td>-6.6982</td>
</tr>
</tbody>
</table>
Cost is simply the overall summation of power from/to grid multiplied by the relevant price for all 15 min periods. The overall summation of multiplication of the price and wasted power on distribution branches for all 15 min periods is defined as Loss. With no loss of generality, it is assumed that the reactive power has one tenth the value of active power.

We can see that scenario 2 will provide the consumer with the most possible profit on balance and this is because of the fact that the battery unit used in scenario 2 is assumed to be of infinite capacity. Therefore there will be chance for utmost storage of power in the battery whenever required and the battery can provide that stored power completely to the Micro-Grid for appropriate usage any time. This is not a practical case though. In scenario 3 which is the practical case compared to the second scenario, battery storage unit is assumed to be of limited capacity and therefore, maximum and minimum limits of the stored energy in the battery might prevent the control system to apply the decided action on the storage unit thoroughly. This might cause a drop in the benefits that consumer will obtain using this approach as it can be seen by comparing the values of Balance for the two scenarios 2 and 3. However, by improvements in the battery production technologies this issue can be solved to good extents.
Conclusion

The proposed Fuzzy-Logic based control method is applied for Battery Management in Micro-Grid Systems. In the micro-grid system three buses are considered as renewable generator and storage, utility, and load (smart house). The goal was to reduce the balance which is based on distribution loss and cost. The Micro-Grid was simulated under three scenarios. Simulation results obtained for Micro-Grid under scenario 2 where the ideal infinite-capacity storage is involved with the Fuzzy controller outperform the other two scenarios. However this is not practical. In third scenario, ideal limited-capacity storage was involved and the results were satisfactory. Therefore, using fuzzy controller it is possible to reduce the cost of the Micro-Grid system, and even let the customers make profit from selling the excess power to the utility.
Particle Swarm Optimization

Particle swarm optimization (PSO) is inspired by social behavior of bird flocking or fish schooling, originally introduced by Eberhart and Kennedy [51] PSO is suitable for optimization problems that are relatively irregular, noisy, or dynamic Each particle updates its position based on the following factors: its best solution (Pbest), a best solution of swarm (gbest), and a best solution of its neighbors (nbest).

Pbest is the best position that each particle found by the previous iterations. Each particle has a special Pbest. gbest is the best position that all of particles found by previous iterations. gbest is same for all of particles. We can consider some neighbors for each particle. nbest is the best position that all of neighbors of each particle found by previous iterations. Each particle has a special nbest.

There are several means to initialize positions of particles. One of them used in this thesis is random initialization. In random initialization, particles are placed in random positions in the space. The update equation of positions is:

\[ V = c_0 X + c_1 r_1 \times (\text{pbest} - X) + c_2 r_2 \times (\text{gbest} - X) + c_3 r_3 \times (\text{nbest} - X) \]  
(48)

\[ X = X + V \]  
(49)

Where \( c_0, c_1, c_2 \) and \( c_3 \) are constants and \( r_1, r_2 \) and \( r_3 \) are random numbers between 0 and 1. Also, \( V \) is velocity of each particle. In this study, we consider \( c_0 = 0.8, c_1 = 1.5, c_2 = 1.5, \) and \( c_3 = 0 \) (which these amounts show the best results rather than other amounts). As mentioned before, the problem is to maximize comfort function under certain conditions. For
doing this, \( p \) particles with random positions are produced. Then, their fitness (comfort function) is calculated and pbest and gbest are obtained.

The velocity of particles is obtained and their positions are updated. This procedure is continued iteratively until a stopping condition is satisfied. Our stopping condition is that the number of iteration reaches a maximum or the increase of the fitness (comfort function) is smaller than a given threshold (\( k \) denotes the iteration number):

\[
\left| g_{\text{best}}^{k} - g_{\text{best}}^{k-1} \right| < \delta
\] (50)

In this study, the first one is chosen because the second one may be trapped in a local optimum. Here, \( X \) or each particle is considered as the amount of power to be delivered or taken.

Comfort Function applied for Our Specific 3-bus Micro Gird Model:

\[
\text{comfort}(p) = -e_1 \cdot (\text{price}(t))^2 \cdot \sin\left(\frac{\pi}{2} t \right) \cdot x(l, p) - \text{price}(t) \cdot (|V_{\text{Grid}}| + |\text{Loss}_{\text{total}}|).
\] (51)

Simulations for PSO

Figure 43 illustrates when PSO is applied for given Load, RE, and Price profile. As it shown in Figure 43, the power coming out from RE bus is completely satisfy required load and once the price in at peak and less load is needed, it consumes more power from RE to minimize cost.
As shown in Figure 44, PSO makes battery to charge when electricity is low (0-8 hours) and discharge when price is high (8-16). Also, the stored battery in low price period is consumed for required load when price is high. This figure verifies the perfect and intelligent performance.
of PSO for this kind of model that every input parameter is stochastic and hard to assign fuzzy logic rules and useless to use deterministic optimization methods.

![Diagram](image)

Figure 45 all profiles and battery behavior through PSO utilization

The results shown in figures (43-45) were for when the sufficient renewable energy exists. Following results will be showing for when the renewable energy is not enough.
Figure 46: The RE power, price, and load profile when RE power is not sufficient for given load.

Figure 47: Battery charging and discharging states.
As depicted in figure 46, there is no ample renewable energy for needed load. Figure 47 shows that battery stores low price power as much as possible for high price power period. As shown in 48, at hour 18, when the price has its maximum value, the battery does not let grid power to be increased and decrease the grid power as much as possible. Based upon results shown in figures 43-48, the PSO performs acceptable for Micro Grid model that has stochastic parameters.
Figure 49 Battery power, input profiles and Grid Power
CHAPTER SEVEN: CONCLUSION

This thesis, presents the Cognitive Radio framework for wireless Ad Hoc networks. The proposed Cognitive Radio framework is a complete model for Cognitive Radio that describes the sensing and sharing procedures in wireless networks by introducing Queued Markov Chain method in spectrum sensing and Competitive Indexing Algorithm in spectrum sharing part.

Queued Markov Chain method is capable of considering waiting time and is very well generalized for unlimited number of secondary users. It includes the sharing aspect of Cognitive Radio. Power-law distribution of node degree in scale-free networks is important for considering the traffic distribution and resource management thus we consider the effect of the topology on sensing and sharing performances. We demonstrate that CIF outperforms Uniform Indexing (UI) algorithm in Scale-Free networks while in Random networks UI performs as well as CIF.

Also, in this thesis, a framework is presented based on 4G Cognitive Radio (CR) network capable of communicating with high numbers of geographically dispersed smart meters for command and control feature concurrently with private cellular network. Our approach uses pervasive smart grid systems (i.e. cloud data centers) as the central communication and optimization infrastructure supporting metropolitan area based smart meter infrastructure. In this thesis, we investigate the performance of various scheduling algorithms in context with CR units to provide a satisfactory tradeoff between maximizing the system capacity, achieving fairness among cognitive users. We lay as a framework evaluation 3GPP LTE system model simulations. Our system level simulation results show that the 4G CR network model meets the smart grid protocols requirements for a multi-user CR network of Smart meters.
This thesis addresses improvements in the multiuser capacity in unplanned networks with high levels of co-channel interference. We view this as the likely system scenario for future cognitive radio (CR) networks. For this reason, this thesis presents a novel opportunistic interference aware scheduling protocol ideally suited for maximum channel reuse in unplanned networks. We present results for maximum capacity CR networks, many of which may be based upon the future IEEE 802.22 standard. In addition, we show that the IEEE 802.22 protocol enabling Federal Communication Commission (FCC)-CR can support future distributed smart grid communication network comprised of smart meters. We analyze the application of SISO and MIMO interference aware scheduling to maximize the capacity and number of scheduled smart meters. We present simulation results that show significant improvement in the total capacity and number of scheduled smart meters in comparison to traditional scheduling schemes. Finally, we show that our system meets the DOE smart grid communication protocol requirements in terms of capacity.

Moreover, a Fuzzy Logic-based framework is proposed for control of Battery Storage Unit in Micro-Grid Systems to achieve Efficient Energy Management. Typically, a Micro-Grid system operates synchronously with the main grid and also has the ability to operate independently from the main power grid in an islanded mode. Distributed renewable energy generators including solar, wind in association with batteries and main grid supply power to the consumer in the Micro-Grid network. The goal here is to control the amount of power delivered to/taken from the storage unit in order to improve a cost function, defined based on summation of payment required for purchasing power from main grid or profit obtained by selling power to the main grid and distribution power loss, through reasonable decision making using predetermined human reasoning-based fuzzy rules. Profiles of system variables such as
Consumer’s Load Demand, Electricity Price Rate, and Renewable Electricity Generation Rate are assumed arbitrarily for obtaining general results. Measures of payment/profit will be extracted to compute amounts of cost and balance for the network which represents benefits of using Fuzzy logic for Storage Unit control with and without considering storage unit capacity limits. Simulation results are presented and discussed.
REFERENCES


Pengbo Si; Enchang Sun; Ruizhe Yang; Yanhua Zhang;., "Cooperative and distributed spectrum sharing in dynamic spectrum pooling networks," *Wireless and Optical*
Communications Conference (WOCC), pp. 1-5, 2010.


106


VITA

Amir Rajaee (Student member of IEEE) received Bachelor of Science in electrical engineering from Iran University of Science and Technology (IUST), Tehran, Iran in 2010. He is currently pursuing Master of Science in Electrical and Computer Engineering department at the University of Texas at San Antonio (UTSA). His current research areas are Spectrum Sensing and Management in Cognitive Radio (Ad Hoc and Cellular Networks), Communications and Optimization for Smart Grid with CPS Energy group and he had worked on Speech Processing with focus on localization in DSP Lab in IUST. In addition, He was part of telemetry project for Tehran’s electrical network as a wireless network designer.