



Integrating Fuzzy Logic into Cognitive Radio Systems

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Article's Information	Abstract
Received: 30.08.2025 Accepted: 29.03.2026 Published: 15.06.2026	This paper presents a mathematical formulation and implementation framework of Fuzzy Logic Controllers in cognitive radio operations. The approach is rooted in fuzzy set theory, enabling linguistic rule-based decision-making for spectrum sensing, power control, and channel selection. In Cognitive Radio Networks, a primary difficulty is determining how Cognitive Radio may utilize a licensed channel without disrupting Primary Users and when to relinquish that channel. In this work, we define a fuzzy logic model that manages the operation of Cognitive Radio to prevent interference with Primary Users. Our proposed model does not just decide the handover according to the Primary Users power but also on the performance of the Secondary User and achievement of quality of service on both Primary Users and Secondary User.
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1. Introduction

The innovative wireless communications technique known as cognitive radio (CR) enables devices to use spectrum in an intelligent and adaptable manner. Traditional spectrum allocation often leads to inefficient usage, leaving many bands underutilized. Cognitive radio addresses this by allowing secondary users to access unused licensed spectrum without interfering with primary users. One major challenge in CR is making decisions in real-time under uncertainty and environmental dynamics. The core concept of cognitive radio is its capacity to accurately assess spectrum circumstances to enhance spectrum use efficiency. It does this by attempting to determine whether it overlaps or interferes with licensed users' signals without affecting their transmission. Only when the total interference value between the secondary user and the primary user is somewhat less than the permitted threshold can each primary user (Pu) and secondary user (Su) synchronize their transmissions [1]. In [2], Lotfi Zadeh created fuzzy logic, a mathematical tool for dealing with uncertainty and imprecision. Unlike classical binary logic, fuzzy logic deals with degrees of truth, making it well-suited for complex decision-making tasks such as those found in CR environments. Fuzzy Logic Controllers (FLCs), introduced by Zadeh in 1965,

provide a means to incorporate human-like reasoning and uncertainty management in decision-making. The FLCs offer advantages such as robustness, nonlinearity handling, and simplicity in modeling complex systems using linguistic rules. This paper explores how FLCs can be mathematically integrated into CR frameworks, focusing on their application in spectrum sensing, power control, and choosing a channel. Nowadays, fuzzy logic is commonly employed in cognitive radio networks. Using fuzzy logic, a dynamic spectrum allocation system was created in [3] for the Internet of Things device-focused cognitive radio networks, accounting for quality of service (QoS), signal strength, interference, and user priority. The authors in [4] presents a fuzzy logic-based decision-making model that performs better than conventional methods by combining many elements to find the optimal spectrum allocation in cognitive radio networks. [5] used to improve network resilience and quality of service, the smart sensing framework employs fuzzy logic for dynamic spectrum management. [6] is relevant for current implementations of fuzzy logic. We detail the theoretical basis, present a methodology for controller design, simulate its performance, and compare it to existing approaches. Our objective is to illustrate how fuzzy logic can enhance spectrum

access decisions, power control, and overall system adaptability. When (Pus) and (Sus) coexist, there is actually a great deal of ambiguity because of a number of reasons. Firstly, because the decision-making process is decentralized, the inputs used to make decisions on the activity of the Pus, their transmission properties, or the Pu receivers' specific position is quite ambiguous. Second, like any wireless channel, fading, route loss, interference, and noise add an inherent element of uncertainty. Third, the many inputs used in decision-making (such as power levels, QoS indicators, signal to noise ratios (SNR), etc.) are diverse and not directly comparable. Last but not least, the spectrum handoff method used at the Su endpoint side needs to be simple and quick to execute in order to quickly evacuate allowed channels when needed [7]. Therefore, the difficulty is in figuring out the highest transmit power to achieve QoS that a secondary user might employ without interfering with the quiet receiver of the primary user. In order to prevent interference, the distance between the primary and secondary users is a crucial element, particularly when the primary user's receiver is situated between the primary user's transmitter and the secondary user. This paper focuses on a standalone architecture, analyze the difficulties in delegating spectrum usage decision-making authority, and establish the secondary user's choice based on the spectrum sensing data at hand. Because they are causing detrimental interference to the principal users, the secondary users' choice to transfer to a different frequency channel presents a difficult challenge [8]. Fuzzy logic is used to handle the incompleteness and variety of cognitive radio settings. It is also used to guide decision-making in these types of circumstances. A mathematical method for handling ambiguous data and issues having several, rather than singular, answers is fuzzy logic. Despite being used in digital computers that can only make yes-or-no judgments, fuzzy logic solves issues using ranges of values, which is more in line with human reasoning. When real-time systems and expert systems need to respond to an imperfect environment with highly fluctuating, volatile, or unexpected situations, fuzzy logic is utilized to solve the problem. It, in a sense, "smooths the edges," avoiding the sudden shifts in functioning that can arise from depending on conventional either-or and all-or-nothing reasoning [9-12]. Section two covered the theoretical background and related work, while section three described the fundamentals of the fuzzy logic system. In part four, the fuzzy logic model is introduced, followed by the mathematical formulation, analysis and results, and mathematical

algorithm. The last parts provide a summary of the conclusion and future works.

2. Theoretical Background and Related Work

Mitola and Maguire (1999) popularized the idea of CR with the goal of developing radios that are able to recognize and adjust to their surroundings. CR systems' primary capabilities are mobility, spectrum management, and spectrum sensing. Because CRs must evaluate sensed data and choose the best settings in the face of ambiguity, decision-making is very crucial [13]. A number of methods for making decisions have been suggested:

- **Rule-based systems** are straightforward yet inflexible.
- **Machine learning techniques:** Need a lot of data and processing power.
- **Fuzzy logic controllers:** Provide a harmony of interpretability, flexibility, and simplicity.

3. Fuzzy Logic System Fundamentals

Fuzzy logic has been effectively used in a number of domains, such as communication, control systems, and robotics. Transmission power control [14], dynamic spectrum access [15], and spectrum sensing [2] have all made use of fuzzy logic in CR. Its capacity to function in unpredictable circumstances and minimal processing complexity make it very appealing.

Mathematically, a fuzzy logic system (FLS) can be expressed as a mapping:

$$\text{FLS: } \mathcal{R}^n \rightarrow \mathcal{R},$$

where $\mathbf{x} = (x_1, x_2, \dots, x_n) \in \mathcal{R}^n$ are crisp input variables and $y \in \mathcal{R}$ is the output. Fuzzy rules are linguistic constructs in the following forms:

If x_1 is A_1 and x_2 is A_2 then y is H ,

where A_1 , A_2 and H are fuzzy sets with membership functions defined by:

$$\mu_A(x) = \begin{cases} 1 - \left| \frac{x-c}{a} \right|, & |x-c| \leq a; \\ 0, & \text{otherwise,} \end{cases}$$

for a triangle membership function with width $2a$ and center c .

The FLS operates in three main steps:

- I. **Fuzzification:** Maps each crisp input x_i to a fuzzy set $\mu_{A_i}(x_i) \in [0, 1]$;
- II. **Inference:** Evaluates fuzzy rules using logical operations (e.g., min, max);

III. **Defuzzification:** Converts the fuzzy result into a crisp output using methods such as the centroid method:

$$y^* = \frac{\int \hat{y} \mu(\hat{y}) d\hat{y}}{\int \mu(\hat{y}) d\hat{y}}$$

4. Model of Fuzzy Logic

The proposed algorithm is based on two fuzzy logic circuits as shown in Figure 1.

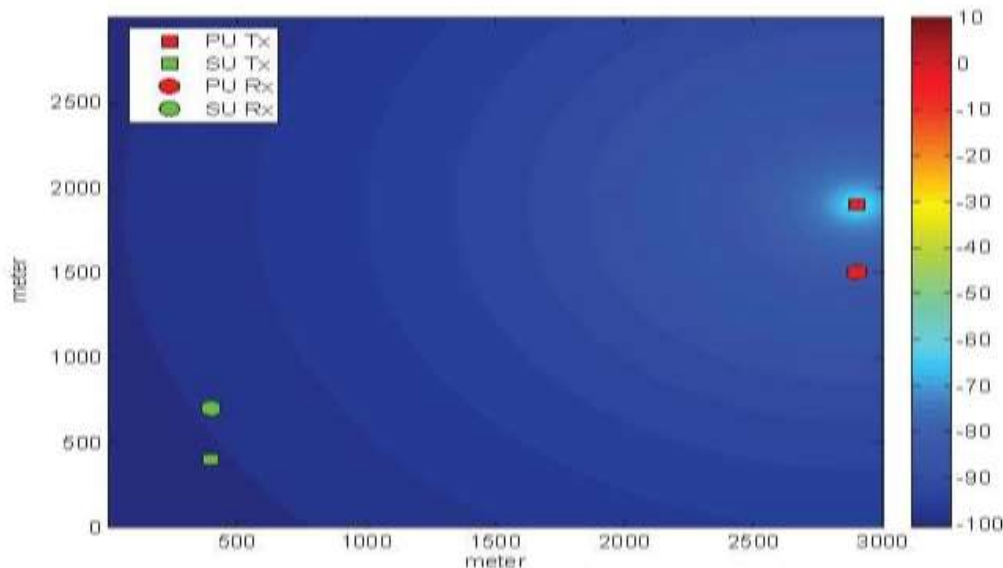


Figure 1. RSS and PU over 3000 m by 3000 m.

Figure 1 shows one Pu transmitter with one silent Pu receiver. Also, it shows one Su transmitter and one Su receiver. The Su transmitter senses RSS value over different channels. When the RSS value is low at one of the channels, the Su considers a free channel and computes the possible Signal-to-noise ratio and interference (SINR) at the Su receiver and evaluates the achieved QoS at the Su receiver. In the first fuzzy logic circuit, the input will be the received signal strength indicator (RSSI), and the secondary user's power will be the output, so it will be responsible for estimating the distance between the primary user and secondary user (P_{su}) and then for evaluating the power that the secondary user should

transmit without any effect on the neighbouring primary user (Pu). The second fuzzy logic circuit is responsible for making decisions for the spectrum handoff. The inputs for this block will be the SNIR of the primary user, the desired quality of surface (R_b), which is in Kbps, and finally the output of the first fuzzy logic circuit (P_{su}). There will be two outputs characterized in this block: Handoff (HO), which signals whether or not handoff must be implemented, comes first, followed by reconfiguration (reconfig.), which searches for new values to check, this indicates that the secondary user's power should be adjusted in order to lower spectrum rate handoff while avoiding handoff.

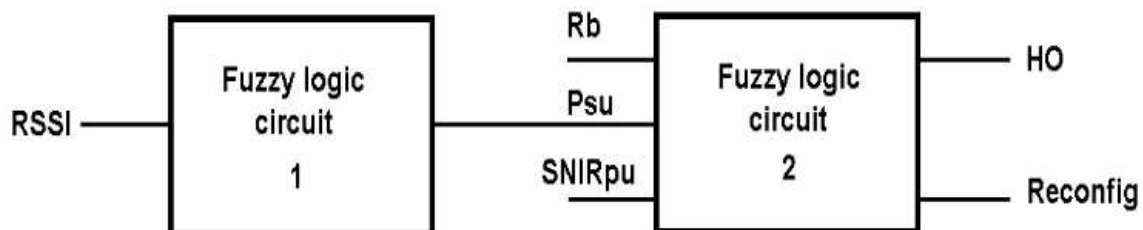


Figure 2. A block diagram of the Fuzzy logic algorithm.

The first fuzzy-logic circuit was created to determine how much power should be sent by the secondary user without interfering with the main users' (Pus') ability to function. Considering primary user power is constant (10 dB), secondary users can estimate the primary user's position by calculating their distance from one another [16] [17]. After making optimizations in MATLAB, we take these values as the result for the system, therefore, a "high" signal intensity at the secondary user's receiver indicates a "low" distance between the first and secondary users.

5. Mathematical Formulation

A non-linear mapping is used to represent the decision-making process in the suggested Fuzzy Logic Controller (FLC):

$$FLS: \mathcal{R}^3 \rightarrow \mathcal{R}^2.$$

The vector $x = [P_{su}, R_b, SINR]^T$ is defined as the input, where the secondary user capacity $SINR$ is obtained from the Shannon-Hartley relation:

$$SINR = B_c \log \left[1 + \frac{P_{su}}{I + N_0} \right].$$

Where B_c is the channel bandwidth, I is the aggregate interference, and N_0 is the thermal noise. The membership functions seen in Figure 3 define the input ($RSSI$) and output (P_{su}) of fuzzy logic circuit 1, each of which is defined by a collection of three fuzzy sets [7]:

$$T(RSSI) = T(P_{su}) = \{ \text{High, Medium, Low} \}.$$

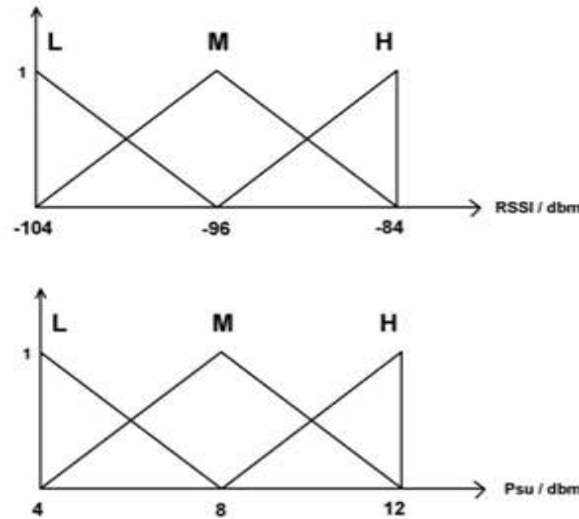


Figure 3. Fuzzy logic circuit 1 fuzzy rule.

Fuzzy logic circuit 1's fuzzy rules are displayed in Table 1; it is the relation between $RSSI$ and P_{su} . For example, in rule 2, if the $RSSI$ is "low," then the P_{su} will be high, meaning that the distance between the primary user and the secondary user is estimated to be "high"

Table 1. Fuzzy logic circuit 1 rules.

IF		THEN
Rule	$RSSI$	P_{su}
R.1	H	L
R.2	L	H
R.3	M	M

The purpose of the second fuzzy logic circuit is to determine whether or not a spectrum handoff should

be implemented. It has two outputs and three inputs; Figure 4 displays the membership functions. As demonstrated, each input is described by a collection of three fuzzy:

$$T(P_{su}) = T(R_b) = T(SINR) = \{ \text{High, Medium, Low} \}.$$

$$T(HO) = \{ \text{Yes, Pro. Yes, No} \}.$$

Fuzzy-logic circuit 2, on the other hand, contains two alternative outputs (handoff or reconfiguration) as follows: HO, which signals whether or not handoff must be accomplished, and reconfig, which searches for new values to verify in order to determine whether the power of the secondary user has to be varied.

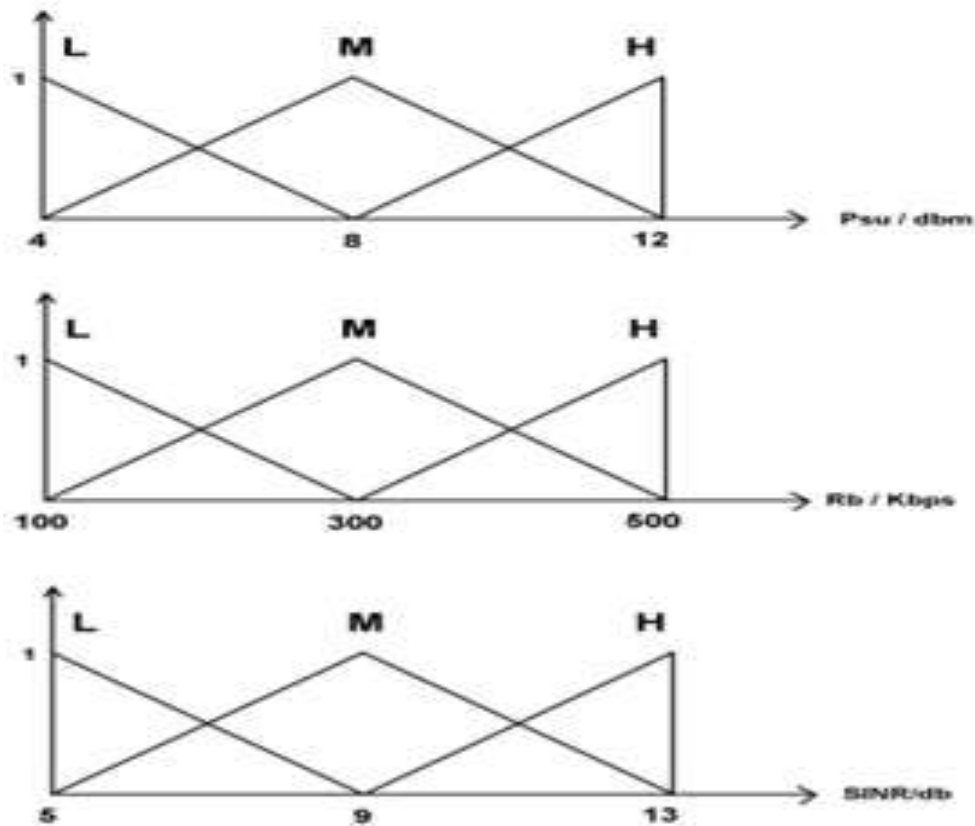


Figure 4. Fuzzy logic circuit 2 fuzzy rules.

The primary particular step in fuzzy logic is referred to as implication, exemplified by the "clipping the top of the triangle" technique. This research requires the subsequent steps:

1. The Fuzzy Set (The Triangular Model): The result "Handoff" in Table 2 below is a linguistic variable rather than just a single integer. On a graph, each variable (such as "Probably Yes") is shown by a geometric form, typically a triangle. This triangle symbolizes that choice's "full potential."
2. The Input Strength (Degree of Membership): The system determines a degree of membership (represented as μ) based on environmental sensors, such as Pu and Psu levels.
 - For instance, the rule "Probably Yes" may only be true by 60% in the given circumstances.
 - This "level" of 0.6 is where the clipping will take place.
3. The Clipping Procedure (The Illustrated Description): The system cannot utilize the whole triangle (100%) for its final computation since the rule is only 60% true.
 - At a height of 0.6, a horizontal line is drawn.
 - Above that line, the triangle's top is chopped off (clipped).
 - A trapezoid—a triangle with a flat top—is the end product.
4. The Mathematical Reason: In this study, the ultimate conclusion is made using the Center of Area (COA) approach.
 - Several of Table 2's rules may be active at any given time (for example, one rule may state "Yes" at 0.2 strength while another states "Probably Yes" at 0.8 strength).
 - The trapezoids, which are clipped forms, are combined by the algorithm into a single, large, complicated shape.
 - The combined shape's center of gravity serves as the ultimate numerical determination.

Table 2 displays the fuzzy rules found in fuzzy logic circuit 2, which are the relationships between two outputs (HO and reconfig.) and three inputs (*Psu*, *Rb*, and *SINR*).

Table 2. Fuzzy logic circuit 2 rules.

<i>IF</i>				<i>THEN</i>
Rule	<i>Psu</i>	<i>Rb</i>	<i>SINR</i>	<i>HO or Reconfig.</i>
R.1	L	L	L	HO
R.2	L	M	L	HO
R.3	L	H	L	HO
R.4	M	L	L	HO
R.5	M	M	L	HO
R.6	M	H	L	HO
R.7	H	L	L	HO
R.8	H	M	L	HO
R.9	H	H	L	HO
R.10	L	L	M	HO
R.11	L	M	M	HO
R.12	L	H	M	HO
R.13	M	L	M	Reconfig
R.14	M	M	M	Reconfig
R.15	M	H	M	Reconfig
R.16	H	L	M	Reconfig
R.17	H	M	M	Reconfig
R.18	H	H	M	Reconfig
R.19	L	L	H	HO
R.20	L	M	H	HO
R.21	L	H	H	HO
R.22	M	L	H	Reconfig
R.23	M	M	H	Reconfig
R.24	M	H	H	Reconfig
R.25	H	L	H	Reconfig
R.26	H	M	H	Reconfig
R.27	H	H	H	Reconfig

Let's examine Table 2 as a Smart Decision Matrix to clarify the outcomes. This table is used in this study to balance two competing objectives: preventing interference with the Pu and maintaining the connection of the Su. This is a summary of the table's mathematical and logical operations:

- I. Fuzzy Logic's "Voting" System: In terms of math, every row in Table 2 is a "Rule." Instead, then selecting a single row when the system detects the environment, it determines how much each row relates to the present circumstance.
- II. Table 2's Three Outcome Groups: Three mathematical results may be derived from the table's 27 rules:
 - Inputs (*X*): ***Psu***, ***Rb*** and ***SINR***.
 - The Intersection (***AND***): The Minimum operator is used in the calculation. If a rule states, "If Power is High ***AND*** Signal is Medium," and the signal is only 40% medium but your power is 90% high, the rule will only be activated at 40%.

Table 3. Three Outcome Groups.

Situation	Math Logic (Inputs)	Result (Outputs)	Simple Explanation
Exit	H Power + H Signal	HO = Y	You are too loud and too close to the owner; leave now.
Fix	M Power + M Signal	HO = P. Y / Reconfig = L	You might be causing trouble; lower your volume by 3dB first.
Stay	Low Signal (Pu is far)	HO = No	The owner is far away; stay and keep working.

III. The Centroid and Clipping Geometric Calculation: The arithmetic takes the following steps to translate these "If-Then" principles into an actual action (such as a command to a radio chip):

- Clipping: The system uses the output triangle (such as the "Probably Yes" triangle) for each rule that is "triggered," cutting off its top at the input strength level. The triangle is cut at 0.4 height if a rule is only 40% true.
- Aggregation: It consolidates all the truncated shapes from each of the 27 principles into a single, intricate final form by stacking them sequentially.
- Center Determination (Defuzzification): The system computes the Center of Area (COA).
- The Final "Binary" Choice: The math result, y^* , is a number in the range of 0 to 1. Now, we can apply the final dissertation:
 - If $y^* < 0.5$, the "Handoff" command is sent.

- If $y^* \geq 0.5$, no handoff occurs; the main user stays on the channel.

6. Analysis and Results

For the first fuzzy, we take **RSSI** as input and **Psu** as output. For the **RSSI**, we take this range from -104 to -85 dBm. This range was chosen because the minimal power required to surpass background noise is -85 dBm. The signal disappears below the physical noise level at -104 dBm, where it is 80 times weaker. After making optimization, for the output **Psu**, we have the range from 4 to 12 dB. We use these results from the system to implement it in the fuzzy logic circuit, and we can see that the **RSSI** is inversely proportional to the **Psu**, where it is good to keep **RSSI** less than (-85) to avoid problems. The range of **Psu** less than 9 dB could not achieve the desired QoS, making handoff at the output because the interference will happen then, as shown in Figure 5.

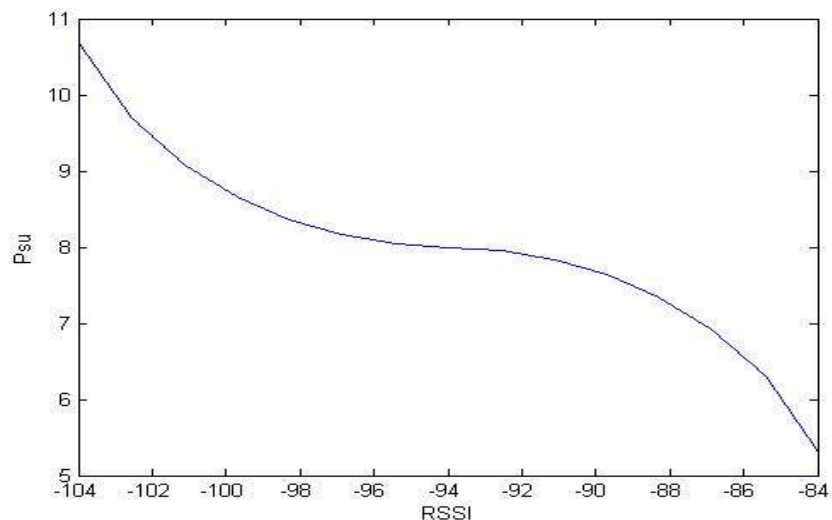


Figure 5. Fuzzy logic circuit 1's input and output.

We have two outputs and three inputs for fuzzy logic circuit 2. For the inputs, one of them will be the output of fuzzy logic circuit 1 with a range of 4 to 12 dB. The second input is required Rb with a range from 100 to 500 Kbps; this range achieves the

reconfiguration output, meaning no handoff. For the third input, SINR, it's range is 5 to 13 dB. After implementing these data in fuzzy logic, we get this result as shown in Figure 6:

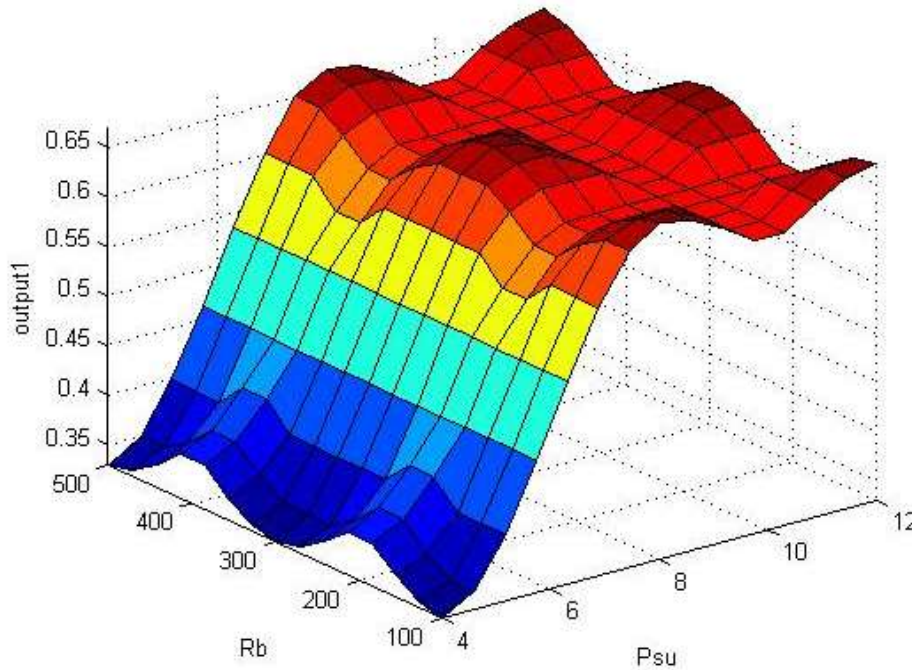


Figure 6. Fuzzy logic circuit 2's input/output.

The handoff will be achieved in two cases: if we do not achieve the desired QoS required or if we reduce the SINR of the Pu. In fact, we can maintain the SINR by reducing allowable power, but this will not achieve the required Rb. As we can see, the SINR is below 10 dB; handoff will be the output. Regardless of other inputs, which mean the secondary user is close to the primary user, if SINR is larger than 10 dB, then we can depend on other inputs to make the decision of the output; the Psu's range is less than 8 dB, which doesn't achieve the Rb range and will make a handoff.

7. Mathematical Algorithm

Here is a four-step summary of the Fuzzy Logic Controller's mathematical technique used to make the spectrum handoff decision:

- I. Input Mapping (Shannon-Hartley Relation).
- II. Fuzzification: Convert crisp inputs $X = \{P_{su}, R_b, SINR\}$ into fuzzy sets $A \in \{L, M, H\}$.

III. Rule Inference (Table 2 Logic).

IV. Aggregation & Defuzzification (Decision): To obtain a clear result HO combine all rules (27) and compute the Center of Area.

V. Decision Logic: If $HO < 0.5$, initiate spectrum handoff.

8. Conclusions and Future Works

Fuzzy logic is preferable to "standard" math primarily because with normal math, even a slight change in the signal might cause the machine to "panic" and sever the connection. In Table 2 Fuzzy Logic Math, the system transitions smoothly. It may try to slightly lower the power (reconfig.) before deciding to give up and handoff (HO), which leads to fewer lost connections and improved spectrum use. Fuzzy logic offers a promising direction for managing uncertainty in cognitive radio environments. This paper presents a structured, mathematical framework for implementing fuzzy logic in spectrum sensing, power control, and channel selection. The

primary issue that cognitive radio systems face is decision-making for these networks, which is extremely challenging for a number of reasons. For example, the decision-making process is based on decentralized entities, which means that the information gathered about the secondary users will be ambiguous and incomplete due to the spectrum sensing process, and the available inputs may be ambiguous or heterogeneous due to wireless channel characteristics. Fuzzy logic is therefore a highly helpful tool for mathematically simplifying complicated processes for which it is challenging to create a mathematical model. Using fuzzy logic is an excellent method to guarantee prompt judgments in short real time. This model's mathematical extensions will be the subject of future studies through:

- I. Algebraic Optimization: To lower computational cost in real-time systems, the Weighted Average Method $y^* = \frac{\sum \mu_i \cdot z_i}{\sum \mu_i}$ is substituted for the integral-based COA.
- II. Stochastic Modelling: Using Type-2 Fuzzy Sets to control the Shannon Capacity formula's "Interval of Uncertainty" in noisy settings.
- III. Cross-Domain Applications: Financial Math, Energy Systems, and Medical Physics.
- IV. Topological Improvements: Using Gaussian Membership Functions instead of triangular ones to improve gradient-based learning algorithms' differentiability.

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