Frequency Analysis and Selection for Cognitive Radio using Fuzzy Logic System

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Abstract

The spectrum scarcity is a great challenge in the future development of wireless communication devices. The idea of Cognitive radio was proposed for the solution of this problem. The research work presented in this paper addresses the Frequency Analysis and Selection for Cognitive Radio (CR) using Fuzzy logic based Adaptive Control System. Fuzzy logic controller FLC is designed for this purpose to optimize the use of available radio-frequency (RF) spectrum resources while minimizing the chances of interference due to primary users. The FLC is used to deal with the incompleteness, uncertainty and heterogeneity of a cognitive radio scenario. Two cascaded fuzzy logic controllers are used. The first fuzzy inference system takes four inputs i.e. environment condition, distance between primary user and the secondary user, speed of secondary user and signal power received at SU (Psu). The only one output of FLC-1 is Psu, which is the signal power of secondary user (SU). The second fuzzy inference system FLC-2 will take four inputs i.e. transmission power of SU (Psu), signal to noise ratio (SNRpu), used frequency spectrum and duration of used frequency. The result of FLC-2 is appeared in the form of available frequency hole.

Keywords: Cognitive Radio, Frequency analysis, Adaptive Control, Fuzzy Logic System

1. Introduction

Wireless communication creates a revolution in our lives. The mobile communication is the most successful wireless service. New wireless devices are offering a better data rate and new and useful services. Normally, Mobile communication systems operate at a frequency less than 3.5GHz (Andreas F, Larry J, & Mansoor, May 2009). With the increase of the mobile services, the bandwidth requirements are also increasing. For the new services the bandwidth availability is a problem. Currently the spectrum is utilized in static way. There are two types of the bandwidth allocation, one is the licensed band allocation and the 2^{nd} are ISM bands, which can be utilized by any user. The new wireless applications and devices are basically designed for the unlicensed bands, e.g. last mile broadband wireless access, health care, wireless PANs/LANs/MANs and cordless phones are working in unlicensed bands. According to FCC 2002 report, the licensed bands are underutilized and the ISM bands are over utilized ((FCC), 2002). This situation is creating the spectrum scarcity. According to FCC report the licensed band spectrum are underutilized .The spectrum usage lies in between 15-85%.This situation occurs due to static spectrum allocation policy adopted by the governments worldwide. Due to this policy, the spectrum bands are vacant temporarily. These vacant spectrum bands are known as the spectrum holes white spaces. The holes are available at particular time or in particular locations. In 1992 Joe-Mittola presents the idea of Software Defined Radio (Mitola, May 1995). Software defined radio (SDR) is a programmable device which has the ability of Multichannel and Multicarrier communication. The SDR has the ability to change its parameter and quality of service (QOS) by programming according to demand. The solution of this problem was suggested by Mr. J.Mittola during his PhD at KTH Sweden. The Cognitive radio is a spectrum agile system which has the ability to sense the communication environment dynamically and it can intelligently adapt the communication parameters (carrier frequency, bandwidth, power, coding schemes, modulation scheme etc) (Seung & Giannakis, 2009).

The idea of fully cognitive radio presented by J.Mittola III et.al is still practically not possible. The hierarchical model is presented in which spectrum is accessed and bandwidths are adopted by 2^{ndary} users with priority of the primary users. Normally unlicensed users are considering as the secondary users. The Cognitive radios (Secondary users) are allowed to coexist with the primary users if they can maintain a minimum level of noise interference. The RF bands operated at the frequency <3.5 GHZ ,Cellular bands and fixed wireless access bands with a center frequency 2.5 GHz and 3.5 GHz are the potential candidates for cognitive Radio deployment (Andreas F, Larry J, & Mansoor, May 2009). In United States, FCC allowed the dynamic access of the UHF TV bands by the cognitive radio devices. The Cognitive radio operation depends upon the spectrum sensing information regarding activity, channel conditions ,codebooks, messaging to other nodes, modulation schemes, noise variance, decision about the spectrum parameter adaptation.

In November 2008, it was ruled by Federal Communication Commission FCC that unused part of RF spectrum, named as white spaces will be available for public use. The devices for the use of white noise were required to improve their technologies to avoid from interference of used frequencies. These devices must include the capability of geo location finding capabilities and spectrum hole finding techniques. Spectrum sharing method gives the best frequency scheduling like generic media access control problem (Wendang, Yueming, & Youyun, 2007).

In 2004, IEEE 802.22 equipped with air interface standard of wireless regional area networks WRAN for CR sensing operation for unlicensed devices in spectrum allocation of TV services. Signal strength and instantaneous collision probability are the components of channel selection in dynamic mode (stevenson, chouinard, Zhongding, & Wendong, january 2009).

The rest of the paper is organized as: Section 2 describes the cognitive radio using Fuzzy Logic. Fuzzy Inference system is explained in Section 3. Section 4 illustrates the MATLAB simulations. Section 5 explains the algorithm design. Section 6 consists on results and discussions and conclusion and future work is explained in section 7.

2. Cognitive Radio using Fuzzy Logic

The fuzzy sets theory was initiated by Loft Zadeh in 1965. FLC is used for decision making is useful in control process considering linearity and time-invariance issues of mathematical model. Information processing based fuzzy logic control has been deployed successively in many real world automatic systems including autonomous robot navigation, autofocus cameras, image analysis, diagnosis systems, washing machines, automobile transmissions, air conditioners and aerospace. Fuzzy logic helps multidimensional problems of decision making for uncertain distributed environment in dynamic mode and reduces the computational complexity.

Fuzzy logic based hardware and software solutions are required to face new challenges to in the field of CRs and CR networks. Fuzzification process is useful to change the probability of imprecise collision for each channel using fuzzy set for inference rules determining traffic load for each channel. At each node utility factor is used for decision making of dynamic channel selection. Radio frequency signal strength is the function of distance between wireless node and access point. Radio frequency signal strength is also the function of channel conditions. Channel utility function depends on collision probability and received signal strength. Three efforts: modeling & control, forecasting and management, and performance estimation are useful approaches to deal fuzzy logic in telecommunication networks. FLC is designed for this purpose to optimize available RF spectrum with minimum interference using FLC to deal CR scenario of heterogeneity, incompleteness and uncertainty problems in decision making.

In real processes FL proposes to translate human subjective knowledge to manipulate knowledge of practical interest with some uncertainty level. The set of fuzzy rules describe the behavior of systems as IF <premise> THEN <consequent> terms (Le & Ly, Opportunistic spectrum access using fuzzy logic for cognitive radio networks, 2008).

The design of future CRS will face new challenges like 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. The problems need multidimensional optimization problems with conflicting requirements. In the current research paper discussed problem is the detection of the spectrum holes (A.Dey, 2011) (taghavi & Abolhassani, 2011).

The proposed fuzzy inference system takes three inputs i.e. time, weather condition and distance between PU and the SU and returns the suitable spectrum hole as an output. The fuzzy inference mechanism consists of three stages: in the 1st stage, the values of the numerical inputs are mapped with membership function, this operation is called fuzzyfication. In the 2nd stage, the fuzzy system processes the rules with the firing strengths of the inputs. In the 3rd stage, the resultant fuzzy values are converted into numerical values; this operation is called defuzzyfication. Essentially, this procedure makes the use of fuzzy categories in the representation of the ideas in accordance to human beings in description of decision taking procedure (Islam & M, 2006) (Matinmikko & T, December 2009) (L & A, 2008).

3. Fuzzy Inference System

A fuzzy inference system FIS deals with the mapping of input data using fuzzy rules and gives output. The mapping process uses the following components.

- Input/output membership functions.
- II. Fuzzy logic operator
- Fuzzy if-then rules
- Aggregation of output sets
- Defuzzification

Four components of FIS: fuzzifier, inference engine, rule base and defuzzifier are shown in Figure 1.

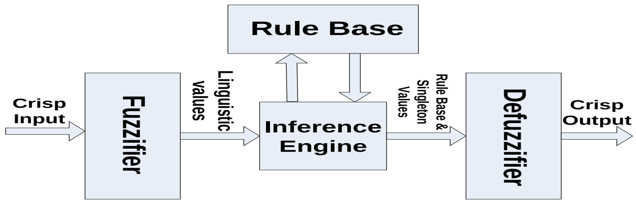


Figure 1. Block Diagram of Fuzzy Inference System (FIS)

3.1 Fuzzifier

A fuzzifier converts input crisp value in fuzzy set, this process is called fuzzification. For each input, a fuzzy set consists of two values known as degree of belongingness with certain membership function.

3.2 Inference Engine

IF-THEN fuzzy logic rules are assembled as IF antecedent- THEN consequent, the inference engine fires appropriate rule. The inference engine defines mapping from input fuzzy sets into output fuzzy sets and determines the degree to which the antecedent is satisfied for each rule.

3.3 Rule Base

The rule base contains linguistic rules that are provided by experts. It is also possible to extract rules from numeric data. Once the rules have been established, the FIS can be viewed as a system that maps an input vector to an output vector. Outputs for all rules are then aggregated. During aggregation, fuzzy sets that represent the output of each rule are combined into a single fuzzy set. Fuzzy rules are fired in parallel, which is one of the important aspects of FIS. In FIS, the order in which rules are fired does not affect the output (L & A, 2008).

3.3 Defuzzifier

The defuzzifier maps output fuzzy sets into a crisp number. Given a fuzzy set that encompasses a range of output values, the defuzzifier returns one number, thereby moving from a fuzzy set to a crisp number. Defuzzification is a process through which we can convert linguistic values to crisp values. This process is taken place in defuzzifier. Against each output one defuzzifier is required (Wendang, Yueming, & Youyun, 2007).

In order to process the input to get the output reasoning there are six steps involved in the creation of a rule based fuzzy system.

1. Identification, names and ranges to inputs.
2. Identification, names and ranges to outputs.
3. For each input and output, creation of the degree of fuzzy membership functions.
4. Construct the rule base for the system to operate.
5. Decide how the action will be executed by assigning strengths to the rules
6. Defuzzify the output by combining the rules.

The fuzzy inference process can be described completely in the five steps as shown in Fig. 2

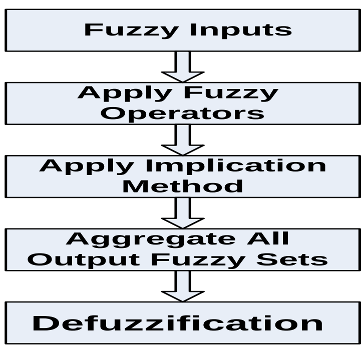


Figure 2. Steps of Fuzzy Inference Process

Step 1: Fuzzy Inputs

The first step is to take inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions.

Step 2: Apply Fuzzy Operators

Once the inputs have been fuzzified, we know the degree to which each part of the antecedent has been satisfied for each rule. If a given rule has more than one part, the fuzzy logical operators are applied to evaluate the composite firing strength of the rule.

Step 3: Apply the Implication Method

The implication method is defined as the shaping of the output membership functions on the basis of the firing strength of the rule. The input for the implication process is a single number given by the antecedent, and the output is a fuzzy set. Two commonly used methods of implication are the minimum and the product.

Step 4: Aggregate all Outputs

Aggregation is a process whereby the outputs of each rule are unified. Aggregation occurs only once for each output variable. The input to the aggregation process is the truncated output fuzzy sets returned by the implication process for each rule. The output of the aggregation process is the combined output fuzzy set.

Step 5: Defuzzify

The input for the defuzzification process is a fuzzy set (the aggregated output fuzzy set), and the output of the defuzzification process is a crisp value obtained by using some defuzzification method (Kaufmann, 1975) (M & M, August 2010) (Hiremath & Patra, 2010).

4. MATLAB Simulations

The tool of MATLAB for fuzzy logic simulation comprises the following editors and viewers.

- FIS Editor
- Membership Function Editor
- Rule Editor
- Rule Viewer
- Surface viewer

The FIS Editor is used to select the needed number of input and output variables assigning their names for the use of fuzzy inference system (FIS).

The Membership Function Editor is used to select the number of membership functions for input and output variables according to their required ranges, peak value and working range of variable.

Rule Editor is used to establish the working rules for the system. In Rule Editor we select the required combination of membership functions of inputs and outputs for every rule.

Rule Viewer shows the values of output variables according to the selected values of inputs on the basis of previous steps.

Surface Viewer gives the different versions of graphs between selected variables of input and output.

In this research work, two fuzzy logic controllers FLC-1 and FLC-2 are used in cascaded form.

4.1 Simulation for FLC-1

This fuzzy controller deals with three input variables: Environment condition, distance of SU from PU, and the signal strength received at secondary user SU from the primary user PU (SS_{PU}). Each linguistic variable is characterized by a term set of three fuzzy sets given as:

T(Environment)={Normal, Bad, Worst} ={N,B,W}

T(Distance) ={Small, Medium , Large}={ S, M , La}

T(SS_{PU})={Low, Medium, High}={L,M,H}

The one output variable, transmission power of SU (P_{SU}) is also characterized by a term set of three fuzzy sets: Small, Medium and High

T(P_{SU})={ Low, Medium , High}={ L, M , H}

Total numbers of active rules for FLC-1 are 27.

Total number of active rules= $m^n=3^3=27$

Where, m=Maximum number of overlapped fuzzy sets=3, n=Number of inputs=3

Figures 1, 2 and 3 show Membership Functions MFs Graphs for three inputs of FLC-1. The range is taken 0-100. The range can be scaled according to the actual range of input variables. Fig. 4 shows, Membership Functions MFs Graph for one output of FLC-1. The range is taken 0-100. This range can be scaled according to the % value of actual range of output variable. Table 1 shows the ranges of membership functions for input and output variables for FLC-1.

Table 1. Ranges of Membership Functions for Input and Output Variables of FLC-1

Membership Function	Ranges	Environment	Distance	SSpu	Psu
MF1	0-50 %	Normal (N)	Small(S)	Low(L)	Low(L)
MF2	0-100 %	Bad(B)	Medium(M)	Medium(M)	Medium(M)
MF3	50-100 %	Worst(W)	Large(La)	High(H)	High(H)

Figure 3 shows the selection of FIS Editor of FLC-1 for three inputs: Environment, Distance and SSpu, and one output Psu.

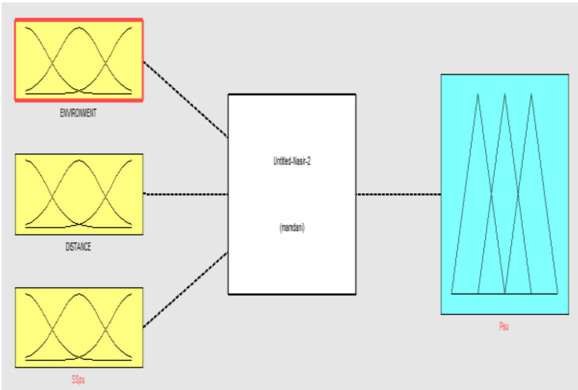


Figure 3. FIS Editor for FLC-1

Table 2 shows the possible fuzzy logic rules ($3^3 = 27$) used in FLC-1. These rules are entered in Rule Editor of MATLAB for further proceedings.

Table 2. Possible Fuzzy Logic Rules for FLC-1

	IF			THEN
Rule No.	**Environment**	**Distance of SU from PU**	**SS_{PU} Signal strength received at SU from the PU**	**P_{SU} Transmission power of SU**
1	W	S	L	**H**
2	W	S	M	**M**
3	W	S	H	**L**
4	W	M	L	**M**
5	W	M	M	**M**
6	W	M	H	**L**
7	W	La	L	**H**
8	W	La	M	**M**
9	W	La	H	**M**
10	B	S	L	**M**
11	B	S	M	**M**
12	B	S	H	**M**
13	B	M	L	**M**
14	B	M	M	**M**
15	B	M	H	**M**
16	B	La	L	**H**
17	B	La	M	**M**
18	B	La	H	**L**
19	N	S	L	**M**
20	N	S	M	**M**
21	N	S	H	**L**
22	N	M	L	**M**
23	N	M	M	**M**
24	N	M	H	**L**
25	N	La	L	**H**
26	N	La	M	**M**
27	N	La	H	**M**

Figures 4, 5, 6 and 7 give the various graphs between input and output using MATLAB Surface Viewer for FLC-1.

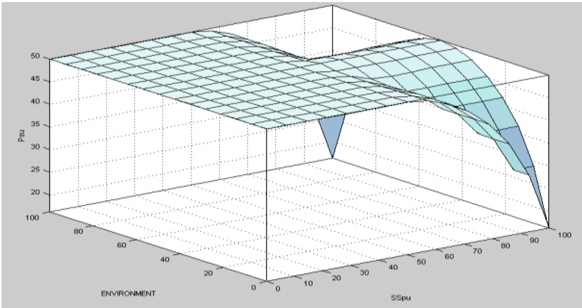


Figure 4. Graph of Surface Viewer Showing Relation of SSpu, Environment and Psu for FLC-1

Figure 4 shows that Psu decreases with the bad condition of environment, and Psu is not affected with environmental condition up to the certain values of SSpu.

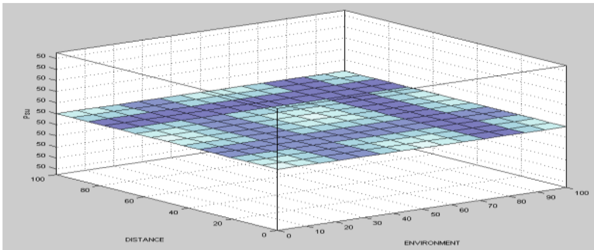


Figure 5. Graph of Surface Viewer Showing Relation of Environment, Distance and Psu for FLC-1

Figure 5 shows that the value of Psu maintains a minimum fix value for all values of distance and for a fix distance; environment is not affecting Psu value.

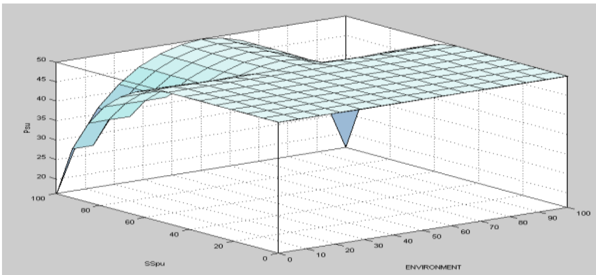


Figure 6. Graph of Surface Viewer Showing Relation of Environment, SSpu and Psu for FLC-1

Figure 6 is showing that Psu decreases with the bad condition of environment, and Psu is not affected with environmental condition up to the certain values of SSpu.

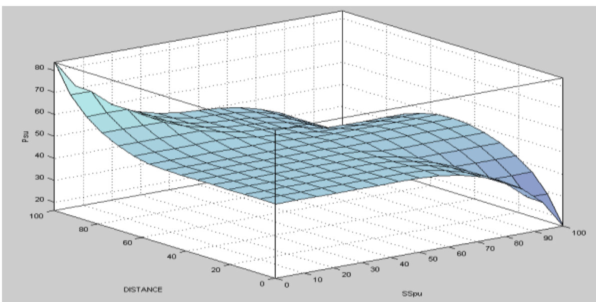


Figure 7. Graph of Surface Viewer Showing Relation of SSpu, Distance and Psu for FLC-1

Figure 7 shows that value of Psu remains fix at lower values of SSpu and distance but Psu needs to be increased at higher distance values at lower range of SSpu (Le & Liang, An efficient power control scheme for cognitive radios, 2007) (Berthold & Hand, 2003) (S & Patra, 2010).

4.2 Simulation for FLC-2

The Fuzzy Logic Controller FLC-2 deals with four input variables: transmission power of SU without interfering the PU (P_{SU}), Signal to noise ratio at the PU (SNR_{PU}), Used Spectrum and Duration (Seung & Giannakis, 2009).

Each input variable is characterized by a term set of three fuzzy sets given as: T(P_{SU})=T(SNR_{PU})=T(used Spectrum)=T(Duration)= {Low, Medium, High}={L,M,H}

The one output variable is Available Hole.

The output available hole linguistic variable is characterized by a term set of the three fuzzy sets: Low, Medium and High.

T(Available Hole)={Low, Medium, High}= ={L,M,H}

Total numbers of active rules for FLC-2 are 81.

Total number of active rules= $m^n=3^4=81$

Where, m=Maximum number of overlapped fuzzy sets=3, n=Number of inputs=4

In the given below table the ranges of membership function is given.

Table 3. Ranges of membership function

Membership Function	Ranges	Psu	SNRpu	Used Spectrum	Duration	Available Hole
MF1	0-50%	Low(L)	Low(L)	Low(L)	Low(L)	Low(L)
MF2	0-100%	Medium(M)	Medium(M)	Medium(M)	Medium(M)	Medium(M)
MF3	50-100%	High(H)	High(H)	High(H)	High(H)	High(H)

Table 4. ABLEE 4. Possible Fuzzy Logic Rules for FLC-1

Rule No	P_{SU} Power of SU	SNR_{PU} Signal to noise ratio at PU	Used Spectrum	Duration	Available Hole
1,2,3	L	L	L	L,M,H	M,M,M
4,5,6	L	L	M	L,M,H	H,M,M
7,8,9	L	L	H	L,M,H	M,H,H
10,11,12	L	M	L	L,M,H	L,L,L
13,14,15	L	M	M	L,M,H	M,H,H
16,17,18	L	M	H	L,M,H	H,M,M
19,20,21	L	H	L	L,M,H	L,L,L
22,23,24	L	H	M	L,M,H	M,M,M
25,26,27	L	H	H	L,M,H	H,H,H
28,29,30	M	L	L	L,M,H	M,M,M
31,32,33	M	L	M	L,M,H	H,M,M
34,35,36	M	L	H	L,M,H	M,H,H
37,38,39	M	M	L	L,M,H	L,L,L
40,41,42	M	M	M	L,M,H	M,L,L
43,44,45	M	M	H	L,M,H	H,M,M
46,47,48	M	H	L	L,M,H	L,L,L
49,50,51	M	H	M	L,M,H	M,M,M
52,53,54	M	H	H	L,M,H	H,H,H
55,56,57	H	L	L	L,M,H	M,M,M
58,59,60	H	L	M	L,M,H	H,H,H
61,62,63	H	L	H	L,M,H	M,M,M
64,65,66	H	M	L	L,M,H	L,L,L
67,68,69	H	M	M	L,M,H	M,M,M
70,71,72	H	M	H	L,M,H	H,H,H
73,74,75	H	H	L	L,M,H	L,L,L
76,77,78	H	H	M	L,M,H	M,M,M
79,80,81	H	H	H	L,M,H	H,H,H

Figure 8 shows the selection of FIS Editor for FLC-2 three inputs: Psu, SNRpu, used spectrum and duration, and one output available hole.

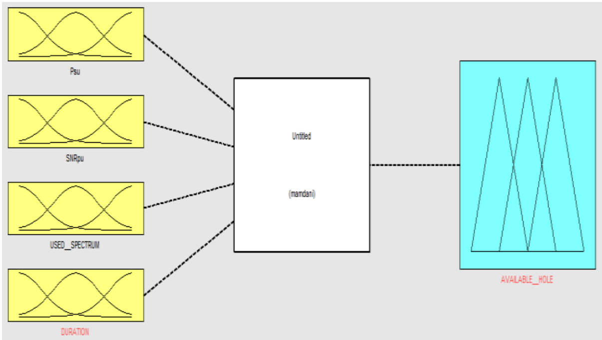


Figure 8. FIS Editor for FLC-2

Figure 9 shows the outlook of MATLAB fuzzy logic Rule Editor used for FLC-2 simulation.

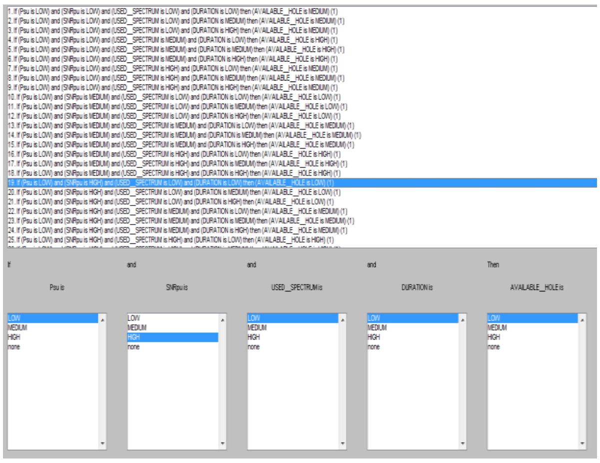
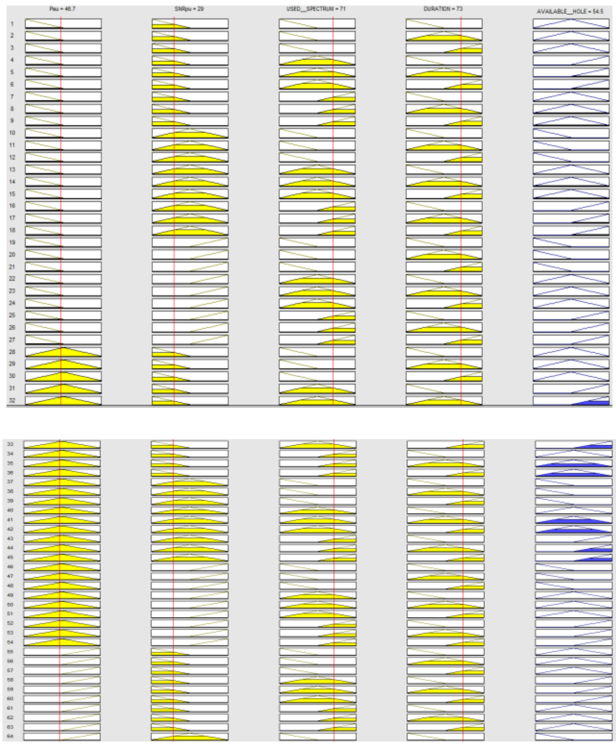


Figure 9. Rule Editor for FLC-2

Figure 10 shows the outlook of MATLAB fuzzy logic Rule Viewer used for FLC-2 simulation and finding the output values corresponding to the inputs.



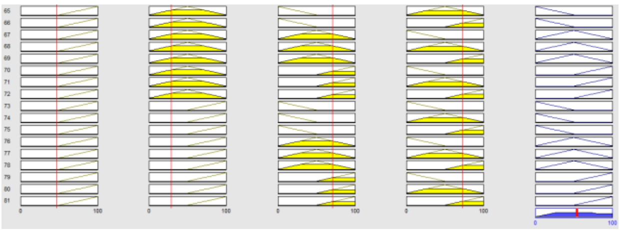


Figure 10. Diagram of Rule Viewer for FLC-2

Figures 11, 12, 13, 14 and 15 show the various graphs between input and output using MATLAB Surface Viewer for FLC-2.

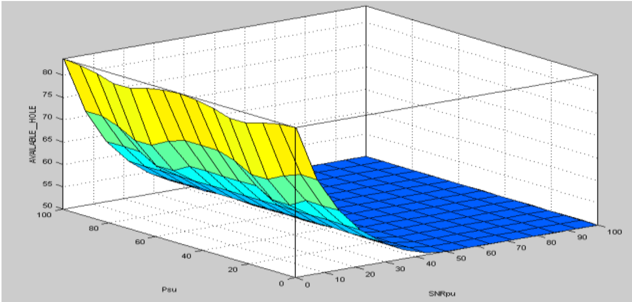


Figure 11. Graph of Surface Viewer Showing Relation of SNRpu, Psu and Available Hole for FLC-2

Fig. 22 shows that at low SNRpu, finding the hole requirement increases, where at high value of SNRpu, it is low. At low SNRpu, Psu does not affect but low SNRpu effect more on hole finding.

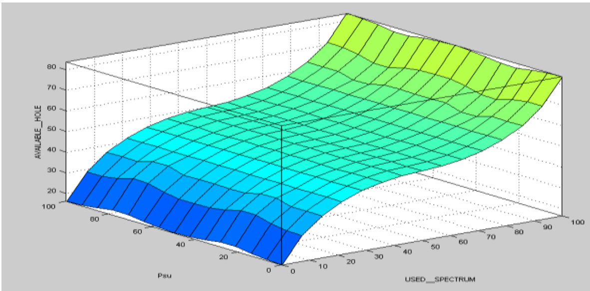


Figure 12. Graph of Surface Viewer Showing Relation of Used Spectrum, Psu and Available Hole for FLC-2

Figure 13 show that at constant Psu, high used spectrum value needs high available hole.

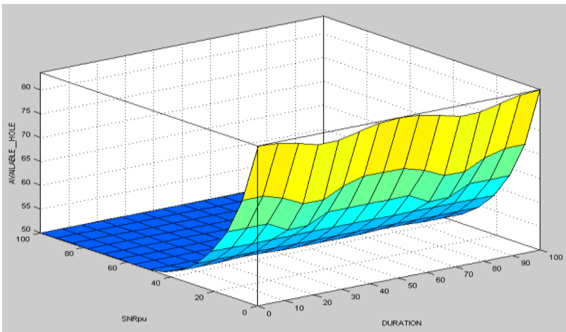


Figure 13. Graph of Surface Viewer Showing Relation of Duration, SNRpu and Available Hole for FLC-2

Figure 14 shows at low SNRpu, the need of hole finding increases. It also shows that at constant duration, the need of hole decreases

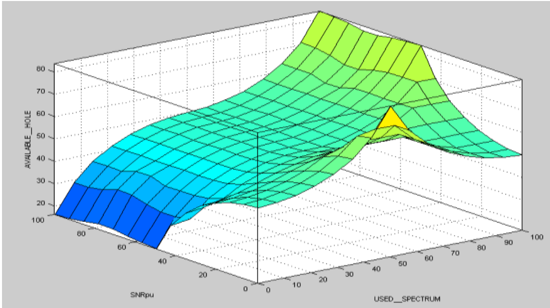


Figure 14. Graph of Surface Viewer Showing Relation of Used Spectrum, SNRpu and Available Hole for FLC-2

Figure 15 shows that the demand of frequency hole increases with increase of used spectrum up to certain extent but it decreases afterwards at constant SNRpu.

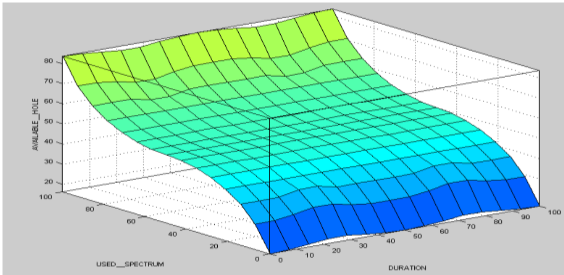


Figure 15. Graph of Surface Viewer Showing Relation between times Duration, Used Spectrum and Available Hole for FLC-2

Figure 16 shows that demand of frequency hole increases with increase of used spectrum even duration is constant (Le & Liang, An efficient power control scheme for cognitive radios, 2007) (Berthold & Hand, 2003) (Hiremath & Patra, 2010).

5. Algorithms Design

5.1 For FLC-1

% values of input and output variables for FLC-1 are given below:

Environment =40, Distance = 32, SSpu = 80 and Psu = 46.7

Environment

The % value of input variable (Environment) for FLC-1 lies in region 1 of membership function's graph. MSFs involved are: NORMAL (N) & Bad (B).

The degree of membership function values f1 and f2 for this value are:

f1 = (50-40)/50 = 10/50 = 0.2

f2 = 1- f1 =1-0.2 = 0.8

The finding of f1 and f2 for the Value Environment=40 is shown in Fig.27

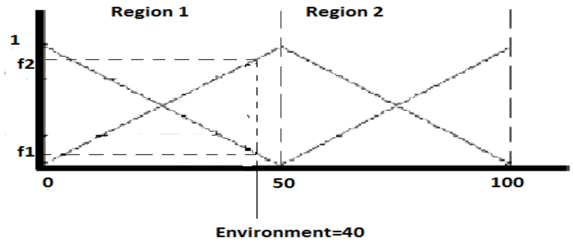


Figure 16. Shows Degree of Belongingness f1 and f2 for the Environment value=40.

Distance

The % value of input variable (Distance) for FLC-1 lies in region 1 of membership function's graph. Membership functions involved are: SMALL (S), MEDIUM (M).

The degree of membership function values f3 and f4 for this value are:

f3 = (50-32)/50 = 18/50 = 0.36

f4 = 1- f3 = 1-0.36 = 0.64

The findings of f3 and f4 for the Distance value =32 is shown in Figure17

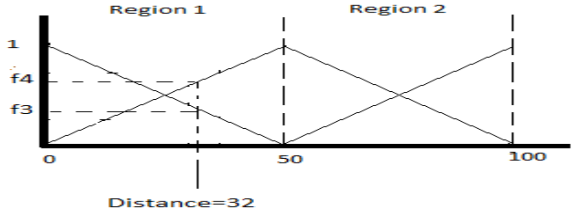


Figure 17. Shows Degree of Belongingness f3 and f4 for the Distance Value =32.

SS_{PU}

The % value of input variable (SS_{PU}) for FLC-1 lies in region 2 of membership function's graph. M.Fs involved is: MEDIUM (M) & HIGH (H).

The degree of membership function values f5 and f6 for this value are:

f5 = (100-80)/50 = 0.4

f6 = 1- f5 =1-0.4 = 0.6

The finding of f5 and f6 for the value SSpu=80 is shown in Fig. 18

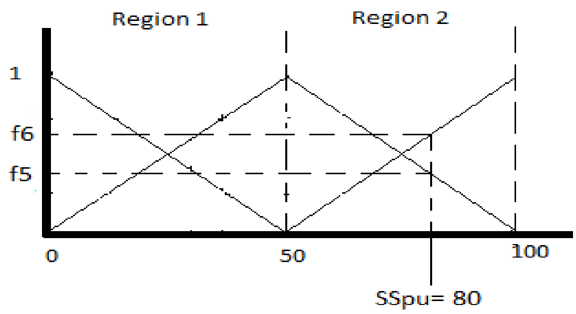


Figure 18. Shows Degree of Belongingness f5 and f6 for the Value SSpu=80

For the given values of three inputs (Environment= 40, Distance= 32 and SSpu =80), the following eight rules shown in Table 5 are being used.

Table 5. FLC-1 Eight Rules Used for Given Values

Rule No.	Environment	Distance	SSpu	Psu	Singleton Values
R_0	N	S	M	M	$S_0 = 0.5$
R_1	N	S	H	L	$S_1 = 0$
R_2	N	M	M	M	$S_2 = 0.5$
R_3	N	M	H	L	$S_3 = 0$
R_4	B	S	M	M	$S_4 = 0.5$
R_5	B	S	H	M	$S_5 = 0.5$
R_6	B	M	M	M	$S_6 = 0.5$
R_7	B	M	H	M	$S_7 = 0.5$

Rule No.	
R0	f1 ^ f3 ^ f5
R1	f1 ^ f3 ^ f6
R2	f1 ^ f4 ^ f5
R3	f1 ^ f4 ^ f6
R4	f2 ^ f3 ^ f5
R5	f2 ^ f3 ^ f6
R6	f2 ^ f4 ^ f5
R7	f2 ^ f4 ^ f6

.

$$\sum R_i = R_0 + R_1 + \ldots\ldots\ldots\ldots + R_7$$

$\sum S_i * R_i = S_0 * R_0 + S_1 * R_1 + S_2 * R_2 + S_3 * R_3 + S_4 * R_4 + S_5 * R_5 + S_6 * R_6 + S_7 * R_7$

According Mamdani's Model the value of output variable Psu (crisp value) = $[(\sum S_i * R_i) / \sum R_i] * 100$

5.2 For FLC-1

% values of input and output variables for FLC-2 are given as:

Psu = 46.7

SNRpu = 29

Used Spectrum = 71

Duration = 73

P_{SU}

The % value of input variable (Psu) for FLC-2 lies in region 1 of membership function's graph. MSFs involved are: LOW (L) & MEDIUM (M).

The degree of membership function values f1 and f2 for this value are:

f1 = (50-46.7)/50 = 3.3/50 = 0.066

f2 = 1- f1 =1-0.066 = 0.934

The finding of f1 and f2 for the Value Psu=46.7 is shown in Figure 19

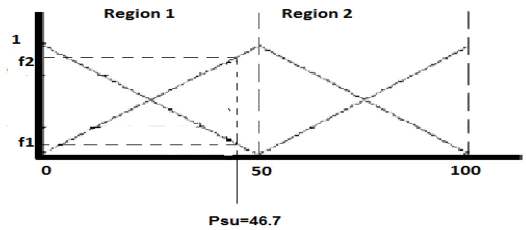


Figure 19. Degree of Belongingness f1 and f2 for the Value Psu=46.7

SNR_{PU}

The % value of input variable (SNRpu) for FLC-2 lies in region 1 of membership function's graph. Membership functions involved are: LOW (L), MEDIUM (M).

The degree of membership function values f3 and f4 for this value are:

f3 = (50-29)/50 = 21/50 = 0.42

f4 = 1- f3 = 1-0.42 = 0.58

The finding of f3 and f4 for the Value SNRpu=29 is shown in Fig.20

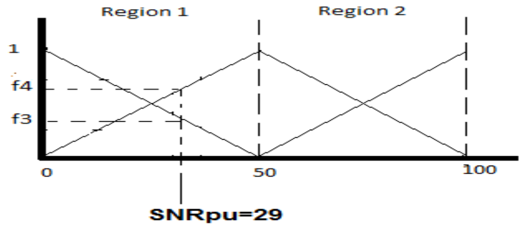


Figure 20. Degree of Belongingness f3 and f4 for the Value SNRpu=29

Used Spectrum

The % value of input variable (Used Spectrum) for FLC-2 lies in region 2 of membership function's graph. M.Fs involved is: MEDIUM (M) & HIGH (H).

The degree of membership function values f5 and f6 for this value are:

f5 = (100-71) /50 = 0.58

f6 = 1- f5 =1-0.58 = 0.42

The finding of f5 and f6 for the Value Used Spectrum=71 is shown in *Fig*.21

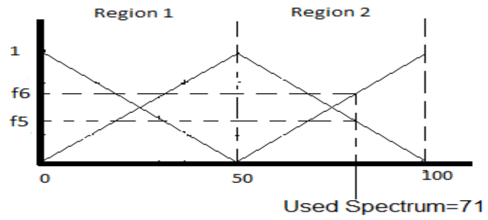


Figure. 21 Shows Degree of Belongingness f5 and f6 for the Value Used Spectrum =71

Duration

The % value of input variable (Duration) for FLC-2 lies in region 2 of membership function's graph. M.Fs involved is: MEDIUM (M) & HIGH (H).

The degree of membership function values f7 and f8 for this value are:

f7 = (100-73) /50 = 0.54

f8 = 1- f7 =1-0.54 = 0.46

The finding of f7 and f8 for the Value Duration=73 is shown in Figure 22

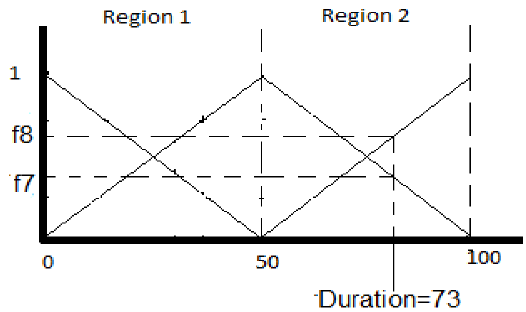


Figure 22. Degree of Belongingness f7 and f8 for the Value Duration=73

For the given values of four inputs (Psu=46.7, SNRpu=29, Used Spectrum=71 and duration=73), the following sixteen rules being used in FLC-2 are shown in Table 6

TABLEE 6. Sixteen Rules of FLC-2 Used for Given Values

Rule No.	Psu	SNRpu	Used Spectrum	Duration	Available Hole	Singleton Values
R1	L	L	M	M	M	S1=0.5
R2	L	L	M	H	M	S2=0.5
R3	L	L	H	M	H	S3=1
R4	L	L	H	H	H	S4=1
R5	L	M	M	M	H	S5=1
R6	L	M	M	H	H	S6=1
R7	L	M	H	M	M	S7=0.5
R8	L	M	H	H	M	S8=0.5
R9	M	L	M	M	M	S9=0.5
R10	M	L	M	H	M	S10=0.5
R11	M	L	H	M	H	S11=1
R12	M	L	H	H	H	S12=1
R13	M	M	M	M	L	S13=0
R14	M	M	M	H	L	S14=0
R15	M	M	H	M	M	S15=0.5
R16	M	M	H	H	H	S16=1

Rule No	Description
R1	f1 ^ f3 ^ f5 ^ f7
R2	f1 ^ f3 ^ f5 ^ f8
R3	f1 ^ f3 ^ f6 ^ f7
R4	f1 ^ f3 ^ f6 ^ f8
R5	f1 ^ f4 ^ f5 ^ f7
R6	f1 ^ f4 ^ f5 ^ f8
R7	f1 ^ f4 ^ f6 ^ f7
R8	f1 ^ f4 ^ f6 ^ f8
R9	f2 ^ f3 ^ f5 ^ f7
R10	f2 ^ f3 ^ f5 ^ f8
R11	f2 ^ f3 ^ f6 ^ f7
R12	f2 ^ f3 ^ f6 ^ f8
R13	f2 ^ f4 ^ f5 ^ f7
R14	f2 ^ f4 ^ f5 ^ f8
R15	f2 ^ f4 ^ f6 ^ f7
R16	f2 ^ f4 ^ f6 ^ f8

$\sum R_i$ = R1+R2+..................+R16

$$\sum S_i * R_i = S_1 * R_1 + S_2 * R_2 + S_3 * R_3 + S_4 * R_4 + S_5 * R_5 + S_6 * R_6 + S_7 * R_7 + S_8 * R_8 + S_9 * R_9 + S_{10} * R_{10} + S_{11} * R_{11} + S_{12} * R_{12} + S_{13} * R_{13} + S_{14} * R_{14} + S_{15} * R_{15} + S_{16} * R_{16}$$

According to Mamdani's Model output variable Available Hole (crisp value) = $[(\sum S_i * R_i) / \sum R_i] * 100$ [21, 22, 33]

6. Results and Discussion

6.1 For FLC-1

% values of input and output variables for FLC-1 are given as:

Environment =40, Distance = 32, SSpu = 80 and Psu = 46.7

The values of rules R0, R2,………….., R7 are shown in Table 7

Table 7. Values of Rules for FLC-1.

Rule No.	
R0	f1 ^ f3 ^ f5 = 0.2^ 0.36 ^ 0.4= **0.2**
R1	f1 ^ f3 ^ f6 = 0.2 ^ 0.36 ^ 0.6 = **0.2**
R2	f1 ^ f4 ^ f5 = 0.2 ^ 0.64 ^ 0.4= **0.2**
R3	f1 ^ f4 ^ f6 = 0.2 ^0.64^ 0.6= **0.2**
R4	f2 ^ f3 ^ f5 = 0.8 ^ 0.36 ^ 0.4= **0.36**
R5	f2 ^ f3 ^ f6 = 0.8 ^ 0.36 ^ 0.6= **0.36**
R6	f2 ^ f4 ^ f5 = 0.8 ^ 0.64 ^ 0.4= **0.4**
R7	f2 ^ f4 ^ f6 = 0.8 ^ 0.64 ^ 0.6= **0.6**

$\sum R_i$ = $R_0 + R_1 +$ ....+ R_7

=0.2+0.2+0.2+0.2+0.36+0.36+0.4+0.6 = 2.52

$$\sum S_i * R_i = S_0 * R_0 + S_1 * R_1 + S_2 * R_2 + S_3 * R_3 + S_4 * R_4 + S_5 * R_5 + S_6 * R_6 + S_7 * R_7$$

Si x Ri	
0.5*0.2	0.10
0*0.2	0
0.5*0.2	0.10
0*0.2	0
0.5*0.36	0.18
0.5*0.36	0.18
0.5*0.4	0.20
0.5*0.6	0.30
∑ Si * Ri	1.06

According to Mamdani's Model, the value of output variable Psu (crisp value) =

$[(\sum S_i * R_i) / \sum R_i] * 100$

$= [1.06 / 2.52] * 100 = 42.1$

MATLAB Simulation Value	46.7
Design Value	42.1

Difference between MATLAB Simulation Value and Design Value , Diff= 4.6

% error = [Diff/Original] x100= [4.6/ 46.7] x 100

% error = 9.8 %

6.2 For FLC-2

% values of input and output variables for FLC-2 are given as:

Psu = 46.7, SNRpu = 29, Used Spectrum = 71 and Duration = 73

Rule No	Description of Rule Base Calculations
R1	f1^f3^f5^f7=0.066^0.42^0.58^0.54=0.066
R2	f1^f3^f5^f8=0.066^0.42^0.58^0.46=0.066
R3	f1^f3^f6^f7=0.066^0.42^0.42^0.54=0.066
R4	f1^f3^f6^f8=0.066^0.42^0.42^0.46=0.066
R5	f1^f4^f5^f7=0.066^0.58^0.58^0.54=0.066
R6	f1^f4^f5^f8=0.066^0.58^0.58^0.46=0.066
R7	f1^f4^f6^f7=0.066^0.58^0.42^0.54=0.066
R8	f1^f4^f6^f8=0.066^0.58^0.42^0.46=0.066
R9	f2^f3^f5^f7=0.934^0.42^0.58^0.54=0.42
R10	f2^f3^f5^f8=0.934^0.42^0.58^0.46=0.42
R11	f2^f3^f6^f7=0.934^0.42^0.42^0.54=0.42
R12	f2^f3^f6^f8=0.934^0.42^0.42^0.46=0.42
R13	f2^f4^f5^f7=0.934^0.58^0.58^0.54=0.54
R14	f2^f4^f5^f8=0.934^0.58^0.58^0.46=0.46
R15	f2^f4^f6^f7=0.934^0.58^0.42^0.54=0.42
R16	f2^f4^f6^f8=0.934^0.58^0.42^0.46=0.42

$\sum R_i$ = R1+R2+....................+R16

=0.066+0.066+0.066+0.066+0.066+0.066+0.066+0.066+0.42+0.42+0.42+0.42+0.54+0.46+0.42+0.42= 4.05

$\sum Si * Ri = S_1 * R_1 + S_2 * R_2 + S_3 * R_3 + S_4 * R_4 +$
$S_5 * R_5 + S_6 * R_6 + S_7 * R_7 + S_8 * R_8 +$
$S_9 * R_9 + S_{10} * R_{10} + S_{11} * R_{11} + S_{12} * R_{12} + S_{13} * R_{13} + S_{14} * R_{14} + S_{15} * R_{15} + S_{16} * R_{16}$

Si x Ri	
0.5*0.066	0.033
0.5*0.066	0.033
1*0.066	0.066
1*0.066	0.066
1*0.066	0.066
1*0.066	0.066
0.5*0.066	0.033
0.5*0.066	0.033
0.5*0.42	0.210
0.5*0.42	0.210
1*0.42	0.420
1*0.42	0.420
0*0.54	0
0*0.46	0
0.5*0.42	0.210
0.5*0.42	0.210
∑ Si * Ri	2.076

According to Mamdani's Model, the value of output variable Available Hole (crisp value)

$[\sum S_i * R_i / \sum R_i] * 100 = [2.076 / 4.05] * 100 = 51.26$

MATLAB Simulation Value	**54.5**
Design Value	**51.26**

Difference between MATLAB Simulation Value and Design Value, Diff_= 3.24

% error = [Diff_/Original] x100= [3.24/ 54.5] x 100

% error = 5.9 %

7. Conclusion and future work

In frequency analysis and selection for cognitive-radio using fuzzy logic controller as an adaptive control system, it is worth to mention that fuzzy logic controller provides the opportunity to solve interdependence complex problem in a dynamic environment. In this system, two FLCs were used in a cascaded manner to establish the authenticity of decision for cognitive radio system requirements considering different parameters. The surface graphs and established rules showed the new approach of Spectrum Hole decision. The software based solution using fuzzy logic techniques was also established. MATLAB simulation results and the design based results were almost in agreement. This future work will provide the rapid estimation of CRS problems for design and analysis in all sorts of scenarios. MATLAB Simulink also provides the facility to verify the proposed circuits for FLC. In future more efforts will be done to develop this dire needed area of communication. Fuzzy logic can helps in the selection of the best spectrum hole out of available spectrum holes.

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