OPTIMIZED FUZZY BASED POWER CONTROL STRATEGY IN COGNITIVE RADIO NETWORKS IN MULTI FADING PROPAGATION ENVIRONMENTS

Praneeth Kumar Bejjenki
Muneeb Ahmed Goraya
Syed Fovad Moid

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Supervisor: Prof. Wlodek J. Kulesza
Co-supervisor: Prof. Elisabeth Rakus- Andersson

Prof. Abbas Mohammad

Examiner: Dr. Sven Johansson

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School of Engineering
Blekinge Institute of Technology
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ABSTRACT

In this thesis we have considered a cognitive radio network (CRN) with a pair of primary user (PU) and secondary user (SU) in spectrum sharing networks in path-loss and without path-loss propagation environments under identically distributed m-Nakagami fading channel. The thesis consists of three parts. In the first part we propose an optimized Takagi-Sugeno Fuzzy Inference System (FIS) based power control strategy in cognitive radio networks (CRN) in spectrum sharing network in without path-loss propagation environment. The second part proposes an optimized Takagi-Sugeno FIS based power control strategy in cognitive radio networks in spectrum sharing network in path-loss propagation environment.

For without path-loss propagation environment the proposed FIS takes the interference channel gain ratio between SU transmitter (CUtx) and PU receiver (PUrx) and Signal to Noise Ratio (SNR) towards PU transmitter (PUtx) as antecedents and outputs the power scaling factor for SU. For path-loss propagation environment the proposed FIS takes the relative distance ratio between CUtx and PUrx and SNR towards PUtx as antecedents and outputs the power scaling factor for SU. The output power scaling factor is used to vary the transmit power of SU such that it does not degrade the quality of service (QoS) of PU link.

The third part presents an implementation of orthogonal frequency division multiplexing (OFDM) transmission technique in CRN. The OFDM technique has intellectual attractive features like coping with the inter symbol interference (ISI), while providing increasing spectral efficiency and improved performance. This can be used in emergency conditions where transmission requires reliability and high data rate. The OFDM transmission technique is applied towards SU transmitter in CRN, which enables SU to utilize the spectrum efficiently under various fading environments. Spectrum sharing networks in with and without path-loss propagation environments and OFDM transmission were tested for bit error rate (BER) performance after fading effects from m-Nakagami fading channel.

We conclude that by applying Takagi-Sugeno Fuzzy Inference System (FIS) based power control strategy we can improve the BER performance of PU when compared with no power control strategy and with other fuzzy based power control technique. OFDM transmission technique gives us better data rate and slightly improved BER in CRN hence making it suitable for use in emergency conditions.

Keywords: Cognitive Radio Networks, Spectrum Sharing Networks, Power Control, Takagi-Sugeno Fuzzy Inference System, m-Nakagami fading channel, OFDM.
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Table of Contents

CHAPTER 1. INTRODUCTION ........................................................................................................ 7
  1.1. CODIGITE RADIO ........................................................................................................ 7
  1.2. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING .................................. 8
  1.3. THESIS MOTIVATION AND OBJECTIVES .................................................. 9
  1.4. THESIS ORGANIZATION ..................................................................................... 9

CHAPTER 2. SURVEY OF RELATED WORKS .......................................................................... 11

CHAPTER 3. PROBLEM STATEMENT AND RESEARCH QUESTION ................................. 13
  3.1. PROBLEM STATEMENT .......................................................................................... 13
  3.2. RESEARCH PROBLEM ......................................................................................... 13
  3.3. THESIS CONTRIBUTION ...................................................................................... 14

CHAPTER 4. FUZZY CONTROLLER FOR SPECTRUM SHARING IN WITHOUT PATH-LOSS PROPAGATION ENVIRONMENT ................................................................. 16
  4.1. A MODEL OF AN OPPORTUNISTIC SPECTRUM SHARING IN WITHOUT PATH-LOSS PROPAGATION ENVIRONMENT ................................................................. 16
  4.2. MODELING OF TAKAGI-SUGENO FUZZY INFERENCE SYSTEM .......................... 17
  4.3. MODELING OF M-NAKAGAMI MULTIPATH FADING CHANNEL .......................... 18
  4.4. IMPLEMENTATION OF AN OPPORTUNISTIC SPECTRUM SHARING IN WITHOUT PATH-LOSS PROPAGATION ENVIRONMENT ................................................................. 20
    4.4.1. Signal to Noise Ratio, Signal to Interference Noise ratio and Outage Probability .......... 20
    4.4.2. Power Control Principles for Spectrum Sharing Network in the without path-loss propagation environment ................................................................. 22
  4.5. IMPLEMENTATION OF TAKAGI-SUGENO FUZZY CONTROLLER IN SPECTRUM SHARING NETWORK IN WITHOUT PATH-LOSS ENVIRONMENT ........................................... 23
    4.5.1. First fuzzy antecedent: PU_SNR RATIO ......................................................... 24
    4.5.2. Second fuzzy antecedent: Interference channel gain ratio ...................................... 26
    4.5.3. Implementation of rule-based decision ............................................................... 27
    4.5.4. Defuzzification using weight average method .................................................... 29
  4.6. VALIDATION OF SPECTRUM SHARING NETWORK IN WITHOUT PATH LOSS PROPAGATION ENVIRONMENT .................................................................................. 30

CHAPTER 5. FUZZY CONTROLLER FOR SPECTRUM SHARING NETWORK IN WITH PATH-LOSS PROPAGATION ENVIRONMENT .................................................................... 33
  5.1. A MODEL OF AN OPPORTUNISTIC SPECTRUM SHARING IN WITH PATH-LOSS PROPAGATION ENVIRONMENT .................................................................................. 33
  5.2. IMPLEMENTATION OF AN OPPORTUNISTIC SPECTRUM SHARING IN WITH PATH-LOSS PROPAGATION ENVIRONMENT .................................................................................. 34
    5.2.1. Signal to Noise Ratio, Signal to Interference Noise ratio and Outage Probability: ........ 35
    5.2.2 Power Control Principle ..................................................................................... 36
  5.3 IMPLEMENTATION OF TAKAGI-SUGENO FUZZY CONTROLLER IN SPECTRUM SHARING NETWORK WITH PATH-LOSS PROPAGATION ENVIRONMENT ................................................................................................. 38
    5.3.1. First Fuzzy antecedent: PU_SNR RATIO ......................................................... 39
    5.3.2. Second fuzzy antecedent: Relative distance ratio (D_{ref}/L_{opt}) ............................ 40
    5.3.3. Implementation of rule-based decisions ............................................................... 41
    5.3.4. Defuzzification with weighted average method .................................................... 43
  5.4. VALIDATION OF SPECTRUM SHARING NETWORK IN WITH PATH LOSS PROPAGATION ENVIRONMENT .................................................................................. 44

CHAPTER 6. SECONDARY USER LINK TRANSMISSION USING OFDM ............................... 47
  6.1. OFDM SYSTEM MODEL ......................................................................................... 47
  6.2. OFDM IMPLEMENTATION AT SECONDARY USER LINK ................................... 47
    6.2.1. Working of OFDM Transmitter ........................................................................... 48
    6.2.2. Communication Channel for OFDM transmission ................................................ 49
    6.2.3. OFDM Receiver .................................................................................................. 49
  6.3. VALIDATION OF CU TRANSMISSION WITH OFDM ............................................ 50
CHAPTER 1. INTRODUCTION

The radio or wireless link has a limited resource available to users. Available radio frequencies are used for different wireless applications and are allocated to specific licensed users according to a spectrum allocation policy. The different transmission techniques and protocols are used to transmit the data over wireless links for various applications. Over the past few decades there has been massive increase in wireless applications and usage and subsequently in allocation of available spectrum. The available spectrum is getting scarce because of this surge in wireless link usage. To address the emerging problem of spectrum scarcity many researchers had done survey on utilization of spectrum [1] [2] [3]. In the survey of related works it was observed that many of the licensed users do not utilize the allocated spectrum efficiently, which means that no transmission is taking place on the allocated link for a significant duration. These studies also show that, it is not the physical shortage of spectrum but there is an inefficient and inflexible spectrum usage. In order to assure the development of wireless communication industry, novel solutions are required to enhance the spectrum usage efficiency.

In searching for efficient spectrum utilization policy Joseph Mitola III in 1998 came up with the technique known as Cognitive Radio Networks (CRN) [4] [5]. The proposed method addresses the problem of underutilization of spectrum effectively. According to Mitola, radio users could have the cognitive capacity and capability to adapt according to different transmission environments what makes them able to transmit through the spectrum holes dynamically and opportunistically. Multiple users can transmit data simultaneously over the same spectrum without degrading the performance of licensed user; hence spectrum can be utilized effectively. This technique was later promoted by the Federal Communications Commission (FCC) as a promising technology for efficient utilization of spectrum.

1.1. Cognitive Radio

Cognitive radio as defined in [6] is “An intelligent communication system that is aware of its surrounding environment”. Such a radio can alter its certain operating parameters e.g. transmit-power, carrier-frequency and modulation strategy. A CRN has two types of users:

1. **Primary user (PU)**: Users which has been allocated at a specific band in the available spectrum. PU does not have cognitive capability. This is the licensed user and has priority in accessing the specific part of the spectrum.

2. **Secondary user (SU)**: Users which do not have any allocated spectrum band. This is the unlicensed user and has the cognitive capability. It scans the spectrum looking for spectrum holes for transmission. It is also referred as cognitive users (CU).
The SU should transmit the data only whenever there is a spectrum hole, which means that when PU is not transmitting or when it can share the spectrum simultaneously with PU without degrading the performance of PU. In other words the quality of service (QoS) of PU should not be degraded by SU beyond a specific threshold value. Two types of spectrum access techniques are defined:

a) **Opportunistic spectrum access:** In this method the CU or SU can transmit data only when PU is inactive i.e. not transmitting. Only one user can access the spectrum at a given time. In this method the main research problem is efficient spectrum sensing.

b) **Opportunistic spectrum sharing:** In this method the transmission of SU and PU can be done simultaneously. The transmission of SU is done but with the condition that QoS of PU is not degraded beyond a preset threshold. In this technique the optimal power control strategies are major research topics.

The SU has cognitive capabilities, which means it has the capability of sensing the PU’s parameters; like signal strength of PU, mobility of PU and in extreme cases SU can also acquire the messages of PU with awareness of PU. The information of PU is known as channel state information (CSI). When both PU and SU transmit through the spectrum simultaneously; the coexistence of the both users can cause interference to each other. The PU as a licensed user with high priority can be expected to maintain the desired QoS of the CRN. In other words PU can accept the interference caused by SU up to the level where its performance is not degraded. So, SU should scale its transmission power based upon the interference factor or QoS of PU which can also be considered as a threshold. In other words SU can utilize the spectrum under given interference factor.

### 1.2. Orthogonal Frequency Division Multiplexing

*Orthogonal Frequency Division Multiplexing (OFDM)* is a broadband multicarrier modulation which meets the high-speed data requirements. OFDM divides the total available spectrum bandwidth into multiple carriers to transmit in parallel, so that by placing the carriers closely in spectrum a high data rate is achieved. The technology is based on the concept of *frequency-division multiplexing (FDD)*. The IEEE 802.11a/g/n standards are based on OFDM [36]. The wideband wireless *Metro-Area Network (MAN)* technology, WiMAX (IEEE 802.11e) and the 4G cellular technology standard *Long-Term Evolution (LTE)* use OFDM too. It is also used for digital radio broadcasting like Europe’s DAB and Digital Radio Mondial and for TV broadcasting like Europe’s DVB-T and DVB-H.
1.3. Thesis Motivation and Objectives

The main objective of our thesis was to enhance the user performance in CRN by dynamic spectrum utilization. In a network with opportunistic spectrum sharing technique the SU faces transmit power decision making constraints depending on the performance parameters of PU. This situation can lead to false decision making especially when the parameters vary around the performance sensitive regions like threshold value. False decisions lead to degraded performance for PU.

The situation of false decision making motivated us to introduce efficient Takagi-Sugeno FIS based power control strategy in CRN through which the false decision making can be reduced significantly. We are also interested in finding the merits of Takagi-Sugeno FIS based power control strategy in spectrum sharing networks in various propagation environments.

In this thesis we are considering the opportunistic spectrum sharing technique. In the applied technique, the SU can transmit the data with maximum power only in specific situations: when PU is severely affected by the fading (PU signal strength is degraded fully), when PU is in off state known as idle state and when the signal strength of PU is very strong known as robust state. Other than these three conditions the SU has to scale down its power according to the PU’s QOS.

As the fading plays a major role in accessing the spectrum by SU, the analysis of the influence of various fading conditions is important for SU to access the spectrum more efficiently. In this thesis we also study the effects of various fading conditions in CRN considering m-Nakagami fading channel. The m-Nakagami fading channel is a real time gamma distribution channel which can represent various fading conditions in wireless communications by varying the value of $m$.

Even though SU is unlicensed there should be reliability maintained towards SU by guaranteeing the QoS in terms of signal strength for significant durations. We aim to improve the performance of SU by introducing the OFDM technique towards SU. The OFDM technique has a useful feature like coping with the Inter Symbol Interference (ISI), while providing increasing spectral efficiency and improved performance. This can be used in emergency conditions where transmission requires reliability and high data rate.

1.4. Thesis Organization

Chapter 1 gives a basic introduction, definitions and motivation.

Chapter 2 presents the survey of related works.
Chapter 3 shows the problem statement, research problem and the main contributions of the thesis.

In Chapter 4 we introduce a system model of spectrum sharing networks in without path-loss propagation environment. We also discuss the mathematical relations for the system model like, Signal-to-Noise Ratio (SNR), Signal-to-Interference Noise (SINR), outage probability and evaluation of QoS. Also the modeling and implementation of Takagi-Sugeno fuzzy based power control strategy and $m$-Nakagami multipath fading channel are discussed. Finally we validate our simulation results for without path-loss propagation environment.

In Chapter 5 we introduce a system model of spectrum sharing networks in path-loss propagation environment. We also discuss the mathematical relations for the system model like, SNR, SINR, outage probability and evaluation of QoS. Also the modeling and implementation of Takagi-Sugeno fuzzy based power control strategy in path-loss propagation environment are discussed. Finally we validate our simulation results with error rate performance in $m$-Nakagami multipath fading channel.

Chapter 6 shows the model of OFDM transmission technique for SU transmission in CRN. Its implementation in the CRN environment and validation after transmission over $m$-Nakagami multipath fading channel are discussed.

Finally Chapter 7 gives conclusions and future work.
CHAPTER 2. SURVEY OF RELATED WORKS

As mentioned in the previous chapter, power control has been one of the primary research areas in CRN. Haykin in [6] considers the scenario of cognitive radio networks with two primary objectives: first is to provide the highly reliable communication whenever and wherever needed, second is an efficient utilization of radio spectrum. In this paper the author considered multiuser and two user scenarios in CRN. The author used the gaming theory and water filling methods as a power control strategies to utilize the spectrum opportunistically.

The authors of [7] consider the pair of PU and CU in CRN under the fading environment. The PU has the highest priority in accessing the spectrum with respect to SU. Here the PU and SU utilize the spectrum exclusively i.e. the SU can sense the spectrum to detect the PU presence. If PU transmission is inactive then SU can access the spectrum. In order to utilize the spectrum dynamically the author consider the probability based transmit power control strategy.

The fuzzy based spectrum sensing technique in CRN is introduced [8]. This technique is applicable when both PU and SU share the spectrum exclusively. The antecedents to the fuzzy system are; energy detection, matched filter and cyclo-stationary sensing techniques; and the output is ultimate combination of the three inputs. This technique improves the accuracy in sensing and reduces the false alarms.

The authors of [11] come up with the opportunistic power control strategy for the cognitive users. The CRN consists of a pair of PU and SU under fading channel environment. In this paper the author worked with the instantaneous channel state information through which the synchronization between the PU and SU is significantly relaxed. The SU by opportunistically adapting its transmit power can utilize the spectrum efficiently and maximize its data rate. A target $SNR$ is given as a threshold, assuring a QoS on PU. When the PU’s $SNR$ is below this threshold, the PU is considered in outage state and SU transmits with its peak power; when the PU’s $SNR$ is near to the threshold, the PU link is considered as sensitive to interference constraint, then the SU transmits with a scaled power; when the PU’s $SNR$ is far above the threshold, the PU link is considered as robust state and the SU transmits with its peak power. The spectrum sharing network in without path-loss propagation environment is considered.

The CRN considered in geometric view with calculations, which are based on the path-loss exponent and the statistical relative distance between the users is presented in [42]. Here the authors describe the power transmitting principles of SU and PU in a fixed elusive region and if the receiver is away from the boundary of the elusive region, the power received by user can be zero. The spectrum sharing network in with path-loss propagation environment is considered.
The authors of [12] consider the scenario with multiple SUs in CRN trying to access the spectrum. The decision of SU with greatest requirement to transmit data can be made by *Fuzzy Inference System (FIS)*. The scenario is considered in spectrum sharing networks in path-loss propagation environment. The following descriptors: spectrum utilization of secondary user, degree of mobility of secondary users and its distance to the PU are used as antecedents to FIS.

In [14] and [15], the authors consider a scenario of spectrum sharing network with a multiple cognitive radio network links. The authors define the power scaling law of single-hop cognitive radio networks. The spectrum sharing is done in without path-loss propagation environment.

In [17] the author discusses the advantages of Takagi-Sugeno fuzzy system as computationally efficient in time, accurate and flexible, when compared with Mamdani fuzzy system.

In [18] the comprehensive comparison was done between Mamdani FLS and Takagi-Sugeno FLS and proved the Takagi-Sugeno is economically efficient in certain conditions.

In [19] the author described the machine learning feature of the Takagi-Sugeno system which is more flexible and efficient in decision making with the non-linear systems.

In [33] OFDM is applied to achieve high data rates with different modulation schemes and to calculate BER calculations.

In [34] OFDM is implemented for *Additive White Gaussian Noise (AWGN)* and for multipath fading channels.

Computation of data rate for different modulation schemes and *Fast Fourier Transform (FFT)* sizes is done in [35].

BER performance of *Differential Quadrature Phase Shift Keying (DQPSK)* is analyzed over slowly Nakagami-m fading channels with and without OFDM implementation [38]. The authors have concluded that OFDM transmission improves error rate performance in m-Nakagami fading channel when DQPSK scheme is used.

A simple way of simulating Nakagami channel environment is implemented in [39] with the combination of Rayleigh and Ricean fading environments.

Another method of implementing Nakagami fading environment is discussed in [40]. It uses the fact that Nakagami distribution is based on gamma distribution, and simple Rayleigh distribution to generate Nakagami multipath fading environment.
CHAPTER 3. PROBLEM STATEMENT AND RESEARCH QUESTION

3.1. Problem statement

As it was explained in [11] the two major considerations for SU in opportunistic power control strategy for spectrum sharing networks are: to maintain PU’s desired QoS in terms of signal power strength or outage probability and to maximize the possible data rate for SU. Various optimal power control techniques such as average/peak power control with different transmission states are known [11] [12] [13]. In these previous works the decision of SU about transmission over spectrum is crisp i.e. yes or no. The basis for this decision i.e. whether to transmit with full power or not to transmit is a predetermined threshold value of SNR at PU receiver (PUrx). The decision of SU is correct when the SNR at PUrx is far above or far below the determined threshold value. But when the SNR is fluctuating close to the threshold value, the SU can be in confusion about the transmitting decision, i.e. whether to utilize the wireless link or not. The fluctuations of PU SNR around the threshold can be called as transients and the duration of the occurrence of transient is the transition state. In these situations the transmitting power of SU transmitter (CUtx) has to be scaled according to PU’s QoS requirements. The judgment of transmit power scaling in the transition state is difficult and prone to improper decisions, which can degrade the performance of PU. In other words SU causes interference to PU which in turn degrades the QoS of PU.

In [16] the authors used Mamdani FIS based power control strategy to deal with transition states. In [17], when compared with the other fuzzy systems the Mamdani FIS has significant shortcomings such as computational inefficiency, sensitivity to imprecise inputs i.e. it has difficulty in dealing with overlapped fuzzy sets. Mamdani FIS cannot be trained using learning algorithms, so it is not suitable for non-linear systems and its computational inefficiency can cause delay in the output. These shortcomings of Mamdani FIS make it prone to false decision making and can result in undesired degradation in QoS of PU.

3.2. Research problem

In the previous section we have described the power control problems which can occur in the transition state when SNR is just above or just below the threshold value. These problems can degrade the QoS of the PU in CRN. Mamdani FIS has been used in [16] to make power control decisions in the transitions state of transmission. The transition state can be viewed as partial state in mathematical modeling. Takagi-Sugeno FIS is good at dealing with the partial states, so FIS may be applied as decision making device for power transmission towards SU. We are interested to find out if we can apply fuzzy logic to differentiate the transmission states into different states, which are represented by different membership
functions. With the concept of partial state in fuzzy logic, we can develop a Takagi-Sugeno FIS based optimal power control strategy for spectrum sharing in different propagation environments. Therefore, research problem for first part of thesis is to apply a fuzzy-based optimal power control strategy in the cognitive radio networks under various channel fading and propagation environments.

In the propagation environment without path-loss, the Takagi-Sugeno FIS based optimal power control strategy is based on two input variables: the *PU’s SNR ratio* and *PU’s interference channel gain ratio*. We hypothesize that the spectrum sharing network with the proposed Takagi-Sugeno fuzzy-based optimal power control strategy has a lower *bit error rate (BER)* than that without power control strategy and with other power control strategy for different PU’s interference channel gain.

In the propagation environment with path-loss, the Takagi-Sugeno FIS based optimal power control strategy is based on two input variables: the *PU’s SNR ratio* and *relative distance ratio*. We hypothesize that the spectrum sharing network with the proposed fuzzy-based optimal power control strategy has a lower BER than that without power control strategy and with other power control strategy for different relative distances.

Second research question is to see, if OFDM transmission technique can be used for SU transmission without degrading QoS of PU in emergency conditions when spectrum is being utilized simultaneously.

We hypothesize that OFDM transmission technique is reliable, i.e. it has lower BER for SU transmission while keeping interference towards PU low so that it does not degrade QoS of PU beyond a threshold value. So it is a suitable transmission technique in emergency conditions when spectrum is being utilized simultaneously by PU and SU.

### 3.3. Thesis contribution

The main contribution of our thesis is implementation and validation of Takagi-Sugeno FIS based power control strategy in spectrum sharing networks in various propagation environments, i.e. with and without path-loss propagation. The Takagi-Sugeno FIS is used to control the transmit power of SU.

The validation of fuzzy parameters is done by analyzing the BER performance under *m*-Nakagami channel fading environment. The *m*-Nakagami fading channel simulation and the consequent BER analysis are done in MATLAB.

The second major contribution of our thesis is the incorporation of OFDM transmission technique in CRN to analyze if this is a suitable transmission strategy for emergency
scenarios in CRN. The simulation of OFDM transmission with \( m \)-Nakagami channel fading and the consequent BER analysis are done in MATLAB.
CHAPTER 4. FUZZY CONTROLLER FOR SPECTRUM SHARING IN WITHOUT PATH-LOSS PROPAGATION ENVIRONMENT

This chapter explains the CRN system modeling, implementation of Takagi-Sugeno FIS and its validation in without path-loss propagation environment over $m$-Nakagami fading channel model.

4.1. A model of an opportunistic spectrum sharing in without path-loss propagation environment

Here we consider a scenario of two wireless links one is a pair of primary transmitter and receiver, other is a pair of cognitive transmitter and receiver in a fixed communication region as shown in Fig.4.1. The primary transmitter and receiver are denoted by PUtx and PUrx respectively and the cognitive transmitter and receiver are denoted by CUtx and CUrx respectively. The fading channel scenario under the cognitive radio network environment is shown in Fig.4.2. $H_{pp}$ and $H_{cc}$ are instantaneous channel power gains of the primary and secondary link respectively and $H_{cp}$ is interference channel gain between CUtx and PUrx. $H_{pc}$ is interference channel gain between PUtx and CUrx.

![Fig. 4.1. The CRN with primary user transmitter PUtx and receiver PUrx and secondary user transmitter CUtx and receiver CUrx](image1)

![Fig.4.2. Channel model for a pair of SU (CUtx and CUrx) and PU (PUtx and PUrx), $H_{pp}, H_{cc}$ are primary and secondary channel power gains respectively and $H_{cp}, H_{pc}$ are interference channel gains, $N_0$ is noise](image2)
The basic idea behind opportunistic spectrum sharing technique is signal fading environment, when primary user signal strength is experiencing fading there is more probability that PU will be in outage. The cognitive user can consider the PU outage situation as an advantage and can utilize the spectrum of PU with its maximum transmit power. The both users PU and CU transmit over the spectrum concurrently with unique priorities. The PU link is highly prioritized to utilize spectrum with respect to CU and given a target QoS, which should be assured by CU. The CU link utilizes spectrum without degrading the QoS towards PU.

Here the cognitive radio system is in ergodic state and at specific time $t$ the receive signals at both PU and CU can be defined as

$$y_p = H_{pp} S_p + H_{cp} S_c + N_0$$  \hspace{1cm} (4.1)
$$y_c = H_{cc} S_c + H_{pc} S_p + N_0$$  \hspace{1cm} (4.2)

$y_p$ and $y_c$ are received signals at PU and CU receivers respectively. $S_p$ and $S_c$ are source signals from PU and SU transmitters respectively. $H_{pp}$ is an instantaneous channel power gain between PUtx and PUrx, $H_{cc}$ is an instantaneous channel power gain between CUtx and CUrx, $H_{pc}$ is interference channel power gain between PUtx and CUrx, $H_{cp}$ is interference channel power gain between CUtx and PUrx and $N_0$ is additive white Gaussian noise (AWGN) power. All power gains/fading coefficients such as $H_{pp}, H_{cc}, H_{pc}$ and $H_{cp}$ are random variables with continuous probability density function (PDF).

### 4.2. Modeling of Takagi-Sugeno fuzzy inference system

As shown in Fig.4.3 Takagi-Sugeno FIS consists of four major blocks. The fuzzifier, rule-base, inference system and defuzzifier. The Takagi-Sugeno FIS differs from other fuzzy systems in the defuzzifier block. Takagi-Sugeno FIS is suitable for processing of the numerical, functionally dependent data and linguistic values.

The fuzzifier is used to convert the crisp values into the fuzzy linguistic variables through which they can be interpreted and compared to the rule-base. The inputs to the fuzzifier are called as fuzzy antecedents.

The rule-base block has the knowledge in the form of a set of rules. “IF-THEN” condition is used to define the predetermined rules. The database stores the linguistic terms and their assisting membership functions. The combination of both database and rule-base is known as the knowledge base.
The *inference* system is used to map the fuzzy inputs to fuzzy outputs according to predetermined rules. In Takagi-Sugeno FIS, the *fuzzy consequence* is a function of dependent *fuzzy antecedents*.

![Takagi-Sugeno Fuzzy Inference System](image)

The *defuzzifier* is used to convert the linguistic values/fuzzy sets to a crisp value. The major advantages of Takagi-Sugeno *defuzzifier* over other method are [19]:

1. Since the consequence/output of Takagi-Sugeno system is a numerical value instead of membership function, the *defuzzification* is not computationally very expensive and faster than the other fuzzy methods. Takagi-Sugeno controller is more appropriate for real-time applications.
2. Takagi-Sugeno system works well with the optimization and adaptive algorithms which makes it very flexible with non-linear systems.

There are many *defuzzification* techniques and one of the most commonly used techniques is weighted average method. In this thesis, we have used weighted average *defuzzification* method.

### 4.3. Modeling of m-Nakagami multipath fading channel

There are different multipath fading environment models that are in practice; namely Rayleigh, Ricean and Nakagami. Rayleigh fading model is most common because of its simplicity and it is better for high frequency simulations, but it has limited accuracy in simulation of long-distance fading effects. The Nakagami model which is based on the gamma distribution function provides much better results than both Rayleigh and Ricean models in a wide variety of conditions and is better suited for mobile communication
channels. That is why in our thesis work we have chosen Nakagami fading model for simulating the multipath fading environment instead of more common Rayleigh fading model.

The probability distribution of the Nakagami distribution is [39]:

\[ p(r) = \frac{2^m r^{2m-1}}{\Omega^m \Gamma(m)} e^{-\frac{m r^2}{\Omega}} \]  

(4.3)

Where, \( m \geq \frac{1}{2} \) and \( r \geq 0 \)

Some work has been done in simulation of Nakagami fading environment in MATLAB. Simulation of Nakagami multipath fading is done based on Rayleigh and Ricean fading in [39]. We have used the same simulation method of Nakagami fading environment. The mathematical expression for the simulation is:

\[ R_{\text{nakagami}} = R_{\text{rayleigh}} e^{1-m} + R_{\text{ricean}} (1 - e^{1-m}) \]  

(4.4)

Where, \( R_{\text{rayleigh}} \) is the Rayleigh signal envelope and \( R_{\text{ricean}} \) is the Ricean signal envelope. The parameter \( m \) describes the degree of fading and with different values of \( m \) we can generate different fading environments. When \( m=1 \), there is no LOS component in the resulting signal and the fading environment will be Rayleigh fading. When \( m=1.5 \) there will be a LOS component in the resulting envelope and the fading environment will be Ricean fading.

Pictorial representation of multipath fading channel model is shown in fig. 4.4. The model is used in all three approaches in our thesis. Both the without path-loss and with path-loss propagation model and OFDM transmission model.
4.4. Implementation of an opportunistic spectrum sharing in without path-loss propagation environment

Two major objectives of this thesis are: CUtx should transmit with its peak power opportunistically by utilizing the spectrum efficiently and QoS on PU link, in terms of signal power strength towards PUrx, should be assured. The opportunistic power allocation is linked with the PU’s QoS. It is needed to develop the criterions to evaluate QoS. Thus, we adopt the signal-to-noise ratio (SNR), signal-to-interference-and-noise ratio (SINR) and outage probability as the criterions we defined in below subsections.

4.4.1. Signal to Noise Ratio, Signal to Interference Noise ratio and Outage Probability

The SNR of PU towards PUrx \( (PU_{SNR}) \), when only PU link is transmitting is defined as [10] [11]:

\[
P U_{SNR} = \frac{H_{pp}P_p}{N_0} \quad (4.5)
\]

Outage probability of PU \( (\phi_{p_{out}}) \) which can be measured across the PUrx is defined, according to channel capacity theorem [11] as:

\[
\phi_{p_{out}} = Pr\{log_2(1 + PU_{SNR}) < R_p \} \quad (4.6)
\]
$R_p$ and $P_p$ are the data rate and transmitting power of PU respectively. The SNR of CU towards CUrx ($CU_{SNR}$) when only PU link is transmitting is defined as [10] [11]:

$$CU_{SNR} = \frac{H_{cc}P_c}{N_0}$$  \hspace{1cm} (4.7)

Outage probability of CU ($\varphi_{Cout}$) which can be measured across the CUrx is defined according to channel capacity theorem as [11]:

$$\varphi_{Cout} = Pr\{ log_2(1 + CU_{SNR}) < R_c \}$$  \hspace{1cm} (4.8)

$R_c$ and $P_c$ are the data rate and transmit power of CU respectively.

Both PU and CU are transmitting simultaneously over the spectrum. The signal to interference noise ($PU_{SINR}$) towards primary receiver PUrx is defined as [11]:

$$PU_{SINR} = \frac{H_{pp}P_p}{H_{cp}P_c + N_0}$$  \hspace{1cm} (4.9)

Outage probability of PU ($\varphi_{Pout}$) which measured across PUrx, when both PU and CU are transmitting simultaneously over the same spectrum is defined as [10] [11]:

$$\varphi_{Pout} = Pr\{ log_2(1 + PU_{SINR}) < R_p \}$$  \hspace{1cm} (4.10)

Both PU and CU are transmitting simultaneously over the spectrum. The signal to interference noise ($CU_{SINR}$) towards secondary receiver CUrx is defined as [11]:

$$CU_{SINR} = \frac{H_{cc}P_c}{H_{cp}P_p + N_0}$$  \hspace{1cm} (4.11)

Outage probability of CU ($\varphi_{Cout}$) which measured across CUrx, when both PU and CU are transmitting simultaneously over the same spectrum is defined as [10] [11]:

$$\varphi_{Cout} = Pr\{ log_2(1 + CU_{SINR}) < R_c \}$$  \hspace{1cm} (4.12)

For simplicity, we assume that the CU has a peak power scale $P_{c\text{max}}$ and the CU allocates the peak power scale ratio $\psi$ to assure the desired QoS on the PU link. The $PU_{SINR}$ plays a major role in evaluation of QoS and (4.9) can be rewritten as follows [11]:

$$PU_{SINR}(\psi) = \frac{H_{pp}P_p}{\psi H_{cp}P_{c\text{max}} + N_0}$$  \hspace{1cm} (4.13)
4.4.2. Power Control Principles for Spectrum Sharing Network in the without path-loss propagation environment

Power control principles for CU to maintain the desired QoS on PU link in terms of signal power strength in spectrum sharing network in a without path-loss propagation environment can be defined as follows [11]:

(i) PU is in outage.

\[ PU_{SNR}(\psi) < R_p \]  \hspace{1cm} (4.14)

(ii) PU not in outage.

\[ PU_{SNR}(\psi) \geq R_p \]  \hspace{1cm} (4.15)

Suppose there is a threshold \( R_p \) for the desired QoS, then to assure the desired QoS, the PU’s SINR i.e. \( PU_{SNR}(\psi) \) should be greater than the threshold \( R_p \) during spectrum sharing from (4.15). The CU allocates the peak power scale ratio \( \psi \) to assure that \( PU_{SNR}(\psi) \) is greater than threshold \( R_p \) [11]. From (4.13) and (4.16), the value of \( \psi \) is influenced by the \( PU_{SNR} \) and PU’s interference channel gain \( H_{cp} \). The power control principles for spectrum sharing networks in the propagation environment without path loss can be organized from two different perspectives: PU’s SNR i.e. \( PU_{SNR} \) and PU’s interference channel gain \( H_{cp} \).

Instantaneous power scaling factor \( \psi \), which varies in the range \( 0 \leq \psi \leq 1 \):

\[ \psi \leq \left[ \frac{H_{pp}P_p}{R_p} - N_0 \right] \frac{1}{H_{cp}P_{cmax}} \]  \hspace{1cm} (4.16)

Equation (4.16) is derived from (4.13) and (4.14) according to [11]. From (4.16) we can observe that \( \psi \) is influenced by \( PU_{SNR} \) and interference channel gain \( H_{cp} \).

4.4.2.1. Relationship between power scaling factor \( \psi \) and \( PU_{SNR} \)

In the CRN the CU senses the CSI of PU with the permission of PU and controls its transmitting power conditions and vice versa. Here CU senses the \( PU_{SNR} \) and scales its maximum power \( P_{cmax} \) with power scaling factor \( \psi \) to maintain the desired QoS on PU. The points i to iv below are defined based on (4.5) and (4.13) to (4.16):

i. When the interference channel gain \( H_{pp} \) of PU is very low, the \( PU_{SNR} \) falls far below the threshold value and PU is in outage condition i.e. the PU signal is totally degraded. In this condition the effect of CU on PU link is negligible and CU can
utilize the PU spectrum without maintaining PU restrictions. Here CU may transmit with its peak power.

ii. When the channel gain $H_{pp}$ of PU is low, the $PU_{SNR}$ falls below but close to the threshold value, the desired QoS is not assured and transition state is likely to occur to be in transition state, turning to be assured. The PU link is sensitive to interference and the spectrum utilization of the CU link will cause interference to the PU link. Thus, the CU link should scale its peak power before transmission with $\psi$.

iii. When the channel gain $H_{pp}$ of PU is high the $PU_{SNR}$ falls just above the threshold, the desired QoS is not assured but is likely to be in transition state. The PU link is sensitive to interference and the spectrum utilization of the CU link will cause interference to the PU link. Thus, the CU link can transmit with a fraction of its peak power.

iv. When the channel gain $H_{pp}$ of PU is very high the $PU_{SNR}$ falls far above the threshold and PU is in robust condition i.e. the PU signal strength is strong enough to transmit required data. Here QoS of PU is strongly assured and is not sensitive to the CU transmission. Here CU can utilize the spectrum efficiently and transmit with its peak power.

### 4.4.2.2. Relationship between power Scaling factor $\psi$ and $H_{cp}$

From (4.13), (4.14) and (4.15) we can observe $H_{cp}$ is inversely proportional to $PU_{SINR}$. If the interference channel gain $H_{cp}$ is low, the received interference intensity caused by CU is low and $PU_{SINR}(\psi)$ is greater than the threshold then QoS on PU link is maintained. If $H_{cp}$ is high, the received interference intensity caused by CU is high and the $PU_{SINR}(\psi)$ falls below the threshold then the QoS on PU link degrades.

### 4.5. Implementation of Takagi-Sugeno Fuzzy controller in spectrum sharing network in without path-loss environment

As explained in the previous subsection, the QoS of PU is maintained with power scaling factor $\psi$. Whereas $\psi$ is influenced by $PU_{SNR}$ and interference channel gain $H_{cp}$. We consider $PU_{SNR}/R_p$ (PU SNR RATIO) and interference channel gain ratio $H_{cp}/H_{cpmax}$ as fuzzy antecedents. $H_{cpmax}$ is the maximum interference channel gain. $\psi$ is the fuzzy consequence of the system.

In the fuzzification process, the crisp values are converted to linguistic variables with terms being fuzzy sets. Here we divide each fuzzy antecedent into three intensity levels, which are
represented by fuzzy sets with their assisting membership functions. The fuzzy consequence of each if–then rule of Takagi-Sugeno system is given as:

\[ ax + by + c = f(x, y) \]  \hspace{1cm} (4.17)

where \( a, b, c \) are fuzzy control parameters and \( x, y \) are input membership functions. The Takagi Sugeno System works on the principle of If-Then rules:

\[ IF \text{ } x \text{ is } M1 \text{ and } y \text{ is } M2 \text{ then } z = f(x, y) \]  \hspace{1cm} (4.18)

Here \( M1 \) and \( M2 \) are membership functions of antecedents and \( z \) is a functional fuzzy consequence [25] [26] [27] [28]. Fig 4.5 shows the FIS with two antecedents and consequence.

![Fuzzy System Diagram](image_url)

Fig. 4.5. Takagi-Sugeno fuzzy system in spectrum sharing network without path/loss propagation environment

### 4.5.1. First fuzzy antecedent: PU_SNR RATIO

The first input to the Takagi-Sugeno FIS is ratio of PU_SNR to threshold value of \( R_p \) which is divided into three intensity levels, which can assist fuzzy sets restricted by membership functions. Thus, the linguistic variables of PU_SNR RATIO can be presented by idle, active and robust states as shown in Fig. 4.6. For simplicity we indicate the threshold value of \( R_p \) with \( \varepsilon \). The PU_SNR RATIO \( g \) is represented as:

\[ g = \frac{PU_{SNR}}{\varepsilon} \]  \hspace{1cm} (4.19)
The next step is to define assisting membership functions to the fuzzy sets. The following procedure is used to represent membership functions mathematically.

Consider two points from fuzzy sets \((x_1, y_1)\) and \((x_2, y_2)\) and substitute the points in straight line equation i.e. \(y = ax + b\). The parameters \(a\) and \(b\) are obtained by solving the two equations. Let us take two points \((5, 1)\) and \((15, 0)\) from \(idle\) fuzzy set Fig. 4.6 and substitute in the equation of straight line.

\[
1 = 5a + b \tag{4.20}
\]
\[
0 = 15a + b \tag{4.21}
\]

By solving (4.20) and (4.21) the value of \(a = -0.1\) and \(b = 1.5\) are obtained. The straight line \(-0.1g + 1.5 = \mu(g)\) helps to compute the degree of membership for \(g\) between the range 5 to 15. The same procedure is used to find the degree of membership in three fuzzy sets.

The mathematical forms of representing fuzzy membership functions for three linguistic variables are defined as:

**Idle state:**

\[
\mu_{idle}(g) = \begin{cases} 
1 & \text{for } g < 5 \\
-0.1g + 1.5 & \text{for } 5 \leq g < 15 \\
0 & \text{for } g \geq 1 
\end{cases} \tag{4.22}
\]
Active state:

$$\mu_{Active}(g) = \begin{cases} 0 & \text{for } g < 5 \\ 0.1g - 0.5 & \text{for } 5 \leq g < 15 \\ -0.1g + 2.5 & \text{for } 15 \leq g < 25 \\ 0 & \text{for } g \geq 25 \end{cases}$$ (4.23)

Robust state:

$$\mu_{Robust}(g) = \begin{cases} 0 & \text{for } g < 15 \\ 0.1g - 1.5 & \text{for } 15 \leq g < 25 \\ 1 & \text{for } g \geq 25 \end{cases}$$ (4.24)

4.5.2. Second fuzzy antecedent: Interference channel gain ratio

Suppose a predetermined high value of interference channel gain is taken as a threshold $H_{c_{\max}}$, which is used to differentiate the attribute of $H_{cp}$. The second input to the Takagi-Sugeno FIS is the interference channel gain ratio $H_{cp}/H_{c_{\max}}$ which is divided into three intensity levels which can assist fuzzy sets restricted by membership functions. Thus, the linguistic variables of $H_{cp}$ to $H_{c_{\max}}$ can be presented by low, medium and high states as shown in Figure 4.7. The interference channel gain ratio $h$ is represented as:

$$h = \frac{H_{cp}}{H_{c_{\max}}}$$ (4.25)

![Fig. 4.7. Antecedent 2 Interference Channel Gain Ratio with three fuzzy sets namely, low, medium and high.](image)

The membership functions for the fuzzy sets are calculated and represented in the same procedure as for the first antecedent. They are defined as follows:
Interference channel gain ratio: Low

\[ \mu_{\text{low}}(h) = \begin{cases} 
-2h + 1 & \text{for } 0 \leq h \leq 0.5 \\
0 & \text{for } h > 0.5 
\end{cases} \]  

Interference channel gain ratio: Medium

\[ \mu_{\text{medium}}(h) = \begin{cases} 
2h & \text{for } 0 \leq h \leq 0.5 \\
-2h + 2 & \text{for } 0.5 \leq h \leq 1 
\end{cases} \]  

Interference channel gain ratio: High

\[ \mu_{\text{high}}(h) = \begin{cases} 
0 & \text{for } h < 0.5 \\
2h - 1 & \text{for } 0.5 \leq h \leq 1 
\end{cases} \]  

In the Takagi-Sugeno FIS the output/fuzzy consequence is a dependent variable, which depends upon the inputs i.e. \( f(g, h) = \psi \), the main difference between the Mamdani and Takagi-Sugeno is evaluation of output/fuzzy consequence membership functions. The most commonly used function for output is linear equation of first order i.e. \( ag + bh + c = \psi \). The parameters \( a, b \) and \( c \) optimize the inputs according to the specific application. Output equations are calculated using linear regression method [24].

4.5.3. Implementation of rule–based decision

In spectrum sharing network in without path-loss propagation environment PU_SNR ratio and \( H_{cp}/H_{cpmax} \) are inputs to fuzzy system which are in the form of membership functions. The output of fuzzy system is a first order linear equation, such as \( \psi = ag + bh + c \). The parameters \( a, b \) and \( c \) are the fuzzy control parameters, peak power scale ratio is \( \psi \) and \( (g, h, \psi) \) is a data triplet. The output \( \psi \) for all rules can be calculated regressively using few available data triplets of input and output variables such as \{\( (0, 0, 1) \), \( (15, 0.5, 0.01) \), \( (30, 1, 1) \)\} and with previous experience values [11] [16]. The triplets \( (\text{PU}_\text{SNR ratio}, H_{cp}/H_{cpmax}, \text{power scaling factor}) = (g, h, \psi) \) belong to the set \{\( (0, 0, 1) \), \( (15, 1,0.01) \),\( (30, 1 ,1) \)\}. The dependent variable peak power scale ratio \( \psi = f(g, h) \) is in range 0 to 1. Based on the proposed power control principles for spectrum sharing network in the without path-loss propagation environment, the fuzzy control rules are established as shown in Table 5.1.

Table 5.1 can be explained as follows:

- When the antecedent 1 is idle state and interference channel gain ratio is low the interference caused by CU towards PU is less. So CU can transmit with its maximum power through the PU spectrum.
- When the antecedent 1 is idle state and interference channel gain ratio is in medium the interference caused by CU towards PU increases slowly with respect to rule 1 then CU can transmit with low scaled transmitting power compared to maximum power.
- In rule 4 when antecedent 1 is in active state and interference channel gain ratio is in low state, the PU is sensitive to interference caused by CU. In this case the CU should transmit with much scaled transmitting power than the previous rules.
- In rule 5 when Antecedent 1 is in active state and interference channel gain ratio is in medium state. i.e. channel interference gain is increased, the PU is much sensitive to interference caused by CU then CU should transmit with moderate scaling value with respect to previous rules.
- In rule 6 when antecedent 1 is in active state and interference channel gain ratio is in high state .i.e. interference gain ratio is very high, the PU is very much sensitive to interference caused by CU, than CU should transmit with as minimum power as possible or SU should quit its transmission in this region.
- In rule 9 when antecedent 1 is in robust state and interference channel gain ratio is in high state the QoS of PU is not affected much with the SU transmission. So, CU can transmit with maximum peak power.

Table 5.1: Fuzzy control rules for spectrum sharing networks in without pathloss propagation environment

<table>
<thead>
<tr>
<th>Rule no.</th>
<th>$\frac{\text{PU}_{\text{SNR}}}{\varepsilon}$</th>
<th>$\frac{H}{H_{\text{e}}} \frac{H_{\text{e}}}{H_{\text{e}}}$</th>
<th>$\Psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Idle Low</td>
<td>$\psi_1 = -0.0825g + 0.1h + 0.9$</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Idle Medium</td>
<td>$\psi_2 = -0.03g - 0.1h + 1.14$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Idle High</td>
<td>$\psi_3 = -0.0825g - 0.1h + 1.06$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Active Low</td>
<td>$\psi_4 = 0g + 0.3h + 0.9$</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Active Medium</td>
<td>$\psi_5 = 0.01g - 0.9h + 0.8$</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Active High</td>
<td>$\psi_6 = 0g + 0h + 0.09$</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Robust Low</td>
<td>$\psi_7 = 0.003g + 0.01h + 0.9$</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Robust Medium</td>
<td>$\psi_8 = 0.07g - 0.08h - 1.09$</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Robust High</td>
<td>$\psi_9 = 0.071g - 0.095h - 1.064$</td>
<td></td>
</tr>
</tbody>
</table>

Since the output of Takagi-Sugeno FIS in form of equation this system is flexible to apply to the learning algorithms like adaptive algorithms, back propagation algorithms and LMS algorithms. Through learning algorithms the fuzzy control parameters can be trained and the accuracy of output could improve.
4.5.4. Defuzzification using Weighted Average Method

In Takagi-Sugeno FIS we can use different defuzzification methods. The method we have used in our implementation of FIS is weighted average method which is given by the formula [41]:

\[
\psi = \frac{\sum_l \psi(g,h);l \cdot \alpha(g,h);l}{\sum \alpha(g,h);l}
\]

where \( l = 1, 2, 3 \) \hspace{1cm} (4.29)

Example 4.1 provides a clear understanding of the defuzzification process.

**Example 4.1:**

Let us consider a triplet \((1, 0.01, \psi)\) belongs to \((g, h, \psi)\). If we observe the antecedent one from Figure 4.6, the intensity value of \( g \) falls in the idle region and from Figure 4.7 intensity value of \( h \) falls in between the low and medium region.

The degree of memberships can be calculated using (4.22), (4.27) and (4.28).

\[
\mu_{g\text{ idle}}(1) = 1; \quad \mu_{h\text{ low}}(0.01) = -2 \cdot 0.01 + 1 = 0.98; \quad \mu_{h\text{ medium}}(0.01) = 2 \cdot 0.01 = 0.02
\]

**Step 1:**

We need an estimate \( \alpha(g,h);1 \) calculated using the minimum operation

\[
\alpha(1, 0.01);1 = \min (\mu_{g\text{ idle}}(1), \mu_{h\text{ low}}(0.01)) = \min (1, 0.98) = 0.98
\]

\[
\alpha(1, 0.01);2 = \min (\mu_{g\text{ idle}}(1), \mu_{h\text{ low}}(0.01)) = \min (1, 0.02) = 0.02
\]

**Step 2:**

If \( g \) is idle \( h \) is low then power scaling factor \( \psi_1 = -0.0825 \cdot 1 + 0.1 \cdot 0.01 + 0.9 = 0.885 \)

If \( g \) is idle \( h \) is medium then power scaling factor \( \psi_2 = -0.03 \cdot 1 - 0.1 \cdot 0.01 + 1.04 = 1.09 \)

Where \( \psi_1 \) and \( \psi_2 \) are calculated from the rules defined in Table 5.1

By applying the weighted average defuzzification formula,

\[
\psi = \frac{[\psi_1 \cdot \alpha(1, 0.01);1 + \psi_2 \cdot \alpha(1,0.01);2]}{\alpha(1,0.01);1 + \alpha(1,0.01);2} = 0.95 \approx 1
\]

This can be observed from the three dimensional plot shown in Figure 4.8.

When PU_SNR ratio is in idle state i.e. on \( x \)-axis at point 1 and interference channel gain ratio is in between low and medium i.e. on \( y \)-axis at point 0.01, power scaling factor \( \psi \approx 1 \) i.e on \( z \)-axis. In this situation the interference from CU on PU link does not degrade the QoS, So CU can transmit with max power (rule 1 and 2 from Table 5.1).
- When PU_SNR ratio is in idle state and interference channel gain ratio is turning from 1 to 0, the interference caused by CU on PU link decreases. So $\psi$ is turning to high and CU may transmit with its high power.

- When PU_SNR ratio is in active state and interference channel gain ratio is turning from 0 to 1, the interference from CU on PU link is increases. So $\psi$ is turning from 1 to 0 to control the CU transmitting power.

- When PU_SNR ratio is in robust state and interference channel gain ratio is turning from 1 to 0, the interference caused by CU on PU link decreases. So $\psi$ is turning to high and CU may transmit with its high power.

![Fig. 4.8. Surface plot for defuzzification for without path-loss environment](image)

The weighted average defuzzification method is computationally efficient than other fuzzy system defuzzification methods [25]. Because it is a simple defuzzification process it does not require more expensive methods and is economically good compared to Mamdani fuzzy system. We can observe from the figure that the surface plot is continuous [25] and CU power is distributed linearly according to the specific conditions mentioned in the above subsections.

4.6. **Validation of spectrum sharing network in without path loss propagation environment**

The fuzzy based optimized power control strategy is validated by comparing with other power control strategies (i.e. Mamdani with Takagi-Sugeno Fuzzy Inference method) and without power control strategies in CRN [11] [16] [31] [32]. The validation is performed...
over different fading environments such as from low fading Ricean to severe fading scenarios. The performance differences can be seen from characteristic of the BER as a function of energy per bit to noise power spectral ratio. We use the differential phase shift keying modulation (DPSK) technique a non-coherent modulation technique which is more practical then coherent modulation techniques, DPSK eliminates the need for coherent (synchronization bit) reference signal at the receiver.

In without path-loss propagation environment the Takagi-Sugeno based fuzzy power control strategy is dependent upon the two input variables, PU SNR ratio and interference channel gain ratio. We fix the variable of PU’s interference channel gain ratio at three different scales: low, medium and high, respectively, and let PU’s SNR ratio as the only variable. The Fig. 4.9 depicts the BER vs. $E_b/N_0$ at $H_{cp}/H_{cmax} = 0.2$ (low). Fig. 4.10 depicts the BER vs. $E_b/N_0$ at $H_{cp}/H_{cmax} = 0.5$ (medium). Fig. 4.11 depicts the BER vs. $E_b/N_0$ at $H_{cp}/H_{cmax} = 0.9$ (high). The x axis labels PU’s SNR ratio in $E_b/N_0$ and y axis labels the BER. PU SNR ratio varies from 0 dB to 25 dB. The fading parameter $m$ is set to 1, which imitates Rayleigh fading environment.

Fig. 4.12 to Fig. 4.14 are with fading parameter of $m=2$, which imitates the Nakagami fading environment.

We can observe from the following figures that Takagi-sugeno FIS based power control strategy gives slightly better BER performance when compared to Mamdani FIS on higher $E_b/N_0$ values. We also conclude from the figures that at higher interference channel gains the comparative performance of Takagi-Sugeno based power control strategy is much better when compared to Mamdani based power control strategy. Also, with increasing fading parameter $m$, i.e. changing the multipath fading environment the BER performance is improved.

![Fig. 4.9. fading parameter m=1; Interference channel gain=0.2](image1)

![Fig. 4.10. fading parameter m=1; Interference channel gain = 0.5](image2)
Fig. 4.11. Fading parameter $m=1$; interference channel gain = 0.9

Fig. 4.12. Fading parameter = 2; Interference channel gain = 0.2

Fig. 4.13. Fading parameter $m=2$; Interference channel gain = 0.5

Fig. 4.14. Fading parameter $m=2$; Interference channel gain = 0.9
CHAPTER 5. FUZZY CONTROLLER FOR SPECTRUM SHARING NETWORK IN WITH PATH-LOSS PROPAGATION ENVIRONMENT

This chapter explains the second scenario of our thesis, which is CRN system modeling, implementation of Takagi-Sugeno FIS and validation in without path-loss propagation environment over m-Nakagami fading channel model.

5.1. A model of an Opportunistic spectrum sharing in with path-loss propagation environment

Here we consider the scenario for spectrum sharing networks in path-loss propagation environment as shown in Fig.5.1. PUtil and PUrx are the primary transmitter and receiver. CUtil and CUr are secondary transmitter and receiver. \( D_{pp} \), \( D_{cp} \), and \( D_{cc} \) are relative distances between the respective transmitter and receivers.

![Model for path-loss propagation](image)

Fig. 5.1. Model for path-loss propagation with a PU transmitter-receiver pair PUtil and PUrx and SU transmitter-receiver CUtil and CUr respectively. \( D_{pp} \), \( D_{cc} \) and \( D_{cp} \) are relative distance ratios between primary link, secondary link and CUtil and PUrx respectively.

The system comprises of a pair of PU link and CU link over Nakagami fading environment. We assume that PUtil ; PUrx, CUtil and CUr positioned at different locations and each link have different relative distance as shown in Fig.4.3. In path-loss propagation environment the calculations are considered in geometric point of view, total three links with different relative distances can be observed from Fig.4.3. The relative distance between PUtil to PUrx denoted as \( D_{pp} \), relative distance between CUtil to CUr denoted as \( D_{cc} \) and relative distance between PUrx to CUtil denoted as \( D_{cp} \). The relation between a relative distance and channel fading co-efficient \( H \) can be defined as [14]:
\[ H = \frac{A}{d^\alpha} \] (5.1)

Where \( H \) is the channel fading coefficient, \( A \) is the frequency dependent path-loss constant, \( d \) is the relative distance and \( \alpha \) is the path-loss exponent.

Form (5.1) it is evident that in spectrum sharing networks with path-loss propagation environment the interference intensity towards the \( \text{PUrx} \) is influenced by the relative distance between the \( \text{CUTx-PUrx} \). In other words as the relative distance between the \( \text{PUrx-CUTx} \) increases the interference intensity towards the primary user decreases.

### 5.2. Implementation of an Opportunistic spectrum sharing in with path-loss propagation environment

In the propagation environment with path-loss, the received signal/interference intensity at receiver decreases as the relative distance between the transmitter and receiver increases. Two major objectives of this thesis are: \( \text{CUTx} \) should transmit with its peak power opportunistically by utilizing the spectrum efficiently and QoS on PU link, in terms of signal power strength towards \( \text{PUrx} \), should be assured. The opportunistic power allocation is linked with the PU’s QoS. It is needed to develop the criterions to evaluate QoS. Thus, we adopt the SNR, SINR and outage probability as the criterions we defined in below subsections.

Since we consider the spectrum sharing network in path-loss propagation environment, the relative distance between the transmitter and the receiver are one of the considered variables. For simplicity we assume the elusive region of CRN as maximum effective distance from the respective receivers [15]. The received power intensity of the respected receiver is zero if the relative distance of receiver exceeds the maximum effective distance. We assume the radio links are located in fixed static positions and the received power intensity at PU is defined as [14] [15]:

\[
P_r = P_p A \left[ 1 - \left( \frac{D_{pp}}{L_{pp}} \right)^\alpha \right] \tag{5.2}
\]

The received power at the CU is defined as

\[
P_r = P_c A \left[ 1 - \left( \frac{D_{cc}}{L_{cc}} \right)^\alpha \right] \tag{5.3}
\]

where \( L_{pp} \) and \( L_{cc} \) are the maximum effective distances of PU and CU respectively, \( A \) is the frequency dependent path-loss constant. In order to maintain the sufficient signal strength
towards receivers from respective transmitters, relative distances of the primary user $D_{pp}$ and secondary user $D_{cc}$ should be less than or equal to their maximum effective distances.

### 5.2.1. Signal to Noise Ratio, Signal to Interference Noise ratio and Outage Probability:

The SNR of primary user towards PUrx ($PU_{SNR}$), when only PU link transmitting is defined as [10] [11]:

$$PU_{SNR} = \frac{H_{pp}P_p}{N_0} \left[1 - \left(\frac{D_{pp}}{L_{pp}}\right)^\alpha\right]$$  \hspace{1cm} (5.4)

Outage probability of PU ($\phi_{Pout}$) which can be measured across the PUrx is defined as according to channel capacity theorem [11]:

$$\phi_{Pout} = Pr\{\log_2(1 + PU_{SNR}) < R_p\}$$  \hspace{1cm} (5.5)

$R_p$ and $P_p$ are the data rate and transmitting power of PU.

The SNR of PU towards CUrx ($CU_{SNR}$), when only PU link transmitting is defined as [10] [11]:

$$CU_{SNR} = \frac{H_{cc}P_c}{N_0} \left[1 - \left(\frac{D_{cc}}{L_{cc}}\right)^\alpha\right]$$  \hspace{1cm} (5.6)

Outage probability of CU ($\phi_{Cout}$) which can be measured across the CUrx is defined according to channel capacity theorem, as [11]:

$$\phi_{Cout} = Pr\{\log_2(1 + CU_{SNR}) < R_c\}$$  \hspace{1cm} (5.7)

$R_c$ and $P_c$ are the data rate and transmitting power of CU respectively.

Both PU and CU are transmitting simultaneously over the spectrum. The signal to interference noise ($PU_{SINR}$) towards primary receiver PUrx is defined as [11]:

$$PU_{SINR} = \frac{H_{pp}P_p}{H_{cp}P_c} \left[1 - \left(\frac{D_{pp}}{L_{pp}}\right)^\alpha\right]$$  \hspace{1cm} (5.8)

Outage probability of PU($\phi_{POut}$) which measured across PUrx, when both PU and CU are transmitting adequately over the same spectrum is defined as [10] [11].
Both PU and CU are transmitting simultaneously over the spectrum. The signal to interference noise (\(CU_{SINR}\)) towards primary receiver CUrx is defined as [11]:

\[
CU_{SINR} = \frac{H_{cc}P_c\left[1-\left(\frac{P_{cc}}{I_{CCc}}\right)^a\right]}{h_{cp}P_c\left[1-\left(\frac{P_{cp}}{I_{cpp}}\right)^a\right]+N_0} \tag{5.10}
\]

Outage probability of CU(\(P_{cout}\)) measured across CUrx, when the both PU and CU are transmitting adequately over the same spectrum is defined as [10] [11]:

\[
\Phi_{P_{cout}} = \Pr\{\log_2(1+CU_{SINR}) < R_p\} \tag{5.11}
\]

For simplicity, we assume that the CU has a peak power scale \(P_{cmax}\) and the CU allocates the peak power scale ratio \(\psi\) to assure the desired QoS on the PU link. The \(PU_{SINR}\) plays a major role in evaluation of QoS and (5.8) can be rewritten as follows [11]:

\[
PU_{SINR}(\psi) = \frac{H_{pp}P_p\left[1-\left(\frac{P_{pp}}{I_{cpp}}\right)^a\right]}{\psi P_{cmax}\left[1-\left(\frac{P_{cp}}{I_{cpp}}\right)^a\right]H_{cp}+N_0} \tag{5.12}
\]

### 5.2.2 Power Control Principle

Power control principles for CU to maintain the desired QoS on PU link in terms of signal power strength in spectrum sharing network in a with path-loss propagation environment can be defined as follows [11]:

(i) PU is in outage.

\[
PU_{SINR}(\psi) < R_p \tag{5.13}
\]

(ii) PU not in outage.

\[
PU_{SINR}(\psi) \geq R_p \tag{5.14}
\]

Suppose there is a threshold \(R_p\) for the desired QoS, then to assure the desired QoS, the PU’s SINR \(PU_{SINR}(\psi)\) should be greater than the threshold \(R_p\) during spectrum sharing from (5.14). The CR allocates the peak power scale ratio \(\psi\) to assure that the PU’s SINR \(PU_{SINR}(\psi)\) is greater than threshold \(R_p\) [11]. From the (5.12) and (5.15), the value of \(\psi\) is influenced by the PU’s SNR \(PU_{SNR},\) PU’s interference channel gain \(H_{cp}\) and relative distance \(D_{cp}\). To maintain the relationship between PU SNR and relative distance, we
normalize the interference channel gain ratio to one. The power control principles for spectrum sharing networks in the propagation environment without path loss can be organized from two different perspectives: PU’s SNR $P_{U_{SNR}}$ and relative distance $D_{cp}$. Instantaneous power scaling factor $\psi$, which varies in the range $0 \leq \psi \leq 1$:

$$\psi \leq \left[ \frac{H_{PP}}{H_p} - N_0 \right] \left( \frac{1}{P_{cmax}} \left[ 1 - \left( \frac{D_{cp}}{L_{cp}} \right)^H_{cp} \right] \right)$$  \hspace{1cm} (5.15)

Equation (5.16) is derived from (5.13) and (5.14) according to [11].

5.2.2.1. Relationship between Scaling factor $\psi$ and $P_{U_{SNR}}$:

In the CRN the CU senses the CSI of PU with the permission of PU and controls its transmitting power conditions and vice versa. Here CU senses the $P_{U_{SNR}}$ and scales its maximum power $P_{cmax}$ with power scaling factor $\psi$ to maintain the desired QoS on PU. The points i to iv below are defined based on (5.4) and (5.12) to (5.15):

i. When the channel gain $H_{PP}$ of PU is very low, the $P_{U_{SNR}}$ falls far below the threshold value and PU is in outage condition i.e. the PU signal is totally degraded. In this condition the effect of CU on PU link is negligible and CU can utilize the PU spectrum without maintaining PU restrictions. Here CU may transmit with its peak power.

ii. When the channel gain $H_{PP}$ of PU is low, the $P_{U_{SNR}}$ falls below but close to the threshold value, the desired QoS is not assured and transition state is likely to occur. The PU link is sensitive to interference and the spectrum utilization of the CU link will cause interference to the PU link. Thus, the CU link should scale its peak power before transmission with $\psi$.

iii. When the channel gain $H_{PP}$ of PU is high the $P_{U_{SNR}}$ falls just above the threshold, the desired QoS is not assured and transition state is likely to occur. The PU link is sensitive to interference and the spectrum utilization of the CU link will cause interference to the PU link. Thus, the CU link can transmit with a fraction of its peak power.

iv. When the channel gain $H_{PP}$ of PU is very high the $P_{U_{SNR}}$ falls far above the threshold and PU is in robust condition i.e. the PU signal strength is strong enough to transmit required data. Here QoS of PU is strongly assured and is not sensitive to the CU transmission. Here CU can utilize the spectrum efficiently and transmit with its peak power.
5.2.2.2. **Relationship between scaling factor $\psi$ and Relative distance:**

From system model in Fig 5.1 we can observe that when the relative distance $D_{cp}$ between the PURx and CUtilx is near, the interference caused by CU towards PU link is high. In this situation the CU should scale its transmitting power. When the relative distance $D_{cp}$ between the PURx and CUtilx is far, the interference caused by CU towards PU is low. This means that interference caused by CU towards PU is inversely proportional to relative distance $D_{cp}$.

5.3 **Implementation of Takagi-Sugeno Fuzzy controller in spectrum sharing network with path-loss propagation environment**

As explained in the previous subsection, the QoS of PU is maintained with power scaling factor $\psi$. Whereas $\psi$ is influenced by $\frac{PU_{SNR}}{R_p}$ (PU_SNR RATIO) and relative distance $D_{cp}$. We consider $\frac{PU_{SNR}}{R_p}$ (PU_SNR RATIO) and relative distance ratio $D_{cp}/L_{cp}$. $\psi$ is the fuzzy consequence of the system.

In the fuzzification process, the crisp values are converted to linguistic variables with terms being fuzzy sets. Here we divide each fuzzy antecedent into three intensity levels, which are represented by fuzzy sets with their assisting membership functions. The fuzzy consequence of each if –then rule of Takagi-Sugeno system is given as:

$$ax + by + c = f(x, y)$$  \hspace{1cm} (5.16)

where $a$, $b$, $c$ are fuzzy control parameters and $x$, $y$ are input membership functions. The Takagi-Sugeno System works on the principle of If-Then rules:

$$IF \ x \ is \ M1 \ and \ y \ is \ M2 \ then \ z = f(x, y)$$ \hspace{1cm} (5.17)

Here $M1$ and $M2$ are membership functions of antecedents and $z$ is a functional fuzzy consequence \cite{25, 26, 27, 28}.

Fig. 5.2 shows the FIS with two fuzzy antecedents and fuzzy consequence.
5.3.1. First Fuzzy antecedent: PU\_SNR RATIO

The first input to the Takagi-Sugeno FIS is ratio of PU\_SNR to threshold value of R_p which is divided into three intensity levels, which can assist fuzzy sets restricted by membership functions. Thus, the linguistic variables of PU\_SNR RATIO can be presented by idle, active and robust states as shown in Fig. 5.3. For simplicity we indicate the threshold value of R_p with ε . The PU\_SNR RATIO g is represented as:

\[ g = \frac{PU_{SNR}}{\varepsilon} \]  \hspace{1cm} (5.18)

![Antecedent 1 PU\_SNR RATIO with three intensity levels idle, active and robust.](image-url)
The next step is to define assisting membership functions to the fuzzy sets and is derived according to the same procedure used in the previous chapter. The following procedure is used to represent membership functions mathematically.

The mathematical forms of representing fuzzy membership functions for three linguistic variables are defined as:

**Idle state:**

\[ \mu_{\text{Idle}}(g) = \begin{cases} 
1 & \text{for } g < 5 \\
-0.1g + 1.5 & \text{for } 5 \leq g < 15 \\
0 & \text{for } g \geq 1 
\end{cases} \]  

(5.19)

**Active state:**

\[ \mu_{\text{Active}}(g) = \begin{cases} 
0 & \text{for } g < 5 \\
0.1g - 0.5 & \text{for } 5 \leq g < 15 \\
-0.1g + 2.5 & \text{for } 15 \leq g < 25 \\
0 & \text{for } g \geq 25 
\end{cases} \]  

(5.20)

**Robust state:**

\[ \mu_{\text{Robust}}(g) = \begin{cases} 
0 & \text{for } g < 15 \\
0.1g - 1.5 & \text{for } 15 \leq g < 2 \\
1 & \text{for } g \geq 25 
\end{cases} \]  

(5.21)

5.3.2. Second fuzzy antecedent: Relative distance ratio \((D_{cp}/L_{cp})\)

Suppose a predetermined maximum effective distance \(L_{cp}\) is taken as a threshold, which is used to differentiate the attribute of \(D_{cp}\). The second input to the Takagi-Sugeno FIS is the interference channel gain ratio \(D_{cp}/L_{cp}\) which is divided into three intensity levels which can assist fuzzy sets restricted by membership functions. Thus, the linguistic variables of \(D_{cp}\) to \(L_{cp}\) can be presented by near, medium and far as shown in Fig. 6.4. The Relative distance ratio \(h\) is represented as:

\[ h = \frac{D_{cp}}{L_{cp}} \]  

(5.22)

The membership functions for the fuzzy sets are calculated and represented in the same procedure as for the first antecedent. They are defined as follows:
Relative distance ratio: Near:

\[ \mu_{\text{Near}}(h) = \begin{cases} 
-2h + 1 & \text{for } 0 \leq h \leq 0.5 \\
0 & \text{for } h > 0.5
\end{cases} \]  
(5.23)

Relative distance ratio: Medium:

\[ \mu_{\text{Medium}}(h) = \begin{cases} 
2h & \text{for } 0 \leq h \leq 0.5 \\
-2h + 2 & \text{for } 0.5 \leq h \leq 1
\end{cases} \]  
(5.24)

Relative distance ratio: Far:

\[ \mu_{\text{Far}}(h) = \begin{cases} 
0 & \text{for } h < 0.5 \\
2h - 1 & \text{for } 0.5 \leq h \leq 1
\end{cases} \]  
(5.25)

5.3.3. Implementation of rule-based decisions

The spectrum sharing network in with path-loss propagation environment PU_SNR ratio and \( D_{cp}/L_{cp} \) are inputs to fuzzy system which are in the form of membership functions. The output of the fuzzy system is peak power scale factor \( \psi \), which is a first order linear equation, such as \( \psi = ag + bh + c \). The parameters \( a, b \) and \( c \) are the fuzzy control parameters and \((g, h, \psi)\) can be called as a data triplet. The output \( \psi \) for all rules can be calculated regressively using few available data triplets of input and output variables such as \((0, 0, 1), (15, 1, 0.01), (30, 1, 1)\)and with previous experience values [11] [16]. The triplets \((\text{PU\_SNR ratio, Relative distance ratio, power scaling factor}) = (g, h, \psi)\) belong to the set \((0, 0, 1), (15, 1, 0.01), (30, 1, 1)\). The dependent variable peak power scale ratio \( \psi = f(g, h) \) is in range 0 to 1. Based on the proposed power control principles for spectrum sharing network in the with path loss propagation environment, the fuzzy control rules are established as shown in Table 6.1.
Table 6.1 can be explained as follows:

- When the antecedent 1 is *idle* state and relative distance ratio is *low* state the interference caused by CU towards PU is considerable. CU can transmit with scaled transmitting power.
- When the antecedent 1 is *idle* state and relative distance ratio is in *medium* state the interference caused by CU towards PU decreases slowly with respect to rule 1 then CU can transmit with low scaled transmitting power.
- In rule 4 when antecedent 1 is in *active* state and relative distance ratio is in *low* state, the PU is very sensitive to interference caused by CU. In this case the than CU should transmit with as minimum power as possible or CU should quit its transmission in this region.
- In rule 5 when antecedent 1 is in *active* state and relative distance ratio is in *medium* state. The interference caused by CU on PU link decreases compared to above rule and CU should transmit with moderate scaling value with respect to previous rules.
- In rule 6 when antecedent 1 is in *active* state and relative distance ratio is in *far* state The interference caused by CU on PU link is very less compared to above rule and CU should transmit with almost peak power.
- In rule 9 when antecedent 1 is in *robust* state and relative distance ratio is in *far* state the QoS of PU is not affected much with the SU transmission. So, CU can transmit with maximum peak power.

Table 6.1: Fuzzy control rules for spectrum sharing networks in with pathloss propagation environment

<table>
<thead>
<tr>
<th>Rule no.</th>
<th>(\frac{\text{PU}_{\text{SNR}}}{\text{e}})</th>
<th>(\frac{D_{cp}}{l_{cp}})</th>
<th>(\psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Idle</td>
<td>Near</td>
<td>(\psi_1 = -0.04g - 0.1h + 0.99)</td>
</tr>
<tr>
<td>2</td>
<td>Idle</td>
<td>Medium</td>
<td>(\psi_2 = -0.12g + 0.001h + 0.98)</td>
</tr>
<tr>
<td>3</td>
<td>Idle</td>
<td>Far</td>
<td>(\psi_3 = -0.0031g + 0.025h + 0.96)</td>
</tr>
<tr>
<td>4</td>
<td>Active</td>
<td>Near</td>
<td>(\psi_4 = 0g + 0h + 0.01)</td>
</tr>
<tr>
<td>5</td>
<td>Active</td>
<td>Medium</td>
<td>(\psi_5 = 0.001g + 0.05h + 0.71)</td>
</tr>
<tr>
<td>6</td>
<td>Active</td>
<td>Far</td>
<td>(\psi_6 = 0.019g + 0.21h + 0.95)</td>
</tr>
<tr>
<td>7</td>
<td>Robust</td>
<td>Near</td>
<td>(\psi_7 = 0.0693g + 0.1h - 1.12)</td>
</tr>
<tr>
<td>8</td>
<td>Robust</td>
<td>Medium</td>
<td>(\psi_8 = 0.001g - 0.009h - 0.99)</td>
</tr>
<tr>
<td>9</td>
<td>Robust</td>
<td>Far</td>
<td>(\psi_9 = -0.001g + 0.05h - 0.961)</td>
</tr>
</tbody>
</table>
Since the output of Takagi-Sugeno FIS in form of equation this system is flexible to apply the learning algorithms like adaptive algorithms, back propagation algorithms and LMS algorithms. Through learning algorithms the fuzzy control parameters can be trained and the accuracy of output could improve.

5.3.4. Defuzzification with weighted average method.

The defuzzification method was carried out according to the predetermined conditions of path-loss propagation environment. Here we use weighted average defuzzification process and the calculation process is the same as explained in chapter 4.

Figure 5.5 is a three dimensional plot of two antecedents and once fuzzy consequence. The antecedent PU_SNR ratio is on x-axis, relative distance ratio $D_{cp}/L_{cp}$ is on y-axis and peak-power-scale ratio $\psi$ is on z-axis.

- When PU_SNR ratio is in idle state and relative distance ratio $D_{cp}/L_{cp}$ is turning from 0 to 1 i.e. CUtx moving away from PUrx, the interference caused by CU on PU link is decreasing. So $\psi$ is turning from 0 to 1 through which CU transmitting power can be scaled from minimum to maximum.
- When PU_SNR ratio is in active state and relative distance ratio $D_{cp}/L_{cp}$ is at 0 i.e. CUtx is near to PUrx, CU transmitting power should be scaled to very low with $\psi$.
- When PU_SNR ratio is in active and $D_{cp}/L_{cp}$ ratio is moved from 0 to 1, the CU transmitting power can be scaled to transmit its peak power.
- When PU_SNR ratio is in robust state and relative distance ratio $D_{cp}/L_{cp}$ to 1, CU can transmit with high peak power.
- When PU_SNR ratio is in robust and $D_{cp}/L_{cp}$ ratio is moving from 1 to 0 i.e. CUtx is moving towards PUrx. The CU transmit power is scaled by a high value of $\psi$. 
5.4. **Validation of spectrum sharing network in with path loss propagation environment**

The fuzzy based optimized power control strategy is validated by comparing with other power control strategies (i.e. Mamdani with Takagi-Sugeno Fuzzy Inference method) and without power control strategies in CRN [11] [16] [31] [32]. The validation is performed over different multipath fading environments, from low fading Ricean to severe fading scenarios. The performance differences can be seen from characteristic of the BER as a function of energy per bit to noise power spectral ratio. We use the DPSK technique a non-coherent modulation technique which is more practical than coherent modulation techniques, DPSK eliminates the need for coherent (synchronization bit) reference signal at the receiver.

In with path-loss environment the Takagi-Sugeno based fuzzy power control strategy depends upon the two input variables i.e. PU SNR ratio and relative distance ratio. Suppose the spectrum sharing network is in the free space propagation environment (path loss exponent = 2) and the PU’s interference channel gain ratio $H_{cp}/H_{cp_{max}}$ is fixed and normalized to 1. We choose the variable of PU’s relative distance ratio at three different scales: *near*, *medium* and *far*, respectively, and let PU’s SNR ratio become the only variable.

The Fig. 5.6 depicts the BER vs. $E_b/N_0$ at $D_{cp}/L_{cp} =0.2$ (*near*). The Figure 5.7 depicts the BER vs. $E_b/N_0$ at $D_{cp}/L_{cp} =0.5$ (*medium*). The Figure 5.8 depicts the BER vs. $E_b/N_0$ at
The $D_{cp}/L_{cp} = 0.8$ (far). The x axis labels PU’s SNR ratio in $E_b/N_0$ and y axis labels the BER. The PU SNR ratio varies from 0 dB to 30 dB. The fading parameter $m$ is set to 1, which imitates Rayleigh fading environment.

Fig. 5.9 to Fig. 5.11 are with fading parameter $m=2$, which imitates the Nakagami fading environment. All other parameters are kept same as were in Fig. 5.6 to Fig. 5.8.
From the Fig.5.6 to Fig.5.8 we conclude that in Rayleigh fading environment the BER performance of Takagi-Sugeno FIS system is slightly better as compared to Mamdani FIS at higher SNR values, but the improvement is not as much as it was in without path-loss environment. Similarly with increasing the relative distance the improvement in performance is further minimized. From Fig.5.9 to Fig.5.11 we conclude that by increasing $m$ the overall BER performance is improved, and by increasing relative distance for larger values of $m$ Takagi-Sugeno based power control strategy gives slightly better BER performance as compared to Mamdani based power control strategy for higher $E_b/N_0$ values. We also conclude that by changing the fading parameter $m$ and hence implementing Nakagami environment we get better BER performance as compared to Rayleigh fading environment.
CHAPTER 6. SECONDARY USER LINK TRANSMISSION USING OFDM

We have implemented OFDM on SU link with the presence of PU link interference under m-Nakagami fading environment. Here in this chapter we will explain the modeling of OFDM system, its implementation on SU link, its simulation results and comparison with different order of PSK modulation (i.e. BPSK, QPSK and 8-PSK) used in OFDM technique, and more its comparison with the transmission without OFDM.

6.1. OFDM system model

Fig. 6.1. shows a block diagram of basic OFDM system. Data is randomly generated and is processed through OFDM transmitter. The data are modulated by the selected order of modulation scheme. It is then been processed by Inverse Fast Fourier Transform (IFFT) to generate time version of transmitted signal. Then it passes through the communication channel. The channel affects the signal with addition of AWGN and multipath fading effect. The receiver receives the signal and demodulates it by the selected order of modulation scheme. After removal of guard bits and pilot data are received.

![OFDM system model including transmission channel](image)

Fig. 6.1. OFDM system model including transmission channel

6.2. OFDM Implementation at Secondary User link

We have implemented OFDM on SU link. So, here we are discussing the working and implementation of OFDM in SU link and the explanation of different blocks, as shown in Fig. 6.1.
6.2.1. Working of OFDM Transmitter

The OFDM transmitter in fig. 6.1. consists of following blocks: serial to parallel, M-PSK modulation, pilot insertion, IFFT, cyclic prefix insertion and parallel to serial.

The information to be transmitted is in serial binary form which has to be converted to parallel form. This is done in serial to parallel block. It is then mapped into complex data blocks by using different modulation schemes: BPSK, QPSK and 8-PSK. After PSK modulation, the unused frequency bands are padded with zeros. Then, IFFT is implemented to generate the time domain form of the transmitted signals, which are the time domain signals. These time domain signals are orthogonal to each other, and can cause frequency spectrums to overlap. Therefore, the Pilot bits are added to reduce the effect of phase noise and frequency offset. In the process of cyclic prefix insertion, the copy of 25% of transmitter symbol is inserted in the beginning of the transmitted signal. It is used at the receiver end to synchronize during the process of demodulation of received signal. As, Inter Symbol Interference ISI and Inter Carrier Interference (ICI) are two main concerns for the transmission, therefore cyclic prefix is also used to reduce these interferences [34]. After the addition of cyclic prefix, the modulated time signal is converted back into serial form.

OFDM system is based on mainly IEEE 802.11a specifications as in Table 6.1,

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>nFFT (FFT size)</td>
<td>64</td>
</tr>
<tr>
<td>nDSC (Number of Data Subcarriers)</td>
<td>52</td>
</tr>
<tr>
<td>T_{cp} (Cyclic prefix Duration)</td>
<td>0.8 µs</td>
</tr>
<tr>
<td>T_{d} (Data Symbol Duration)</td>
<td>3.2 µs</td>
</tr>
<tr>
<td>T_{s} (Total Symbol Duration)</td>
<td>4.0 µs</td>
</tr>
</tbody>
</table>

The relation between $E_b/N_0$ (bit energy) and $E_s/N_0$ (symbol energy) is as follows [37]:

$$ E_b = E_s \left( \frac{nDSC}{nFFT} \right) \left( \frac{T_d}{T_d + T_{cp}} \right) $$

(6.1)

The SNR can be calculated from the following relation:

$$ \frac{E_s}{N_0} [dB] = SNR [dB] + 10 \log \left( \frac{T_d}{T_d + T_{cp}} \right) - \log_2 (M) $$

(6.2)

Where, SNR is Signal to Noise Ratio, $M$ is the order of Phase Shift Keying (PSK). $T_d$ is Data Symbol Duration and $T_{cp}$ is cyclic prefix duration (or guard interval).
The major process of OFDM is the usage of FFT and IFFT. As, all carriers with modulation are individually in digital form, so it was subjected to IFFT process, which created the time domain version of a signal for the transmission.

For IFFT, the mathematical discrete-time representation \( x(k) \) of OFDM symbols \( X(n) \) with \( N \) number of samples is [34]:

\[
x(k) = \frac{1}{N} \sum_{n=0}^{N-1} X(n) e^{j2\pi kn/N}, \quad k = 0 \text{ to } N-1
\]  \( (6.3) \)

where \( k \) is integer and \( N \) is the size of FFT

### 6.2.2. Communication Channel for OFDM transmission

The communication channel considered in this part is Nakagami fading channel. The simulation method we have used is a combination of both Rayleigh and Ricean fading channels, which is explained in Chapter 4. In the channel there is some fading effect and the addition of white gaussian noise. Furthermore, since it is in a cognitive user environment, and since we have used OFDM for CU transmission (when PU is also transmitting), then in this scenario there was some interference caused by the PU in CU’s transmission. So, we considered SINR of the cognitive user to calculate the interference at CU link using [11]:

\[
\gamma_c(\eta) = \left( \frac{|h_{cc}|^2 h_{cc} P_{cmax}}{|h_{pc}|^2 h_{cc} P_p + N_0^2} \right) \]  \( (6.4) \)

where, \( h_{cc} \) and \( h_{pc} \) are the power gains on the links representing channel coefficients, \( P_{cmax} \) is the maximum transmitting power of CU and \( P_p \) is the transmitting power of PU and \( N_0 \) is AWGN.

### 6.2.3. OFDM Receiver

After transmission of signal through \( m \)-Nakagami multipath fading channel, the adding interference caused by PU, calculated according to (7.4) and noise (AWGN), the received signal is processed through the OFDM receiver for the recovery of source data. It consists of following blocks (see Fig. 6.1): i.e. serial to parallel, cyclic prefix removal, FFT, pilot removal, M-PSK demodulation, and finally parallel to serial conversion.

The guard interval, which was added in cyclic prefix process, is removed from the received signal. Then, using FFT, the received data symbols are converted back to frequency domain, which is represented by [34]:

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49 | Page
N is the number of point in FFT.

Then, the pilot bits (zeros), which were padded in transmission, are removed to recover the modulated symbols. Thus, the remaining part is the number of discrete signals lined up in parallel. The demodulation of received signal is performed according to the order of PSK which was used at the transmission end. The data recovered after demodulation was in parallel form, which is converted back to series form in order to recover the received data in its original form.

The demodulated received data is later compared with the original sent data in order to find the number of errors. BER is then calculated by dividing total number of errors with the total number of symbols.

6.3. Validation of CU transmission with OFDM:

We have implemented the OFDM transmission for CU, which is in use for emergency conditions transmissions. Such conditions require immediate transmission with good data rate to ensure reliability of communication. Interference caused by PU is also considered. Such interference to the CU occurs when PU is also transmitting.

The modulation scheme considered is QPSK. The results are shown in Fig. 7.2, which shows the BER comparison of transmission with and without OFDM scheme. As we can see there is not much difference between the BER of two transmission schemes, but the benefit of OFDM transmission is spectral efficiency or bandwidth efficiency. It is more resistant to multipath problem in high frequency wireless communication and high data rate can be achieved by using OFDM and we can move closer to Shannon capacity \( C \) by using OFDM transmission technique.

\[
C = B \times \log_2 (1 + \text{SNR})
\]

(6.6)

Where, \( B \) is the bandwidth of the channel.
We did some more work in OFDM transmission to show the results of OFDM transmission technique with different modulation schemes. As shown in Fig. 7.3, with the increase of modulation order the data rate increases but the number of errors also increase. For different size of FFT size i.e. 64 and 256, we can observe that the BER is increasing as shown in Fig. 7.4. As the size of FFT increases the data rate \( R_b \) increases supported by (7.7) but, at the cost of increase in BER [35].

\[
R_b = \frac{n_{FFT} \log_2(M)}{T_s}
\]  \hspace{1cm} (6.7)
Fig. 6.3. Comparison of OFDM transmission with different modulation schemes.

Fig. 6.4. OFDM transmission with different FFT sizes and modulation schemes.
CHAPTER 7. CONCLUSIONS AND FUTURE WORK

In this thesis we have proposed a novel approach of Takagi-Sugeno rule-based fuzzy power control strategy in CRN through which the spectrum utilization can be done opportunistically. The CU accesses the spectrum opportunistically and is dependent upon three factors:

1) PU SNR ratio.
2) Channel interference gain ratio.
3) Relative distance ratio.

The Takagi-Sugeno fuzzy based opportunistic spectrum sharing scenario is analyzed and validated over various multipath fading environments and two different propagation environments namely, with and without path-loss propagation environments.

For an opportunistic spectrum sharing CRN in without path-loss propagation environment we can conclude from our simulation results that the proposed Takagi-Sugeno FIS based power control strategy improves the BER when compared with other power control strategies. The improvement in BER is more when interference channel gain is high, compared to when it is low. Moreover, the errors in transmission are less in Ricean multipath fading channel environment compared to those in the Rayleigh fading environments. This is because in the Ricean fading environment there is a line of sight (LoS) component between the PUtil and PUrx, whereas in Rayleigh fading the LoS is absence and the signal strength towards the PUrx is weak. The absence of LoS component affects the BER adversely.

For an opportunistic spectrum sharing CRN in path-loss propagation environment we conclude from our simulation results that the proposed Takagi-Sugeno FIS based power control strategy improves the BER when compared with other power control strategies. BER at PUrx is significantly good when the relative distance between CUtil and PUrx is near. When relative distance between CUtil and PUrx is near, it means more interference by CUtil towards PUrx. With our proposed Takagi-Sugeno based power control strategy we have reduced BER in the most critical relative distance region. Moreover, as was the case in without path-loss propagation environment BER is minimized in Ricean multipath fading channel compared to Rayleigh fading channel.

We conclude that the Takagi-Sugeno FIS based power control strategy effectively assures the desired QoS on the PU link and the PU link will have a lower BER while the CU link may utilize the spectrum simultaneously.

In future this power control strategy can be implemented with ANFIS learning algorithms to achieve more accurate results and to minimize the error. Here in this thesis we consider a single pair of radio link i.e. one PU link and one CU link. In future this can be done with
multiple radio links. There is also scope to implement this power control strategy with partial CSI instead of full, through which the system will become simpler to implement.

From the simulation results of OFDM transmission technique at CU link in CRN, we observe that we get lesser errors when OFDM transmission is being used compared to when it is not being used. We observed the results for different modulation orders of phase shift keying (PSK). By increasing the modulation order we get more errors but at the same time as an inherent quality of increased modulation order, we get more data rate. So, based on our observations we can conclude that CU can access the spectrum simultaneously with PU in emergency conditions by using OFDM transmission technique.

In future, work can be done by using MIMO-OFDM in order to obtain better data rate and to reduce the total number of errors for better BER.
REFERENCES


