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Performance Enhancement of Cognitive Radio System by distributed interference compensation with MAC Layer Node Cooperation

By

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(065/MSI/614)

Thesis

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A thesis submitted in partial fulfillment of the requirements for the Degree of Master of Science in Information and Communication Engineering

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Recommendation

The undersigned certify that they have read and recommended to the Department of Electronics and Computer Engineering for acceptance, a thesis entitled "**Performance Enhancement of Cognitive Radio System by distributed interference compensation with MAC Layer Node Cooperation**", submitted by **Mr. Sapan Raj Aryal** in partial fulfillment of the requirement for the award of the degree of "**Master of Science in Information and Communication Engineering"**.

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The thesis entitled "**Performance Enhancement of Cognitive Radio System by distributed interference compensation with MAC Layer Node Cooperation**", submitted by **Mr. Sapan Raj Aryal** in partial fulfillment of the requirement for the award of the degree of **"Master of Science in Information and Communication Engineering"** has been accepted as a bonafide record of work independently carried out by him in the department.

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Abstract

The cognitive radio, built on a software-defined radio, is defined as an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding- by-building to learn from the environment and adapt to statistical variations in the input stimuli. Thus the two most popular research areas when it comes to cognitive radios are spectrum sensing and interference management and resource allocation. Spectrum sensing is the ability to find available frequencies/timeslots to transmit in. Research in the area of interference management and resource allocation consists of how to allocate power in channels to maximize capacity while minimizing interference to other users.

This thesis will explore the aspect of interference and resource management in cognitive radio, to see how this can be exploited to enhance the performance of a cognitive radio system. Especially the aspect of simultaneous transmission between secondary (cognitive) and primary users is of interest, as this could potentially enhance the performance of cognitive systems.

So, this thesis proposed an algorithm which utilizes Medium Access Control layer mechanisms for message exchange between secondary nodes that operate in license exempt spectrum bands, in order to achieve interference mitigation. Also, this thesis successfully implements Fuzzy Logic to Cognitive radio in order to deal with complex and vague environmental conditions.

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Abbreviations

CR	Cognitive Radio
SU	Secondary User
PU	Primary User
CRN	Cognitive Radio Network
PHY	Physical Layer
MAC	Media Access Control Layer
SINR	Signal to Interference & Noise Ratio
CRS	Cognitive Radio System
CPE	Customer Premise Equipment
UCS	Urgent Co-existence Situation
FCC	Federal Communications Commission
CBP	Coexistence Beacon Protocol
WRAN	Wireless Regional Area Network
SCW	Self Coexistence Window
DS/US	Down/Up Stream
PPD	Primary Protecting Device
SPD	Secondary Protecting Device

1 Introduction

National regulators are advancing regulations that allow license-exempt devices to operate on a non interfering basis within the portions of the TV spectrum that are not used for broadcasts or required to remain unused in order to protect broadcast stations from interference. The FCC in the United States of America has proposed to allow license-exempt devices to operate on a non-interfering basis within the portions of the TV spectrum that are not used for broadcasts or required to remain unused in order to protect broadcast stations from interference. It is expected that other regulatory bodies will take similar actions. Although the TV channels in these portions are not used for TV broadcasts, low-power, licensed devices, such as wireless microphones operated by broadcasters, do use these channels, and are entitled to protection by regulation to avoid disrupting incumbent services.

With relatively low levels of industrial noise and ionospheric reflections, reasonable antenna sizes, and good non-line-of-sight (NLOS) propagation characteristics, the TV broadcast bands in the high-VHF/low-UHF range are ideal for covering large areas in sparsely populated rural environments. Starting with a Notice of Inquiry by the U.S. FCC in December 2002 exploring the possibility of allowing access to the TV broadcast bands for license-exempt devices on a non interfering basis, and subsequently, a golden opportunity was created to develop a system capable of using these frequency bands on a non interfering basis to bring broadband access to rural areas.

So, it is viewed as a novel approach for improving the utilization of a precious natural resource: the radio electromagnetic spectrum. The cognitive radio, built on a software-defined radio, is defined as an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding- by-building to learn from the environment and adapt to statistical variations in the input stimuli, with two primary objectives in mind:-

(i) Highly reliable communication whenever and wherever needed.

(ii) Efficient utilization of the radio spectrum.

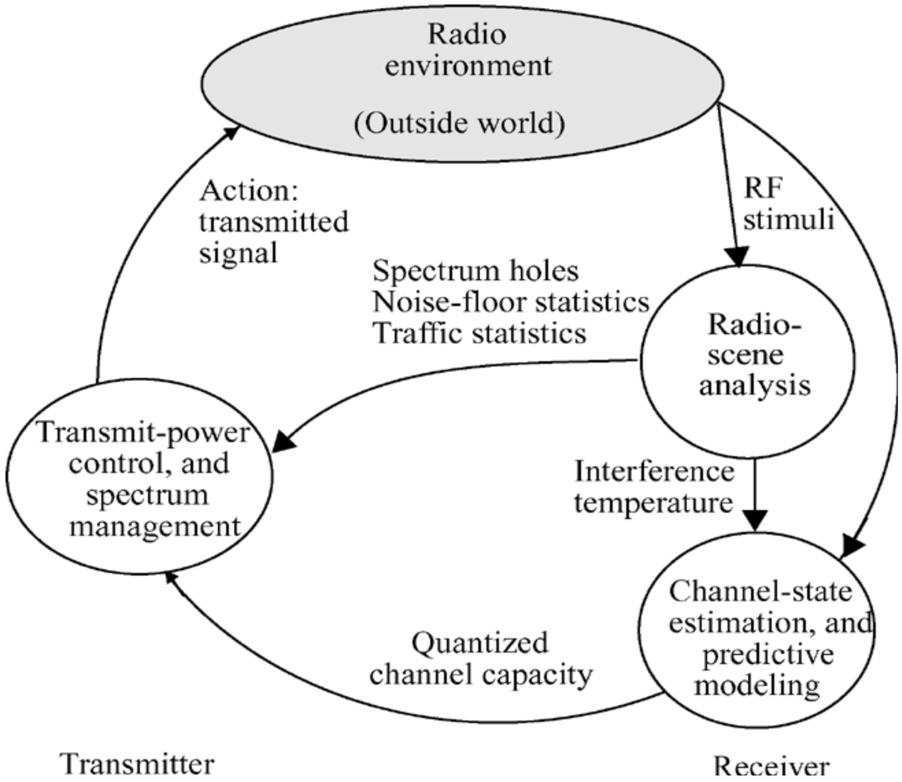

Figure 1-1Cognitive cycle for cognitive radio link

A cognitive network is a network composed of elements that, through learning and reasoning, dynamically adapt to varying network conditions in order to optimize end-to-end performance. In a cognitive network, decisions are made to meet the requirements of the network as a whole, rather than the individual network components.

Cognitive radio systems works as a part of cognitive network and have recently emerged as potential enablers of more efficient use of various resources in future wireless communication systems. Cognitive radio systems can obtain knowledge of their operational environment and internal state, adapt their operations to optimize performance, and learn from the results.

It is a new concept in wireless communications which aims to have more adaptive and aware communication devices which can make better use of available natural resources. One of the most important elements of the cognitive radio concept is the ability to measure, sense, learn, and be aware of parameters related to the radio channel characteristics, availability of spectrum and power, interference and noise temperature, radio's operational environments, user requirements and applications, available networks (infrastructures) and nodes, local policies and other operating restrictions as shown in figure 1-1. These tasks are divided between transmitter and receiver side. In transmitter side transmit power is controlled according to different scheduling algorithm in order to deal with interference. Having the capability of acquiring this awareness enables adaptation and helps realizing cognitive radio concept. Cognitive networks, for our purposes, are wireless networks which consist of two types of users:

Primary users: these wireless devices are the primary license-holders of the spectrum band of interest. In general, they have priority access to the spectrum, and subject to certain Quality of Service (QoS) constraints which must be guaranteed.

Secondary users: these users may access the spectrum which is licensed to the primary users. They are thus secondary users of the wireless spectrum, and are often envisioned to be cognitive radios. For the rest of this chapter, we will assume the secondary users are cognitive radios (and the primary users are not) and will use the terms interchangeably. These cognitive users employ their "cognitive" abilities to communicate while ensuring the communication of the primary users is kept at an acceptable level.

The proliferation of wireless systems has brought about a huge demand for more bandwidth. While the traditional approach of fixed spectrum allocation to authorized networks has lead to that there exists no vacant spectrum to meet these newly increasing requirements of high-rate data services. However, in recent studies especially by the Federal Communications Commission (FCC), some licensed spectrum is under-utilized, with reported utilization as low as 15% [1]. Cognitive radio (CR), which allows secondary users (SUs) to temporarily share the same frequency bands with primary users (PUs) under certain spectrum usage constraints, provides a promising approach to increase the availability of spectrum to new services and enhance the utilization of licensed frequency bands [2], [3].

Resource management in cognitive radio networks (CRNs) is more difficult than in conventional wireless systems. On one hand, PUs is typically protected by designing the secondary system subject to interference power constraints [4], [5]. Furthermore, SUs need to be able to effectively share the spectrum left over by the primary system [6], [7]. On the other hand, SUs' behavior should be transparent to PUs. That is, SUs may opportunistically access segments of the spectrum left vacant by the licensed PUs, and if a PU decides to access the primary channel, all SUs using the corresponding secondary channels must relinquish their transmissions immediately [8].

In general, these unfinished secondary transmissions may be either handed over to other available sub-channels to continue their transmissions or simply discarded. This is effective in protecting PUs from interference by SUs. However, in the studies mentioned above, quality of service (QoS) for the SUs, whose communications are subject to interruptions and disruptions, is rarely considered. It is therefore of interest to develop new scheduling concepts that enable more efficient usage of the spectrum while enhancing the QoS experienced by SUs, which is the main objective of this thesis.

1.1 Types of cognitive behavior

Cognitive behavior, or how the secondary cognitive users employ the primary spectrum, may be grouped into three categories which are explained below.

Interference avoiding behavior (spectrum interweave): the secondary users employ the primary spectrum without interfering with the primary users whatsoever. The primary and secondary signals may be thought of as being orthogonal to each other: they may access the spectrum in a Time- Division-Multiple-Access (TDMA) fashion, in a Frequency-Division-Multiple-Access

(FDMA) fashion, or in any fashion that ensures that the primary and secondary signals do not interfere with each other. The cognition required by the secondary users to accomplish this is knowledge of the spectral gaps (in for example time, frequency) of the primary system. The secondary users may then fill in these spectral gaps.

Interference controlling behavior (spectrum underlay): the secondary users transmit over the same spectrum as the primary users, but do so in a way that the interference seen by the primary users from the cognitive users is controlled to an acceptable level. This acceptable level is captured by primary QoS constraints. This is termed underlay as often the cognitive radios transmit in such a fashion that they appear to be noise under the primary signals. The cognition required is knowledge of the “acceptable levels” of interference at primary users in a cognitive user’s transmission range as well as knowledge of the effect of the cognitive transmission at the primary receiver.

Interference mitigating behavior (spectrum overlay): the secondary users transmit over the same spectrum as the primary users but in addition to knowledge of the channels between primary and secondary users (nature), the cognitive nodes have additional information about the primary system and its operation.

1.2 Spectrum Sensing

Spectrum sensing involves making observations of the radio frequency (RF) spectrum and reporting on the availability of unused spectrum for use by the WRAN. Each station in an 802.22 network is required to perform spectrum sensing. The 802.22 network consists of a base station and a number of client stations, referred to as customer premise equipment (CPE). The base station controls when sensing is performed and the results of all spectrum sensing are reported to the base station. The final decision as to the availability of a television channel is made by the base station. The base station can rely on spectrum sensing results, geolocation information and auxiliary information provided by the network manager, to make its final decision about channel availability. Since all sensing results are reported to the base station one can think of spectrum sensing as a signal processing and reporting function. The draft standard does not mandate use of a specific signal processing technique; instead it mandates specific sensing performance and a standardized reporting structure.

1.3 Deployment scenarios

CRSs can be used to improve the efficiency of the use of various resources in wireless communication systems. Spectrum has been identified as a scarce resource, and its efficient use is of utmost importance. In terms of spectrum, various deployment scenarios are envisaged for CRSs, depending on the types of spectrum bands considered. Here, four deployment scenarios are identified:

a. licensed spectrum
b. unlicensed spectrum
c. primary-secondary setting
d. bands for CRS on which they coexist.

In the first scenario, it is envisaged that CR techniques will be deployed on licensed spectrum bands by the owner of the spectrum to improve the efficiency of its spectrum use, e.g., to accommodate more traffic on the same band. In this case, CR features could be introduced gradually into future developments of current systems that have sole rights to use the given spectrum. Examples of this include mobile communication systems in which operators could deploy home base stations on the same spectrum bands as their macro cells to accommodate more traffic in the same area. This kind of CR operation does not require any regulatory considerations as it is an internal system issue.

In the second scenario, CR techniques could be employed to improve spectrum use of unlicensed bands such as ISM bands. By using CR techniques, more data could be accumulated on the same spectrum band. Different systems could use the

ISM band as an alternative way for, e.g., balancing the load at peak hours by offloading delay-tolerant data to ISM bands with the aid of CR techniques. The current systems using the ISM bands could be enhanced with CR features to improve their performance.

In the third scenario, CRSs could make opportunistic use of temporarily and locally available spectrum that belongs to higher priority systems. Here, the prerequisite for allowing this kind of operation is that the CRS is not allowed to cause harmful interference to the higher priority systems.

In the fourth scenario, different CRSs could coexist with each other on the same spectrum bands following some set of coexistence rules. This is similar to ISM bands in which different systems share the same spectrum but the spectrum use is predicted to be much more efficient, as it has been the major design aim.

In all of these scenarios, the key topic is the coexistence of several systems on a given spectrum band. The systems can have similar or different access technologies, and equal or unequal priority. In any case, a key challenge for the development of CRSs is the development of coexistence techniques and etiquette to optimize resource use.

1.4 Objectives

Cognitive Radio technology has been invoked to provide a solution for frequency management in future heterogeneous wireless networks. The aspects of spectrum management have already been examined in several studies. In order to maintain a holistic view of cognitive networks and the relating issues, however, other aspects are also needed. One of the key issues is to control and/or limit the spatial domain of a tagged wireless network. Generally speaking, limiting the interference caused by SUs is an important issue.

So, the objective of this thesis is to develop advance scheme for interference management of Cognitive radio by:-

i. Analysis of MAC layer message exchange mechanism and calculation of interference arise when a transmitter sets its power level by considering not only its own SINR information, but also the negative impact in utility for other users caused from the interference that will come as a side effect of the increase in transmission power of that particular user.

ii. To design an improved algorithm utilizing MAC layer mechanisms for message exchange (for exchange of interference prices, SINR etc) between the secondary nodes in order to achieve interference mitigation.

iii. To use Fuzzy Logic in order to define the term α and its variation in value due to different parameters (e.g. no of users, mobility, types of users, spectrum etc)

1.5 Scope

As wireless communication systems are making the transition from wireless telephony to interactive Internet data and multi-media types of applications, the desire for higher data rate transmission is increasing tremendously. As more and more devices go wireless, future technologies will face spectral crowding and coexistence of wireless devices will be a major issue. Considering the limited bandwidth availability, accommodating the demand for higher capacity and data rates is a challenging task, requiring innovative technologies that can offer new ways of exploiting the available radio spectrum. Cognitive radio offers a solution to the spectral crowding problem by introducing the opportunistic usage of frequency bands that are not heavily occupied by licensed users.

So, this thesis focuses on Cognitive Radio MAC layer mechanism which is a major and important part of any wireless system in order to enhance the performance of Cognitive Radio system. Also, the result come from this thesis will not be limited to Cognitive Radio only. In MAC layer this thesis gives focus on interference mitigation which is always an important part for any wireless systems. The algorithm designed in this thesis could play a vital role to enhance performance of Cognitive Radio System.

Also in this thesis, a decision making process in cognitive radio is analyzed using fuzzy logic system, in which secondary user can use the spectrum effectively. In complex and dynamic operational environments, future cognitive radio systems will need sophisticated decision making and environment awareness techniques that are capable of handling multidimensional, conflicting and usually non-predictable decision making problems where optimal solutions cannot be necessarily found. The results indicate that fuzzy logic can be used in cooperative spectrum sensing to provide additional flexibility to existing combining methods.

1.6 Application

The algorithm designed by this thesis could be applied on Cognitive Radio for its overall performance enhancement and according to the result obtained some part of the algorithm could be applied to different wireless systems which employ MAC layer in order to schedule different services to different users with minimal interference.

Currently wireless communication systems have been used for many kinds of applications and have become a gateway with next generation super broadband wired network including the Internet and users. Currently many standardization bodies have done standardization for broadband wireless communication systems. The transmission speed has become more than several tens Mbps for broadband wireless access (BWA) system, more than 100 Mbps for wireless local area network (WLAN), and more than 1 Gbps for wireless personal area network (WPAN), respectively and the required transmission bandwidth also has been increasing. So to secure bandwidth for future standardized wireless systems is one of urgent topics considered. One of solutions is to use Cognitive Radio (CR) efficiently which this thesis intends to implement.

The huge increase in user demand for wireless communication and respective application performance requirements made wireless environment very complex and difficult to manage by humans. Hence, Cognitive Radio (CR) concept is becoming a need for future wireless networks since it enables the deployment of self-organizing networks that require the minimum of human intervention.

The frequently advocated applications of cognitive radio are as follows:-

i. Improving spectrum utilization & efficiency
ii. Improving link reliability
iii. Less expensive radios
iv. Advanced network topologies and automated radio resource management

2 Literature Review

2.1 History

Traditionally wireless networks have been operating based on fixed spectrum assignment policies. According to these policies, licensees are granted the rights for exclusive use of frequency bands on a long term basis over vast geographical areas. Because of this static allocation of the available spectrum resources, several portions of the licensed bands are unused or underused at many times and/or locations. On the other hand, several recent technologies - such as IEEE 802.11, Bluetooth, ZigBee, and to some extent WiMAX - that operate in the Industrial, Scientific and Medical (ISM) unlicensed bands, have experienced a huge success and proliferation. As a consequence, the wireless spectrum they are accessing - especially the 2.4 GHz ISM band - has become overcrowded. In an effort to provide further spectrum resources for these technologies, as well as to allow potential development of alternative and innovative ones, it has recently been proposed to allow unlicensed devices, called secondary users, to access those licensed spectrum resources that are unused or sporadically used by their legitimate owners, called primary users. This approach is normally referred to as Dynamic Spectrum Access and the technology that enables secondary users to find and opportunistically exploit unused or underused spectrum bands is called Cognitive Radio.

The concepts of Dynamic Spectrum Access and Cognitive Radio have attracted significant attention by the research community since the recent achievements in the field of Software Defined Radios. These achievements provided the required technological background for the realization of low-power Cognitive Radio transceivers which are able to change their transmitter parameters (operating frequency, modulation and transmission power and communication technology) as a response to changes in the wireless environment. [9]

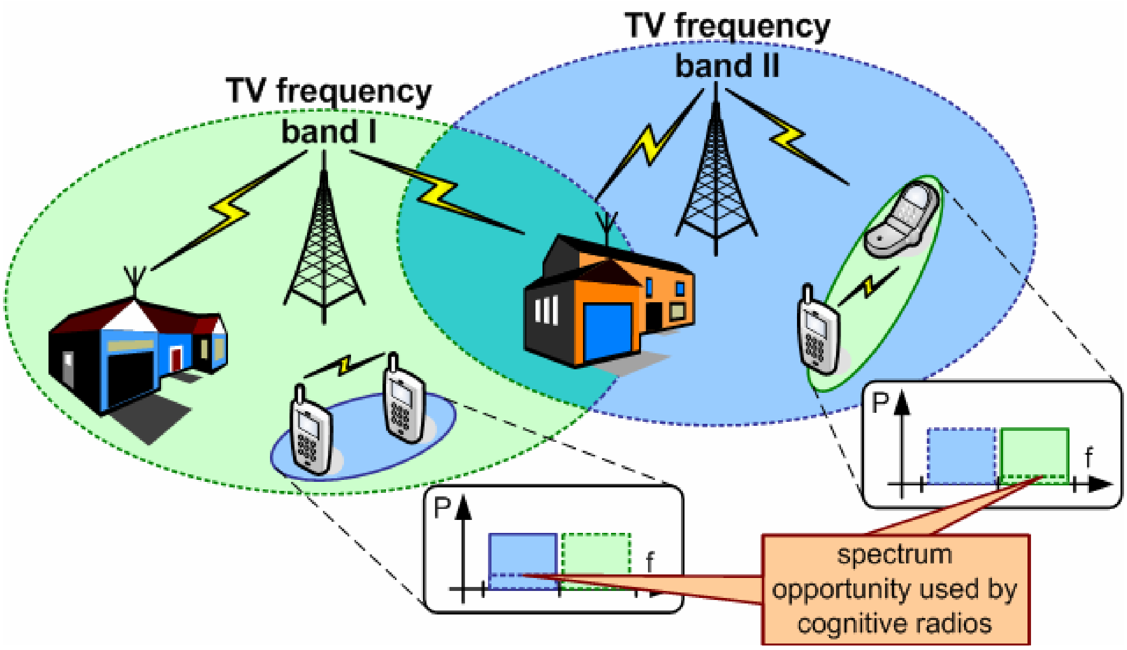

Figure 2-1 Cognitive radios operating in frequency bands of TV and radio broadcasts [10]

As shown on above figure, at different locations the cognitive radios identify different frequencies as unused and regard them as spectrum opportunities. Cognitive Radio Networks have consequently emerged as viable architectural solutions to alleviate the spectrum shortage problem faced by traditional wireless networks by exploiting the existing wireless spectrum opportunistically. However, when designing such solutions it is necessary to consider that, besides the strict requirements imposed by the opportunistic coexistence with Primary Users, Cognitive Radios may also have to deal with other malicious/selfish (adversary) Cognitive Radios that aim at denying/gaining access to the available spectrum resources with no regard to fairness or other behavioral etiquettes. [10]

Hence, in order to opportunistically access the licensed spectrum in a non interfering manner and, at the same time, guarantee their own communications in the face of malicious attacks, Cognitive Radios must rely on mechanisms such as cooperation, learning and negotiation. By observing the wireless environment, exchanging information, and evaluating different actions, Cognitive Radios can take the appropriate countermeasures to guarantee the continuity of their communications and the integrity of Primary Users' activity.

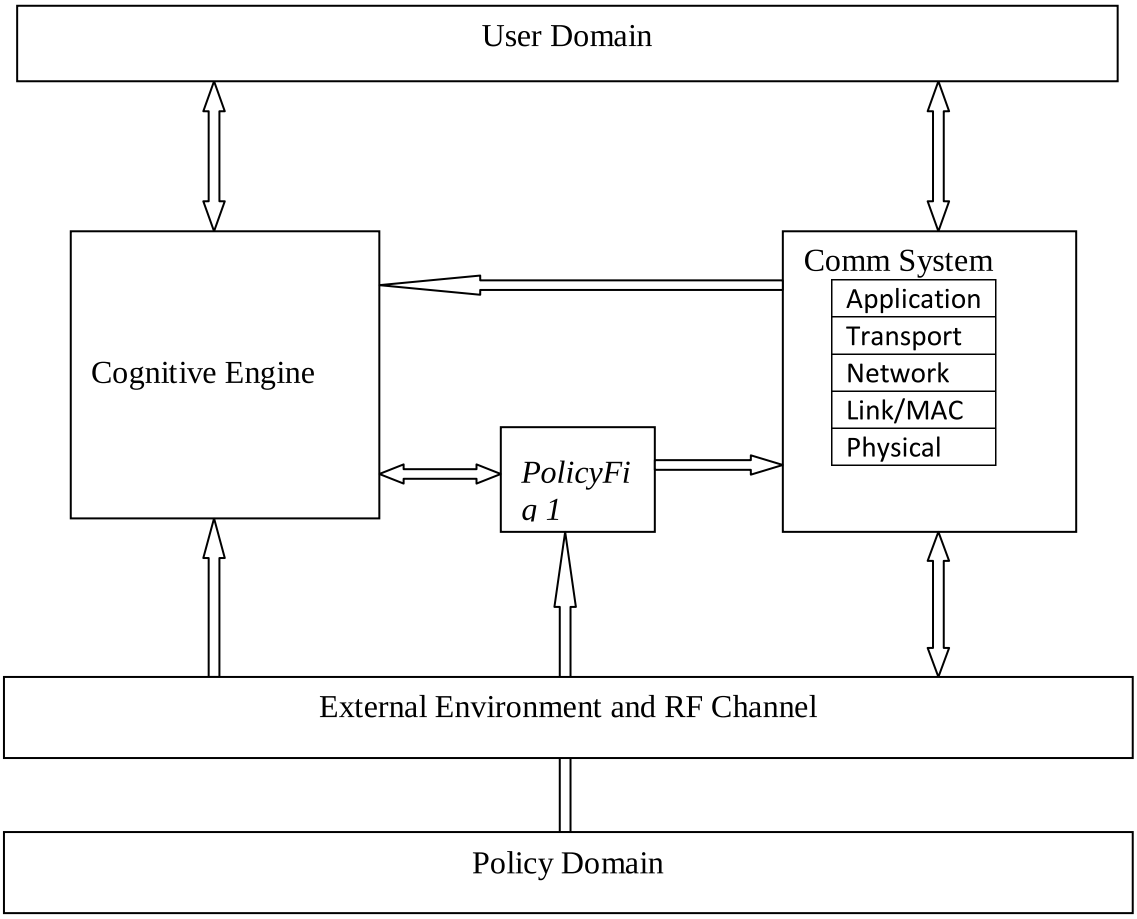

Figure 2-2Generic Cognitive Radio Architecture [11]

Figure above presents a generic architecture for a cognitive radio. The cognitive engine is a separate system within the total solution, which relies on information from the user, radio, and policy domains for instructions on how to best control the communication system. This structure works well as a generalized architecture as it makes no recommendations about how the cognitive engine (and therefore the rest of the cognitive radio) should behave while still mapping the interactions of the rest of the systems. The communications system itself is shown as a simplified protocol stack, again showing the independence of the cognitive engine from the overall system.

In Figure shown above, there are three input domains that concern the cognitive radio. The user domain tells the cognitive engine performance requirements of services and applications. Service and application requirements are related to the quality of service measures of a communications system. As each application requires different QoS concepts like speed and latency, this domain sets the performance goals of the radio.

The external environment and RF channel provide environmental context to the radio's transmission and reception behavior. Different propagation environments cause changes in performance of waveforms and optimal receiver architectures. A heavy multipath environment requires a more complex receiver than simple line of sight only or log-normal models. The external radio environment also plays a significant role in performance and adaptation. This environmental information helps provide optimization boundaries on the decision making and waveform development.

Finally, the policy domain restricts the system to work within the boundaries and limitations set by the regulatory bodies as interpreted by the policy engine. The policy environment might determine a maximum amount of power a radio can use in a given spectrum or other spectrum rights as compared with other users like the recent proposal by the FCC for spectrum reuse in the 700 MHz band. Important regulatory action in the US includes the report and order on cognitive radio, recent action against open source software for software radios, and the regulations on Part 15 devices for use in unlicensed spectrum. The rules from the FCC and other regulatory bodies impose constraints on the optimization space with respect to spectrum use and power. [11]

2.2 IEEE and Cognitive Radio

The IEEE 802.22 working group is developing a standard for a Cognitive Wireless Regional Area Network (WRAN) that will operate in unused television channels and provide fixed wireless access services. The WRAN is based on an orthogonal frequency division multiple access (OFDMA) PHY layer. The IEEE 802 community is currently developing two standards that directly relate to cognitive radio – (802.22 and 802.11h)

[1] 802.22

There are three applications typically discussed for coexistence with initial trial deployments of cognitive radios: television, microwave point-to-point links, and land mobile radio. Each of these applications has been shown to dramatically underutilize spectrum on average. However, only television signals have the advantage of incumbent signals that are easy to detect (as opposed to a microwave point-to-point links) and not involved in life-critical applications (as would be the case for many land mobile radio systems).

Throughout its history, the UHF bands were under-allocated as regulators underestimated the cost-effectiveness of establishing new TV towers in these bands. It was not until the advent of cable TV that smaller TV stations were capable of cost-effective operation. Now with the introduction of HDTV technology, regulators in the US plan to force a nation-wide switch to this more efficient modulation by 2009 accompanied by a completion of a de-allocation from analog TV of 108 MHz of high quality spectrum. With these bands in mind, the 802.22 working group is pursuing the development of a waveform intended to provide high bandwidth access in rural areas using cognitive radio techniques. In a report presented at DySPAN, it is stated that the 802.22 standard intends to achieve spectral efficiencies of up to 3 bits/sec/Hz corresponding to peak download rates at coverage edge at 1.5 Mbps. Simultaneously, the 802.22 system hopes to achieve up to 100 km in coverage. While the PHY and MAC are still under development, the MAC will provide the cognitive capabilities as it manages access to the physical medium, responsible for quickly vacating a channel as needed. The standard under development has specified the following thresholds for vacating a channel for the following signals:

i. Digital TV: - 116 dBm over a 6 MHz channel

ii. Analog TV: - 94 dBm at the peak of the NTSC (National Television System Committee) picture carrier
iii. Wireless microphone: -107 dBm in a 200 kHz bandwidth.

An IEEE 802.22.1 device comprises the physical layer (PHY), which contains the radio frequency (RF) transceiver along with its low-level control mechanism, and the medium access control sub layer (MAC), which provides access to the physical channel for the purpose of transferring information. The upper layers provide services such as selecting an operating channel, deciding on an operating mode (i.e., PPD or SPD), starting and stopping beacon frame transmissions, processing incoming beacon frame information, aggregating data, and handling security errors.

In this standard all transmissions are broadcast. Transmitted data may be received and processed by any device in the area, including WRAN devices and other devices compliant with IEEE Std 802.22.1. Two types of data transfer transactions exist for a device compliant with IEEE Std 802.22.1. The first type is the data transfer from the PPD to an SPD, in which the PPD transmits the data. The second type is the data transfer from an SPD to the PPD, in which the SPD transmits the data.

The beaconing device in this standard at time of manufacture shall be assigned a unique MAC address that will be embedded into its hardware. This MAC address shall resist tampering, i.e., manipulation and change, by any means (e.g., physical, electrical and software). The beaconing device alone will not be able to generat beacon frames with legitimate signatures, so the end user will need to get a license to operate it. The end user will need to go to a licensing authority (e.g., an industry consortium or an appropriate regulatory body) and obtain a license for that particular beaconing device (identified via its MAC address) that may be valid for a number of years. This licensing authority would be responsible for provisioning a private key and a publickey certificate to the beaconing device. It is important that the private key remain a secret, so a good approach would be to provision this private key embedded in a tamper-resistant device such as a secure smart card. The end user would get this smart card, insert it into the beaconing device, and the smart card would be used to create the beacon frame signatures. If a smart card for a beaconing device was ever lost, stolen, or decommissioned, the end user could report this to the licensing authority so that a blacklist of devices could be maintained and periodically queried by receiving devices.

[2] 802.11h

Unlike 802.22, 802.11h is not formulated as a cognitive radio standard. However, the World Wireless Research Forum has noted that a key portion of the 802.11h protocol – dynamic frequency selection – has been termed a “cognitive function”. [12] The IEEE has expressed significant interest in cognitive radio. As a body, IEEE submitted the proposed definition to the FCC noted in Section 2. To allow for more focused development, the IEEE has started the IEEE 1900 group to study the issue of cognitive radio.

The IEEE Communications Society held its first Dynamic Spectrum Access Networks (DySPAN) meeting in November 2005 with a primary focus on discussion of requirement of cognitive radio, including the following:

i. technologies needed to implement cognitive radio ranging from sensing, analysis of interactions, and advanced networking technologies
ii. appropriate regulatory approaches for cognitive radio
iii. potential market opportunities for cognitive radio
iv. trial implementations of cognitive radio systems.

2.3 MAC Layer Description

The function of MAC layer along with other layers is shown in figure below.

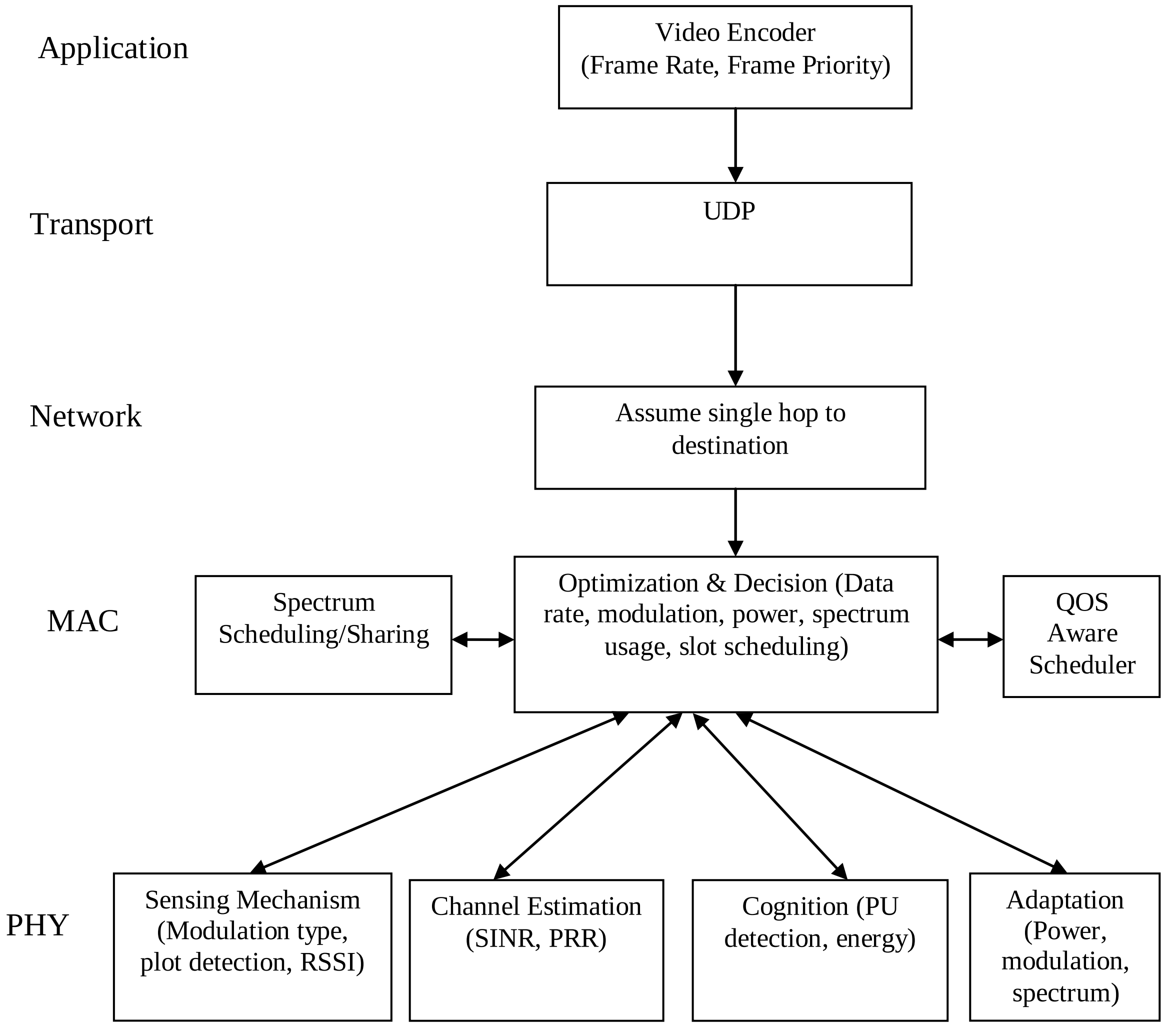

Figure 2-3 Function of different layer in IEEE 802.22 [13]

Presently, in Cognitive Radio, many researches have been made on both MAC and PHY layers which cooperate with each other to enhance spectrum efficiency by adaptively adjusting the data rate, transmission power, modulation level, spectrum usage and slot scheduling. Apart from that, MAC layer also receives information from the APP layer.

MAC layer optimize and decide the best action to suit requirements set by the APP layer and also varying channel conditions. Reconfiguration will be done by the adaptation module at the PHY layer. While, appropriate co-existence technique will be handled by spectrum sharing module in the MAC layer. In addition, APP layer requirements will be executed according to optimum Quality of Service (QoS).

MAC layer perform sensing in either in-band or out-of-band measurements. Both of these are further divided into

– Fast sensing (under 1ms per channel)

– Fine sensing (about 25 ms per channel) is done if the BS feels that more detailed sensing is needed.

The MAC Protocol Data Unit (MPDU) is the smallest unit of transmission/reception in the CMAC. It is comprised of the MAC header, the MAC payload and the CRC (cyclic redundancy checking) field. There are two types of MPDUs. The two types are distinguished by their respective MAC headers, described below:

General MAC header: This header is used for intra-cell general MPDUs. It is used in general MPDUs that contain either higher-layer data traffic or management messages in their payload.

Beacon MAC header: This header is used for inter- cell beacons. An inter-cell beacon only carries beacon Information Elements (IEs) in its payload.

In IEEE 802.22, BSs and CPEs exchange inter-cell control messages using *inter-cell beacons*. Inter-cell beacons play a vital role in incumbent coexistence and self-coexistence mechanisms. Two types of inter-cell beacons are defined in the standard:

BS beacons: These beacons are used to provide in- formation about the BS's traffic schedule, the current operation channel of the cell, etc.

CPE beacons: These beacons are used to provide in- formation about a CPE's current cell of attachment as well as information on the traffic flows between the CPE and its BS.

The IEEE 802.22 MAC provides mechanisms for flexible and efficient data transmission, and supports cognitive capabilities for both reliable protection of incumbent services in the TV band and self-coexistence among 802.22 systems. The IEEE 802.22 MAC is applicable to any region in the world and does not require country-specific parameter sets. The function and structure of MAC layer are described below:-

(i) Data Transmission

An IEEE 802.22 system is a point-to-multipoint network in which a central BS controls the medium access of a number of associated CPE units for broadband wireless access applications. In the downstream direction data are scheduled over consecutive MAC slots, while in the upstream direction the channel capacity is shared by the CPE units based on a demand-assigned multiple access (DAMA) scheduling scheme. The concept of a connection plays a key role in the 802.22 MAC. The mapping of all services to connections, as performed in the convergence sub layer, facilitates bandwidth allocation, QoS and traffic parameter association, and data delivery between the corresponding convergences sub layers. While each 802.22 station has a 48-bit universal MAC address that serves as the station identification, the 12-bit connection identifications (CIDs) are primarily used for data transmissions within an 802.22 system.

(ii) Super frame and Frame structure

There are primarily two structures: A Super frame followed by sub-frames. As depicted in Fig. 4 below, the super frame will have an SCH (Super frame Control Header) and a preamble. These will be sent by the BS in every channel that it's possible to transmit and not cause interference. When a CPE is turned on, it will sense the spectrum, find out which channels are available and will receive all the needed information to attach to the BS. The 802.22 MAC employs a super frame structure in order to efficiently manage data communication and facilitate a number of cognitive functions for licensed incumbent protection, WRAN synchronization, and self-coexistence.

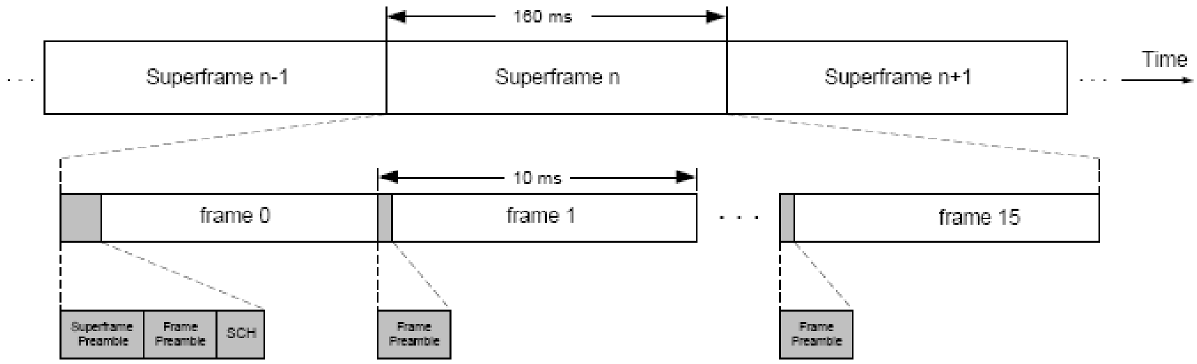

Figure 2-4 Super-frame structure of Cognitive Radio (IEEE 802.22)[14]

As shown in figure 2-4, each MAC frame, with a 10 ms frame size, comprises a downstream sub frame and an upstream sub frame with an adaptive boundary in between. While the DS sub frame only contains a single PHY protocol data unit (PDU), the US sub frame may have a number of PHY PDUs scheduled from different CPE units, as well as contention intervals for initialization, bandwidth request, UCS notification, and self-coexistence.

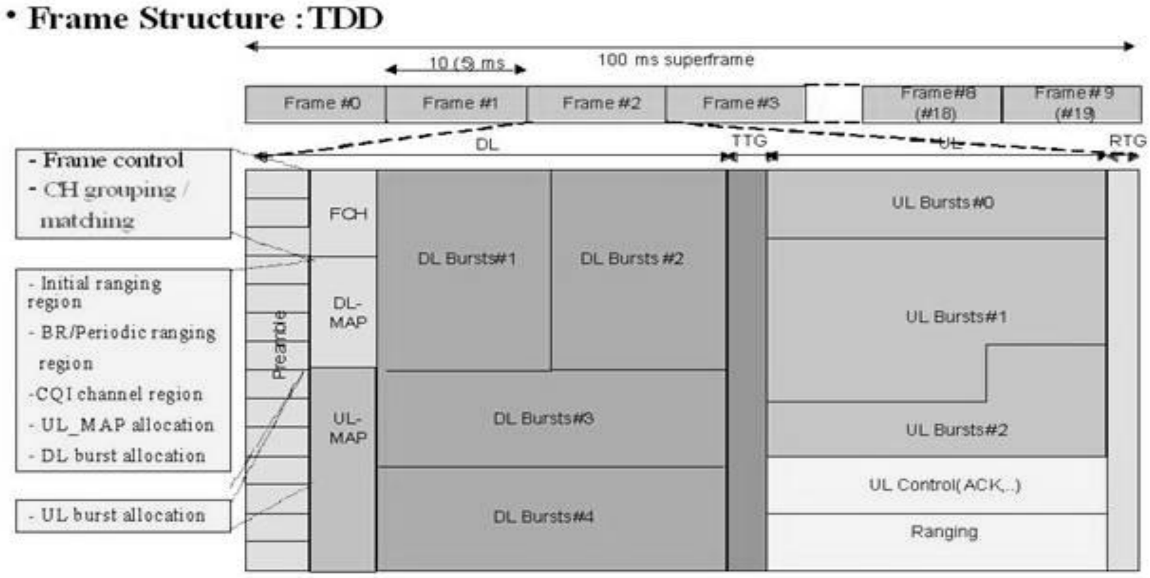

Figure 2-5 Frame structure of Cognitive Radio (IEEE 802.22) [14]

Because the DS traffic for CPE located far from the BS can be scheduled early in the DS sub frame, such a data layout allows the MAC to absorb the round-trip delay for large distances. In order to absorb the propagation delay for a distance of up to 100 km, a time buffer of one symbol is included before and after the self coexistence window. Similarly, in order to absorb the round-trip delay in the initial ranging process, a time buffer of two symbols is included before and after the ranging burst.

(iii) Network Entry and Initialization

Unlike other existing wireless access technologies, the network entry and initialization procedures in the 802.22 MAC not only define processes such as synchronization, ranging, capacity negotiation, authorization, registration, and connection setup, but also explicitly specify the operations of geolocation, channel database access, initial spectrum sensing, internetwork synchronization, and discovery. BSs and CPE will be required to use satellite based geolocation technology, which will also facilitate synchronization among neighboring networks by providing a global time source. The list of available TV channels is obtained by referring to an up-to-date TV channel usage database and augmented by spectrum sensing performed both by BSs and CPE.

(iv) Self Co-existence

In a typical deployment scenario, multiple 802.22 systems may operate in the same vicinity. Mutual interference among these collocated WRAN systems due to co-channel operation could degrade the system performance significantly. To address this issue, the 802.22 MAC specifies a self-coexistence mechanism based on the CBP and consisting of spectrum sharing schemes that address different coexistence needs in a coherent manner.

The CBP is a communication protocol based on beacon transmissions among the coexisting WRAN cells. A CBP packet, delivered in the operating channel through the beacon transmission in a dedicated self-coexistence window (SCW) at the end of some frames, comprises a preamble, an SCH, and a CBP MAC PDU. Its purpose is to convey all necessary information across TV channels to facilitate network discovery, coordination, and spectrum sharing. Note that the beacon transmissions which deliver CBP packets are integral to IEEE 802.22 OFDMA transmissions and therefore different from the IEEE 802.22.1 beacon transmissions that need to be transmitted continuously by the 802.22.1 devices to signal the presence of licensed wireless microphone operations. During a SCW that is synchronized across the TV channels of interest, a WRAN station (BS or CPE) can either transmit CBP packets on its operating channel or receive CBP packets on any channel. For efficient intercell communications, each WRAN system is required to maintain a minimum repeating pattern of SCWs in transmit (or active) mode, although the SCWs can also be scheduled on an on-demand basis. Each WRAN system can reserve its own SCWs on the operating channel for exclusive CBP transmission or share the active SCWs with other co-channel neighbors through contention based access. [14]

2.4 Interference Management

The key feature that characterizes a cognitive radio is its ability to sense its surrounding spectra, because without this feature it would be nothing but a normal radio. Most research in the area of cognitive radio has also been focused on this part by developing algorithms that detect available spectra. But an important aspect of cognitive radios that need to be studied if cognitive radios are going to go commercial is the case of many cognitive radios in the same environment.

Multi channel wireless networks enable multiple parallel transmissions on orthogonal frequency bands, leading to a more efficient utilization of spectrum resources than their single channel counterparts. The use of multiple channels provides increased throughput and robustness to interference generated by other users. As a consequence, the use of multiple parallel channels is expected to bring significant benefits to wireless ad hoc, sensor and cognitive radio networks. In such a multi channel system, nodes need to coordinate in order to efficiently share the available wireless resources.

Interference Management is a fundamental problem in wireless networks. A basic technique for this is to control the nodes' transmit powers. Research in the area of interference management and resource allocation consists of how to allocate power in channels to maximize capacity while minimizing interference to other users. One way is of course to transmit when no one else is using that frequency/timeslot, but given a scenario where there are multiple cognitive users in the same environment this may not be possible and certainly not the way to maximize capacity.

Although extensive research has been done in the area of cognitive radio since the concept first appeared in 1999, one question was put forth in 2007. How can we allow a cognitive user to transmit simultaneously with the primary user as long as the level of interference with the primary user remains within an acceptable range? This field of study will be referred to as interference management. And although many studies have been published in this area, such as the research has been very one-dimensional. The research has been done, almost exclusively, with regard to an environment with one primary and one cognitive user and most studies focus only on the theoretical performance limits in this environment.

Power allocation strategies in distributed networks have been studied for a long time. The difference between power allocation strategies in distributed networks, such as sensor networks, and cognitive networks, is that in sensor networks, the nodes either cooperate fully or they do not. In cognitive networks, the cognitive radios have the ability to sense their environment so that even though they do not cooperate, they still can make intelligent decisions to optimize performance.

A practical cognitive system would not only have to consider power allocation among multiple cognitive users, but would also have to consider the possibility of primary users occupying different frequency bands. In this case, schemes to guarantee primary user QoS under simultaneous transmission is of importance.

In order to show the algorithm proposed in this thesis is an improved one some previous works should also be mentioned. Initially algorithm implementing in a distributed manner with CRs negotiating their best transmission powers and spectrum was proposed. Then a distributed approach to spectrum allocation that starts from the previous spectrum assignment and performs a limited number of computations to adapt to recent topology changes is considered. After that a group based coordination scheme, and distributed group setup and maintenance algorithms where users select coordination channels adaptively are proposed. Finally an algorithm that allows for transmission power and transmission frequencies to be chosen simultaneously by Cognitive Radios competing communicating over a frequency spectrum is proposed.

2.5 Fuzzy Logic

2.5.1 Introduction

The concept of Fuzzy Logic (FL) was conceived at the beginning of the 70s by Lotfi Zadeh, a professor at the University of California at Berkley, and presented not as a control methodology, but as a way of processing data by allowing partial set membership rather than crisp set membership or non-membership. This approach to set theory was not applied to control systems until the 70's due to insufficient small-computer capability prior to that time. Professor Zadeh reasoned that people do not require precise, numerical information input, and yet they are capable of highly adaptive control. If feedback controllers could be programmed to accept noisy, imprecise input, they would be much more effective and perhaps easier to implement.

FL is a problem-solving control system methodology that lends itself to implementation in systems ranging from simple, small, embedded micro-controllers to large, networked, multi-channel PC or workstation-based data acquisition and control systems. It can be implemented in hardware, software, or a combination of both. FL provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information. FL's approach to control problems mimics how a person would make decisions, only much faster. FL is also a convenient way to map input space to output space. It is a multivalued logic that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low etc.

Fuzzy Sets - In fuzzy logic, each object x can be labeled by a linguistic term, where a linguistic term is a word such as “small”, “medium”, “large”, etc so that *x* is defined as a linguistic variable. Each linguistic variable is associated with a term *F(x)*, which is the set of names of linguistic values of *x*. Each element in *F(x)* is a fuzzy set.

Membership functions – The membership function is a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are processed, define functional overlap between inputs, and ultimately determines an output response. The rules use the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output conclusion.

FL offers several unique features that make it a particularly good choice for many control problems.

(i) It is inherently robust since it does not require precise, noise-free inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed. The output control is a smooth control function despite a wide range of input variations.

(ii) Since the FL controller processes user-defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.

(iii) FL is not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute rate-of-change parameters in order for it to be implemented. Any sensor data that provides some indication of a system's actions and reactions is sufficient. This allows the sensors to be inexpensive and imprecise thus keeping the overall system cost and complexity low.

(iv) Because of the rule-based operation, any reasonable number of inputs can be processed (1-8 or more) and numerous outputs (1-4 or more) generated.

(v) FL can control nonlinear systems that would be difficult or impossible to model mathematically.

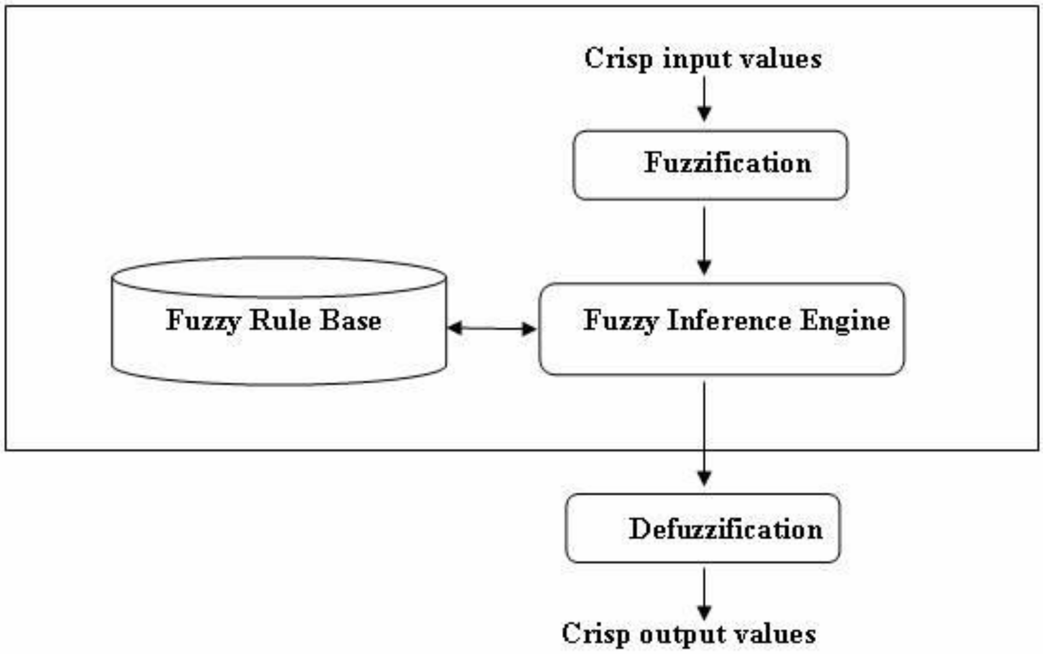

Figure 2-6 Basic diagram of Fuzzy Logic System

2.5.2 Fuzzy Logic in Cognitive Radio

The design of future Cognitive Radio System (CRS) will face new challenges as compared to traditional cellular systems. The operational environment is heterogeneous consisting of several access technologies with diverse sets of terminals with the common goal of providing high user satisfaction. Distributed network architectures will appear alongside with centralized structures. The conventional network design by considering only one isolated network will no longer be sufficient. Indeed, joint resource management across networks will be required for more efficient use of distributed resources such as spectrum. The decision making problem in radio resource management of CRS will have more degrees of freedom due to the increased dimensionality and the dynamic operational environment. As a result of the conflicting requirements and restrictions an engineering compromise needs to be sought, particularly for the decision making process. In fact, in the complex environment with compressed time scales, optimal solutions cannot be found and the design challenge will be to find good enough solutions. Thus in the envisaged scenario for CRS, novel design techniques are needed. [15]

Fuzzy logic is an attractive technique particularly in cases where target problems are difficult to model with traditional mathematical methods, but are at the same time easier for human people to understand.

Fuzzy logic was first introduced by L.A. Zadeh, who studied methods to extend binary logic to cover more general inguistic notation. In general, fuzzy logic and fuzzy decision making is divided into three consecutive phases which are:-

i. Fuzzification:- The input variables are fuzzified using predefined membership functions (MBF). Unlike in binary logic where only 0 and 1 are accepted, also numbers between 0 and 1 are used in fuzzy logic. This is accomplished with the MBFs to which the input variables are compared. The output of the fuzzification is a set of fuzzy numbers.
ii. Fuzzy Reasoning:- Fuzzy numbers are fed into a predefined rulebase that presents the relations of the input and output variables with IF-THEN clauses. The output of the fuzzy reasoning is a fuzzy variable that is composed of the outputs of the THEN clauses.
iii. Defuzzification:- The output of the fuzzy reasoning is changed into a non-fuzzy number that represents the actual output of the system, e.g. control action.

3 Algorithm

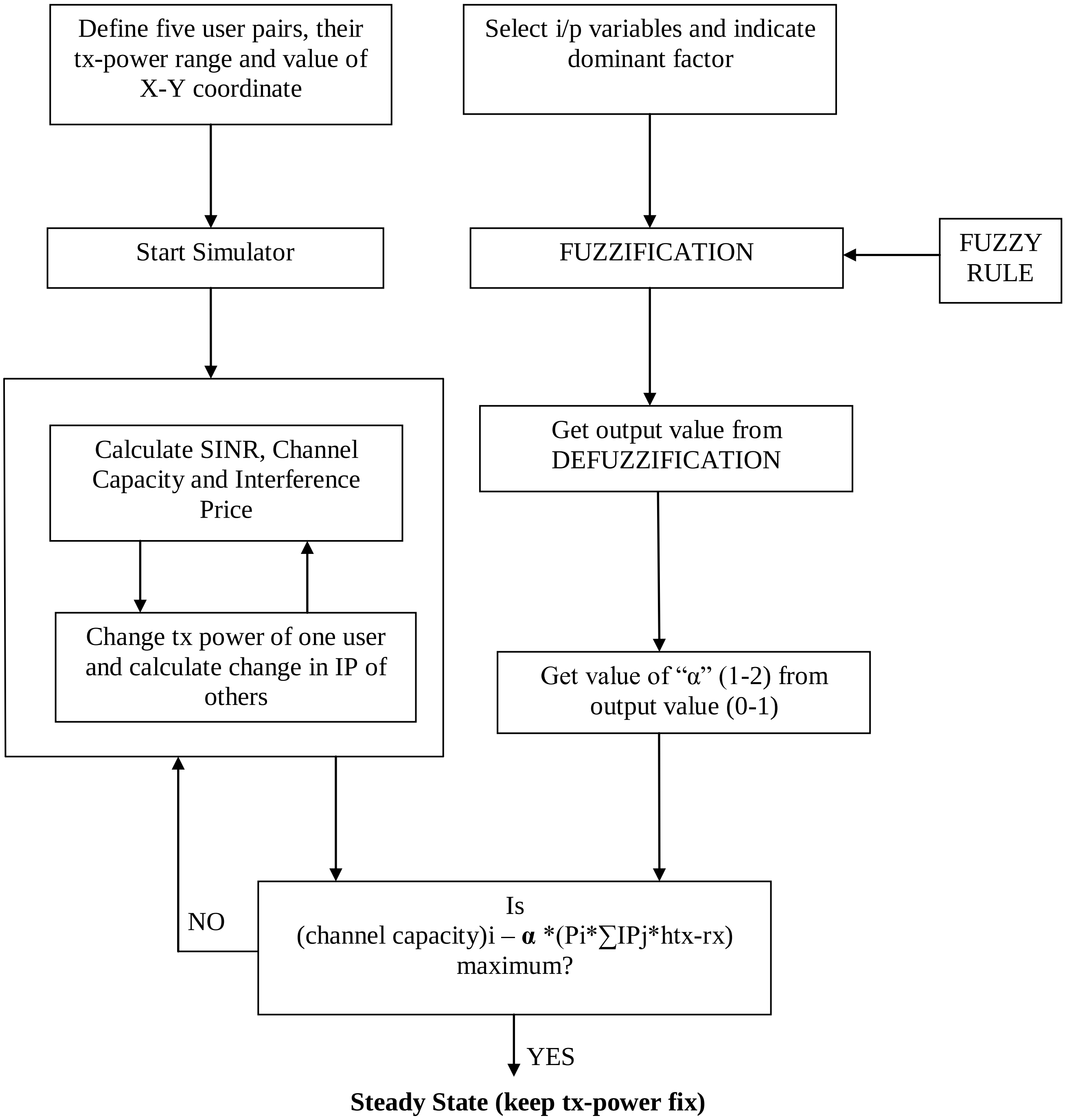

Figure 3-1 Proposed Algorithm for getting desired value of transmission power

The main purpose of the algorithm is to find compensated tx-power value of each transmitter on particular network condition. The algorithm has two parallel columns each of which are dedicated for separate work. First column takes care of interference management by adjusting transmit power. The steps which it follows are explained below

At first no. of user pairs along with its transmission power range is defined. Then assuming all user in static condition, each users X and Y coordinates is defined in order to locate them. When cognitive user turns 'ON' it transmit power is sensed by receiver. Then at Receiver of each pair Interference, SINR and Channel Capacity are calculated and value send to the respective transmitter. A new term called Interference Price (IP) is defined and calculated. This IP is broadcast by every user pair so that all other user should know how much interference they provide to all other users.

The tx-power value is controlled by the Power update term which is given by equation $(\text{channel capacity})_i - \boldsymbol{\alpha} *(Pi*\sum IPj*h_{tx-rx})$ which have two terms. First term is channel capacity of user and another term is capacity loss of all other users due to increase in its own power. So with the help of Power update term, the algorithm checks at which value of power (at particular value of Interference) the above term will be maximum. So the algorithm increase/decrease the tx-power value and fix one value at steady state at which it get highest value of power update term. But as interference and network character changes the algorithm again checks proper value of power and again go to steady state condition.

As we mentioned above that the algorithm take care not only interference but also the network or environment changes. So in parallel in another column another set of process runs as shown above. The environmental changes include lots of factors and it should be selected with in-depth study. After selection of factors, they are defined as i/p linguistic variable. Since each factors have their own properties and unique features with which it create interference. These features are defined by their dominant factor. So, the dominant feature of each i/p variable is also defined.

Then Fuzzification is applied with the help of Fuzzy Rule. Here fuzzy rule plays a crucial role and requires lots of investigation to be done. At first dominant factor of every selected variable is calculated. Then for every variable membership function is also defined and relates with dominant factor. Then no. of output values are defined which are kept between (0-1). In this case it is calibrated in five values which are (0 -0.25 - 0.5 - 0.75 - 1.0). Then every combination of Fuzzy rule is analyzed and allocate one (out of five) value to every combination.

Then finally according to algorithm, Defuzzification is done in order to get output value with range of (0-1). The value of the term defined as 'α' having range (1-2) is calculated with help of output value by simple equation:

$$\alpha = (\text{output value}) + 1$$

Now 'α' is included in the power update term which is common for both columns and then interference is again minimized by further compensating transmit power value. Hence this algorithm at one side address interference to other users due to increment of transmits power of own by interference price. Along with this it also address environmental condition variations by introducing new term α by taking help of fuzzy logic.

3.1 Methodology

3.1.1 Interference Compensation

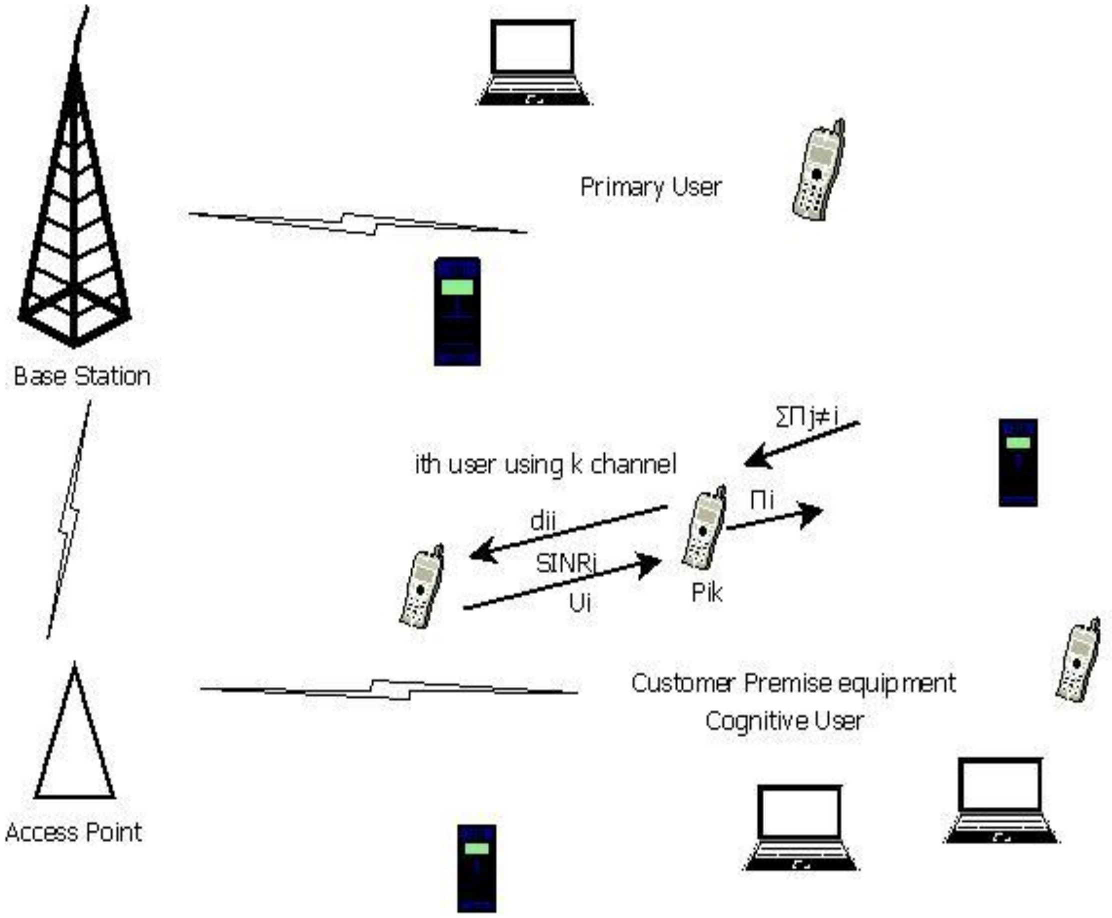

Figure 3-2 System Set-up for proposed algorithm

In this thesis, the environment is assumed to cause average-to-high loss (path loss exponent equals three, a value typical for indoor urban environments), thus the channel gain is $h_{ji} = d_{ji}^{-3}$ where d is the distance between the j_{th} transmitter and the i_{th} receiver.

Every user selects a valid initial value for the transmission power level p_k^i (power for i_{th} user in k_{th} channel) and the interference price π_k^i.

1. Define five users (each with Tx and Rx) and bandwidth

2. Define dimension of each users in X and Y coordinates as shown below

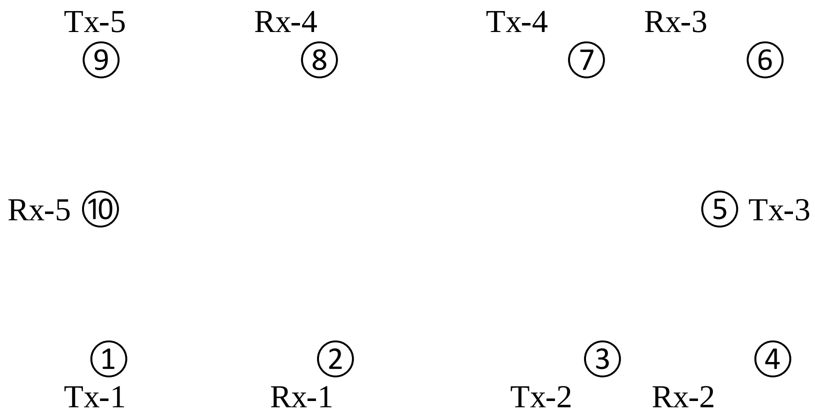

Figure 3-3 Five user pairs located with given value of X and Y coordinate

3. Calculate distance between Tx and Rx by $[(X_1\text{-}X_2)^2\text{-}(Y_1\text{-}Y_2)^2]^2$
4. Define initial Tx. Power level of range (0.7-1.0) mW.
5. Go on increasing power by 0.1mW in each loop as per requirement
6. Assume AWG noise be 1/100 mW
7. Calculate Interference by interference(i)=interference(i)+power(j)*(distance(Rx-Tx))$^{-3}$; j means except user i all other four users.
8. Calculation of SINR

Since SINR value is also major parameter of selecting appropriate transmission power, so SINR of i_{th} user pair $i \in \{1, 2, \ldots, L\}$ in the k_{th} channel, $k \in \{1, 2, \ldots, K\}$, is given by the following equation :-

$$SINR_i = (P_i^k * h_{ii})/(n_o + \sum_{j\neq i} P_j^k * h_{ji})$$

where, P_i^k is the transmission power for user i on channel k

h_{ii} is the link gain between the i_{th} receiver and the i_{th} transmitter,

n_o is the noise level

P_j^k is the transmission power for all other users on channel *k and*
h_{ji} is the transmission power for all other users on channel $k_,$

9. Calculation of channel capacity (Utility)

After calculation of SINR, according to Shannon law, channel capacity (or Utility) is calculated by the following equations:-

Utility of Channel (U_i) = B/W log ($1+SINR_{i)}$

Where, B/W is bandwidth of the channel and assumed to be the QOS factor of the user.

10. Calculation of Interference Price (Π_i)

$$\Pi_i^k = d\, U_i / d(\textstyle\sum_{j\neq i} P_j^k .\ h_{ji})$$

11. Calculation of Power Update

$$(U_i) \quad - \quad P_i^k (\textstyle\sum_{j\neq i} \Pi_j^k .\ h_{ji})$$

Utility of Channel   Utility loss of other users

First fix tx power of ith user (Pi) and go on increasing all other (ie jth) tx power Pj and calculate IP of i. Then fix Pj and increase Pi and calculate ∑IPj and then the power update term in order to find appropriate value of Pi for this condition.

Now set Pj to 5 different values and for each value of Pj increase Pi of tx and repeat step 11.This will give value of Power update term in different interferences (provided by Pj). At last indicate value of Pi for which update term is maximum.

3.1.2 Fuzzy Logic Implementation

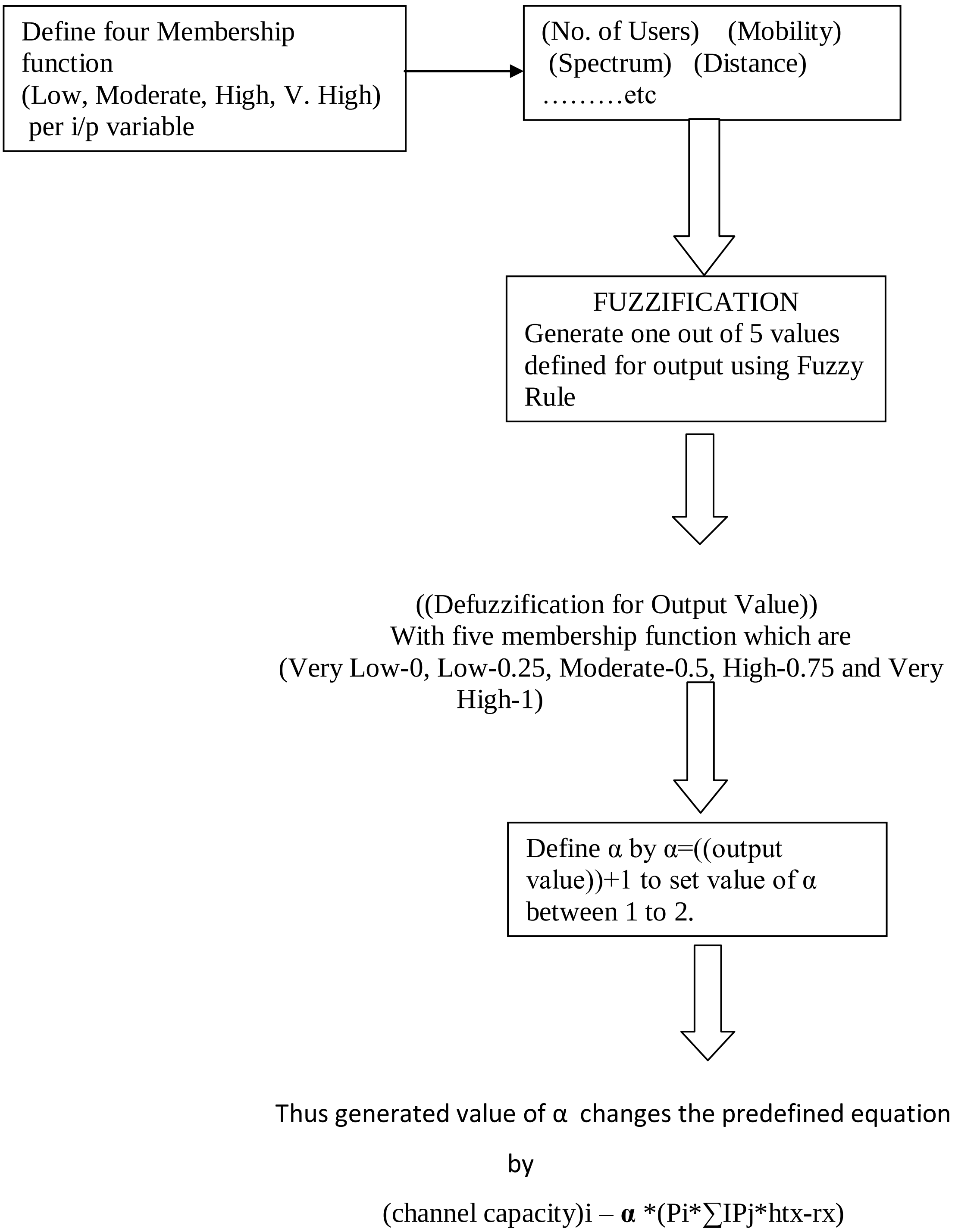

Figure 3-4 Detail Fuzzy Logic implementation for the algorithm

3.1.3 Fuzzy Rule

Rule No.	Input-1 (No. of Users) Dominant factor	Input-2 (Spectrum)	Input-3 (Synchronization constraint)	Input-4 (Mobility)	Output
1.	Low	Low	Low	Low	RU (0)
2.	Low	Low	Low	Moderate	RU (0)
3.	Low	Low	Moderate	High	RU (0)
4.	Low	Low	Moderate	Very High	SI (0.25)
5.	Low	Moderate	High	Low	RU (0)
6.	Low	Moderate	High	Moderate	RU (0)
7.	Low	Moderate	Very High	High	SI (0.25)
8.	Low	Moderate	Very High	Very High	SI (0.25)
9.	Low	High	Low	Low	RU (0)
10.	Low	High	Low	Moderate	RU (0)
11.	Low	High	Moderate	High	SI (0.25)
12.	Low	High	Moderate	Very High	SI (0.25)
13.	Low	Very High	High	Low	MI (0.5)
14.	Low	Very High	High	Moderate	MI (0.5)
15.	Low	Very High	Very High	High	MI (0.5)
16.	Low	Very High	Very High	Very High	MI (0.5)
17.	Moderate	Low	Low	Low	RU (0)
18.	Moderate	Low	Low	Moderate	RU (0)
19.	Moderate	Low	Moderate	High	SI (0.25)
20.	Moderate	Low	Moderate	Very High	SI (0.25)
21.	Moderate	Moderate	High	Low	SI (0.25)
22.	Moderate	Moderate	High	Moderate	SI (0.25)
23.	Moderate	Moderate	Very High	High	SI (0.25)
24.	Moderate	Moderate	Very High	Very High	MI (0.5)
25.	Moderate	High	Low	Low	SI (0.25)
26.	Moderate	High	Low	Moderate	SI (0.25)
27.	Moderate	High	Moderate	High	MI (0.5)
28.	Moderate	High	Moderate	Very High	MI (0.5)
29.	Moderate	Very High	High	Low	MI (0.5)
30.	Moderate	Very High	High	Moderate	MI (0.5)
31.	Moderate	Very High	Very High	High	MI (0.5)
32.	Moderate	Very High	Very High	Very High	HI(0.75)
33.	High	Low	Low	Low	SI (0.25)
34.	High	Low	Low	Moderate	SI (0.25)
35.	High	Low	Moderate	High	SI (0.25)
36.	High	Low	Moderate	Very High	SI (0.25)
37.	High	Moderate	High	Low	MI (0.5)
38.	High	Moderate	High	Moderate	MI (0.5)

39.	High	Moderate	Very High	High	MI (0.5)
40.	High	Moderate	Very High	Very High	MI (0.5)
41.	High	High	Low	Low	MI (0.5)
42.	High	High	Low	Moderate	MI (0.5)
43.	High	High	Moderate	High	HI (0.75)
44.	High	High	Moderate	Very High	HI (0.75)
45.	High	Very High	High	Low	HI (0.75)
46.	High	Very High	High	Moderate	HI (0.75)
47.	High	Very High	Very High	High	HI (0.75)
48.	High	Very High	Very High	Very High	HI (0.75)
49.	Very High	Low	Low	Low	MI (0.5)
50.	Very High	Low	Low	Moderate	MI (0.5)
51.	Very High	Low	Moderate	High	MI (0.5)
52.	Very High	Low	Moderate	Very High	MI (0.5)
53.	Very High	Moderate	High	Low	HI (0.75)
54.	Very High	Moderate	High	Moderate	HI (0.75)
55.	Very High	Moderate	Very High	High	HI (0.75)
56.	Very High	Moderate	Very High	Very High	HI (0.75)
57.	Very High	High	Low	Low	FI (1.0)
58.	Very High	High	Low	Moderate	FI (1.0)
59.	Very High	High	Moderate	High	FI (1.0)
60.	Very High	High	Moderate	Very High	FI (1.0)
61.	Very High	Very High	High	Low	FI (1.0)
62.	Very High	Very High	High	Moderate	FI (1.0)
63.	Very High	Very High	Very High	High	FI (1.0)
64.	Very High	Very High	Very High	Very High	FI (1.0)

** RU-Remain Unchanged, SI-Slightly Increase, MI-Moderately Increase,
HI-Highly Increase, FI- Fully Increase

In figure 3-4 above, the algorithm of fuzzy implementation is given. At first, for every input variable four membership function are defined (Low, Moderate, High, Very High). Also four input variable are defined after some analysis of the nature of the network. Then fuzzification is done with the help of fuzzy rule made after lots of investigation. Then defuzzification is done and output value is found. This gives value of α.

The parameters defined in above rule are No. of Users, Mobility, Spectrum and synchronization constraint. No. of users is normally taken as dominant factor because as it goes on increasing all the factors are increased. So in this thesis also it is regarded as dominant factor. Since for simulation no of users is taken as five, so if it reaches seven then fuzzy rule regard it as moderate increase. If it takes value of ten then its membership function will be HIGH and above ten it’s always Very HIGH. Every user announces a single interference price, therefore the delay that is introduced by the algorithm scales linearly with the number of users. This also implies that, given the fact that the updates are distributed in an asynchronous manner, the complexity of the algorithm is polynomial to the number of users.

The new term included above is the Spectrum which is defined as the ratio of the required spectrum to the available spectrum which gives spectrum efficiency given by (BWs/BWa) where BWs is the required spectrum and BWa is the available spectrum.

Mobility is an important parameter because more will be the chances of secondary user to change the position. It will cause Doppler Effect. If the velocity is more there can be degradation of Quality of service due to non availability of the channel.

Synchronization Constraint deals with the update time interval of message exchange which degrades the service as it increases. Since every user must get Interference Price of all other users in order to calculate power update term, so if it could not get message from even a single user its power update term will not be exact. So synchronization also plays a major role in interference management of cognitive radio.

4 Simulation Result

The expected result of this thesis is estimation of optimal values for transmission power which is achieved by the proposed improved algorithm. In order to simulate the algorithm proposed in this thesis, no. of assumptions are made and steps are followed which are explained below:

At first five no. of user pair is defined and transmit power of 70 mw is assumed for all user. Required bandwidth of all channels is taken as 10. For every user pair (Transmitter and Receiver) X and Y coordinate value is defined in order to locate them at fix point so that distance between transmitter and receiver can be calculated. Here static condition is assumed initially. The value of transmit power and distance is normalized between (0-1).

Now loop starts with no. of calculations. At first IP of i is calculated by increasing power of j by 0.1 from normalized value 0.7 and then graph is plotted which is shown in figure 12 below. Calculation of IP involves calculation of interference, SINR and channel capacity for each increased value of power of j. Here i user pair means the first one and j user pair is assumed to be all other four and finally i user pair get a value of it's transmit power by power update equation. Then power update equation for i user pair by increment of j users is also plotted. For this IP of j is also needed and requires no of calculations.

In next loop, IP of j (which have four values) by increasing power of i by 0.1 is calculated. For this again, for every j interference, SINR and channel capacity is calculated. After that power update equation of i is also calculated. Now power of j is increased by 0.1 and for this value again the above steps is repeated for three times in order to see the nature of graph between power update equation of I versus power of I for three set of different values of j.

In figure below, Interference Price (IP) and Power are plotted. At first part power of j is changed and due to this change IP of i is also changed. As power of j (ie interference for i user) is increased, IP of i also increased. Also in second part power of i user is increased and this increased IP of j (2-4).

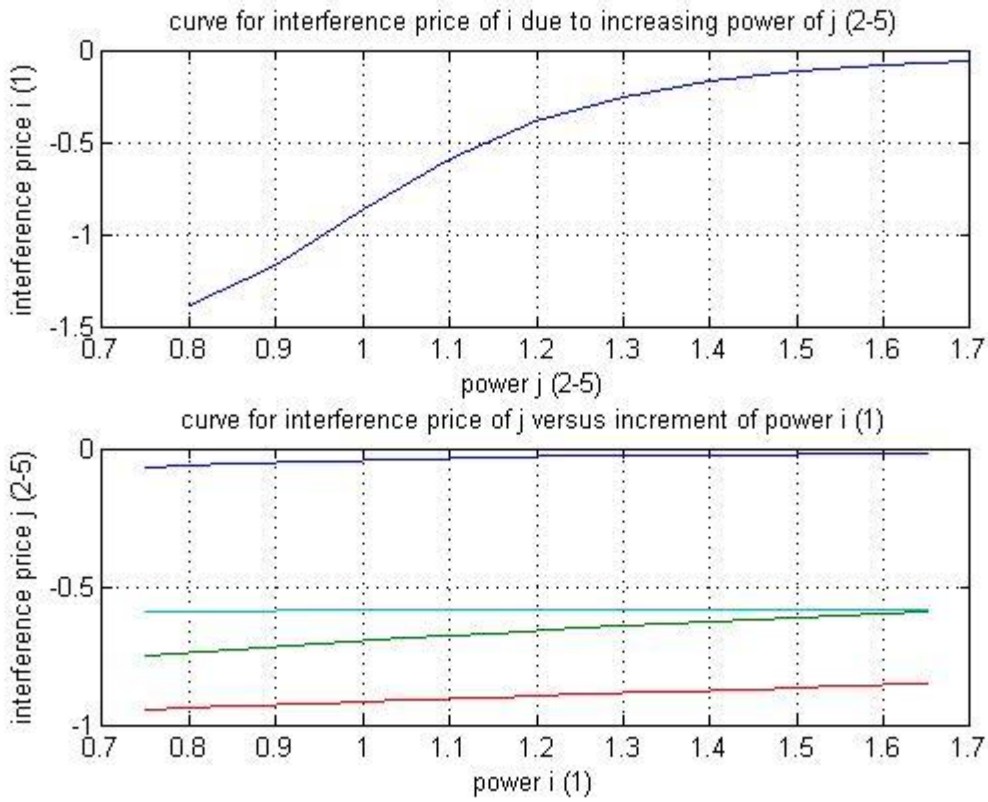

Figure 4-1 Matlab graph plot of power (i,j) verses IP (j,i)

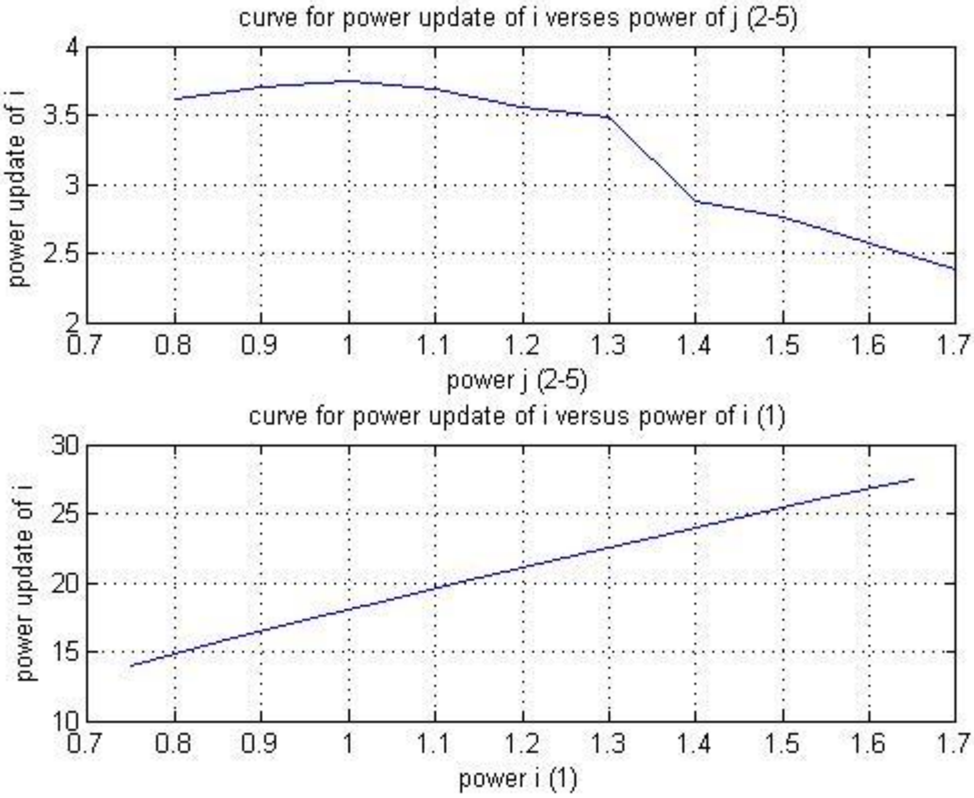

Figure 4-2 Mat lab graph plot of power (i, j) verses power update (i)

In Fig 13 above, graph plot between power update term for i and power of both i and j is shown. As we go on increasing power i it increases power update term also. In this case we assume constant interference (i.e. power of all j is fixed). But in first half part of the figure, as interference (power j) increases keeping power i constant we see the power update term is slightly increased, attain some value and start decreasing.

Since this is static condition, as in dynamic or real scenario the power update term is not straight line. But the concern of the algorithm is to find value power of i at which the power update term is maximum which we can get from the graph.

5 Conclusion

In order to compensate interference, this thesis has introduced an improved algorithm which utilizes MAC layer mechanisms for message exchange. For message exchange the thesis has introduced parameters such as Interference Price along with SINR and Channel Capacity. The main improvement in this thesis is the introduction of a coefficient $\boldsymbol{\alpha}$ that serves as the weight of the interference term, increasing its impact in cases of imperfect message exchange, due to long updates time intervals for interference prices, increased number of users, mobility and Spectrum availability. In such cases, the interference that is caused to other user pairs by an increase in the transmission power of a user is often underestimated. In the presence of such uncertainties, if this underestimation is compensated by a properly defined parameter, the system approximates its optimal behavior as in the case of “perfect” message exchange. The value of the parameter was derived from a fuzzy logic. Fuzzy logic was selected because it is particularly effective in dealing with uncertainties and vague requirements.

5.1 Future Work and Directions

The algorithm presented in this thesis assumes ideal situation such as fair channel condition, infinite processing power of cognitive radio but in real scenario we may face different challenges. So the algorithm should be further improved by studying different instances. Also if the final transmit power for one user is not sufficient for the desirable QoS the user searches for another spectrum area using “priority coefficient” in its utility and again use algorithm. So in this case priority coefficient should also be included in an algorithm in order to solve the problem. To a large extent, security in cognitive radio (CR) networks is an uncharted research area that needs to be further explored.

It is also expected in future to refine and optimize the rules of the Fuzzy Reasoner.

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