Intelligent Spectrum Handoff Decision in Cognitive Radio Networks: A Fuzzy System Approach with Adaptive Membership Functions

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Abstract—**Spectrum scarcity has become a pressing issue due to the rapid growth of wireless devices and increasing demand for data. Cognitive Radio Networks (CRNs) offer a promising solution by allowing dynamic spectrum access, which depends on efficient handoff decisions by Secondary Users (SUs). Accurate handoff decisions are vital to prevent ping-pong effects and interference that could disrupt Primary Users (PUs). In this study, we propose a fuzzy system with adaptive Membership Functions (MFs) to improve handoff decisions in CRNs. Our methodology involved simulating three models (Fuzzy Hybrid, Fuzzy MF Optimization with Particle Swarm Optimization (PSO), and the proposed adaptive MF model) using ten diverse test datasets representing different network conditions. We measured performance by comparing handoff occurrences across the models. Results show that handoff frequency was reduced from 50% in the Fuzzy Hybrid model to 40% with PSO optimization and further to 30% using adaptive membership functions. The adaptive model achieved this reduction through more precise handoff decisions, demonstrating its effectiveness in reducing unnecessary handoff occurrences in CRNs.**

Keywords—**cognitive radio networks, fuzzy system, spectrum handoff, adaptive membership function, handoff decision**

I. INTRODUCTION

Cognitive Radio Network (CRN) has become a major research topic in recent years, mainly due to its potential in solving the problem of radio spectrum scarcity [1]. Spectrum scarcity is a critical issue in telecommunications due to the increasing demand for wireless services and the limited spectrum available [1, 2]. CRN emerged as an innovative solution to this issue by proposing a spectrum allocation method that is more flexible and dynamic than traditional spectrum allocation systems [3]. Through radio spectrum perception and analysis, cognitive radio can access unused spectrum resource opportunities for data transmission, thereby increasing spectrum utilization and reducing spectrum waste [4]. The main concept of CRN is to utilize dynamic spectrum management techniques, which enable more efficient use of the spectrum and reduce the possibility of interference [5]. This is achieved through cognitive radio technology, which enables devices to automatically detect available channels and adjust their transmission parameters according to the surrounding environmental conditions. This enables devices to operate on frequencies not currently used by Primary Users (PUs).

In CRN, there are two categories of users: Primary Users (PUs) and Secondary Users (SUs). PUs are entities licensed to use specific spectrum bands and have priority in their usage. Meanwhile, SUs are opportunistically unlicensed users accessing the spectrum [6, 7]. To avoid interference with PUs, SUs must be intelligent in detecting spectrum availability and only utilize portions not being used by PUs [8].

As an intelligent wireless communication system, CR conducts real-time spectrum detection, management, sharing, and mobility [9]. This technology exploits the available “white spaces” in licensed channels, avoiding interference with licensed users through a process known as spectrum handoff [3]. Spectrum handoff is the transition from one part of the spectrum to another aimed at ensuring smooth communication. Spectrum handoff is a crucial function of Cognitive Radio (CR) that involves changing the operating frequency. The primary issue with spectrum handoff is the extensive time required for searching, selecting, and switching to a new available channel, which can lead to considerable delays during the handoff process [10].

When a PU becomes active, the SU must switch to a different channel, but this can lead to a degraded performance if channel switching occurs so frequently [6]. Fig. 1 illustrates the concept of spectrum holes.

In the context of CRN, the decision-making function for spectrum handoff has a very important role [6]. This function allows SUs to efficiently select portions of the spectrum not used by PUs for their transmissions, known as opportunistic spectrum access. This process can be

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carried out independently or with network support [1]. Spectrum handoff typically occurs due to several factors, including spectrum usage by the PU, degradation of channel quality, interference with the PU's transmission, or movement of the SU out of the coverage area. Improper spectrum handoff management can cause problems such as interference and ping-pong effects, which occur when SUs frequently switch spectrums [1, 12]. This condition causes interference that can potentially harm the PU and reduce network throughput [6, 13]. Approaches such as fuzzy logic are very appropriate to overcome information uncertainty in CRNs, as they enable better decision-making in real-time, especially in the context of spectrum handoff [1].

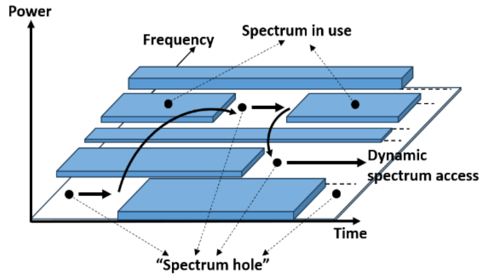

Fig. 1. Spectrum hole concept [11].

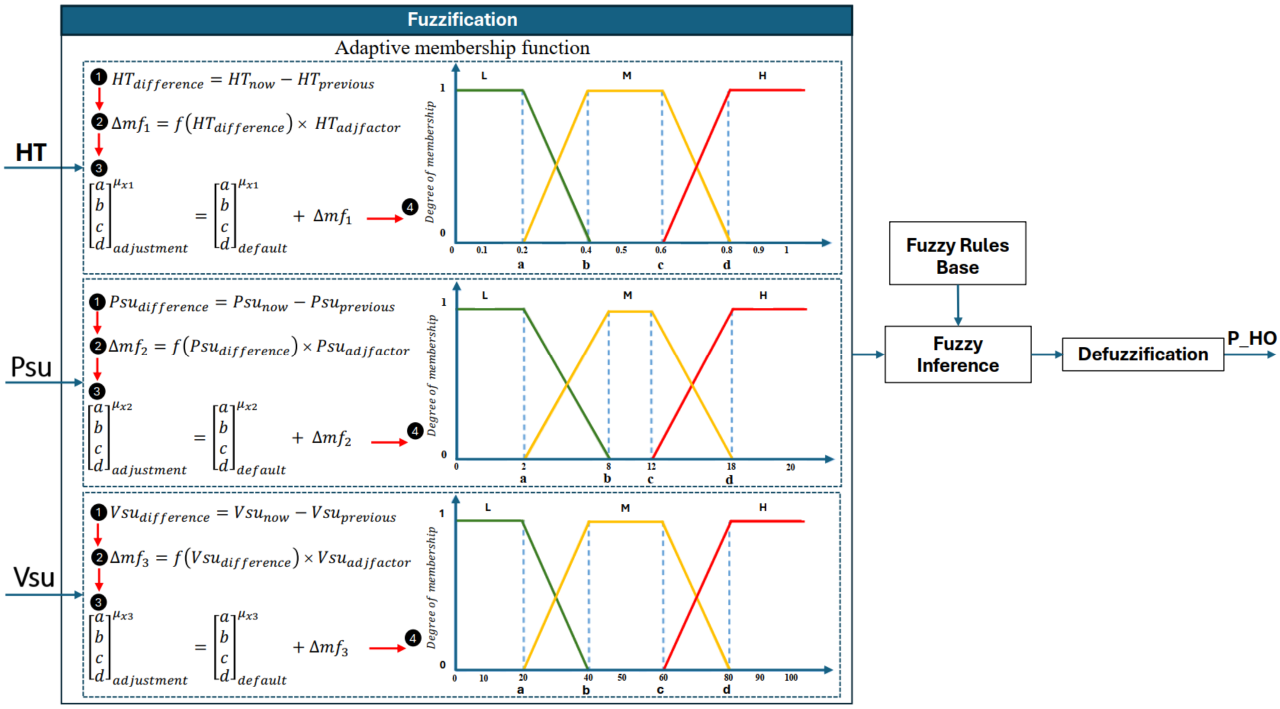

Fig. 2. Model of a fuzzy system supported by adaptive membership functions.

In a highly dynamic CRN environment, using fixed membership functions is less suitable for practical implementation. Therefore, the membership function must be able to adapt to actual conditions so that the performance of handoff decision-making can be improved. This can be achieved through an adaptive fuzzy system so that decisions taken for handoff become more precise. This adaptability can be achieved by implementing an adaptive membership function, which is incorporated in the fuzzification segment of the fuzzy system, as illustrated in Fig. 2, with the remaining parts of the fuzzy system staying unaltered. This research aims to reduce the number of spectrum handoffs by making the right decisions by implementing a model Fuzzy with Adaptive Membership Functions (F-AMF).

This work makes the following contributions:

- System Fuzzy with Adaptive Membership Functions (F-AMF): Our technique introduces an adaptive membership function within fuzzy logic to address rapidly changing environmental conditions in CRN. Unlike fixed membership functions, this adaptation enables our fuzzy system to be more responsive and efficient in real-time decision-making, particularly in responding to fluctuations in factors like signal strength and interference levels.
- Minimize Unnecessary Spectrum Handoffs: The primary goal of our technique is to reduce unnecessary spectrum handoffs in CRN, which often lead to performance degradation. With the adaptive membership function, we achieve a balance between adaptability and stability, resulting in a more effective spectrum handoff decision-making approach and reducing interference with primary users.

The rest of this document is structured in the following: Section II offers a summary of pertinent studies, covering topics including spectrum handoff, fuzzy membership functions and the application of fuzzy logic in decision-making for spectrum handoff. Section III provides a detailed look at the Membership Function (MF) and linguistic variables and Section IV describes the methodology proposed. Section V delves into the outcomes and their analysis, concentrating on simulations, evaluations, discussions, and comparisons between the current system models and the suggested fuzzy system model. In the final section, Section VI, the document details its conclusions and offers insights into future research directions.

II. Literature Review

This section will briefly discuss several methods utilizing fuzzy logic for spectrum handoff in CRN. Naeem *et al.* [1] have developed a fuzzy logic-based system within cognitive radio environments to observe handoffs between primary and secondary users. This research proposes a hybrid system employing two-stage fuzzy logic controllers to reduce the number of handoffs caused by ping-pong effects. While this approach embraces the hybrid concept, errors in the fuzzy model or inaccurate data can lead to imprecise handoff decisions, thereby increasing the risk of interference or connection disruption.

To enhance the performance of handoff decision-making, researchers [14] have optimized the membership function shape in fuzzy systems using PSO. The aim is to achieve the optimal point of the membership function shape in fuzzy logic. Although it yields fewer handoffs than other fuzzy models, a more adaptive fuzzy model is required to support dynamic conditions.

Another study [15] suggests using a fuzzy logic-based scheme to enhance the spectrum handoff process, which considers factors such as interference, bit errors, and signal strength. This approach uses trained neural networks to assess channel gains through a fuzzy model. Although this approach enables more adaptive handoff decisions, its weaknesses include reliance on the accuracy of the fuzzy model and input data. Errors in the model or incorrect data can lead to inaccurate handoff decisions, increasing the risk of interference or connection disruption.

In the context of the IEEE 802.22 standard Wireless Regional Area Network (WRAN), a scheme has been proposed [16] to facilitate channel selection by Secondary Users (SUs). This scheme creates a list of backup and candidate channels, with fuzzy logic controllers determining channel priorities. This allows SU to select the best channels for their transmissions without disrupting PU transmissions. However, this method may face challenges in dynamic environments were PU transmission behaviour changes rapidly. The inability to quickly adapt to these changes could result in ineffective channel selections or interference with PUs.

Furthermore, in [17, 18], fuzzy logic-based schemes have been employed to address various challenges in CRNs, including SU mobility, link quality, and multi-attribute decision-making. While these approaches provide a comprehensive framework for decision-making, their weaknesses include the potential for errors in attribute weighting assignments and the complexity of integrating and analyzing various types of input data. Errors in these assessments could lead to suboptimal channel selections.

The current literature analysis in the field of CRNs highlights intensive research efforts, particularly in three main areas: channel selection, Primary User (PU) activity detection, and strategies for reducing channel handoff frequency. Reducing this handoff frequency is crucial, affecting spectrum efficiency and overall network performance. In this context, the fuzzy model approach with adaptive Membership Functions (MF) emerges as a promising solution for accurately reducing spectrum handoff frequency, thereby minimizing interference, and improving network throughput.

III. Membership Function (MF) and Linguistic Variables

Fuzzy logic is a mathematical modelling technique enabling us to handle uncertainty and ambiguity in decision-making problems. In fuzzy logic, variables can have values ranging from 0 to 1, representing the degree of membership of a variable in a certain set. This approach enables systems to reason based on imprecise rules and address the uncertainties present in Cognitive Radio Networks (CRNs) environments [6]. A Fuzzy Logic Controller (FLC) is a control system that employs fuzzy logic—a mathematical framework dealing with the degrees of truth and uncertainty—to mimic human decision-making processes. It is particularly effective in handling any complex systems with imprecise and uncertain input data. FLC uses linguistic variables and rules to make decisions and control a system, providing a flexible and intuitive approach to deal with non-linear and dynamic processes. Fuzzy Logic Controllers are applied in various fields, including engineering, automation, and artificial intelligence.

In systems employing fuzzy logic for decision-making, the membership function is of paramount importance. It forms the core of decision-making architecture in fuzzy logic applications [19]. The definition of the membership function is crucial in fuzzy logic, as its design significantly affects the system's decision consistency, precision, and overall quality [20]. In FIS, overlapping fuzzy segments, like High (H), Medium (M), and Low (L), categorize each input variable, ensuring the comprehensive coverage of the entire spectrum (or universe-of-discourse) for that input. These segments, defined by different membership functions, overlap, allowing an input value to be the part of multiple segments [21]. In both Mamdani-type and New Reasoning Fuzzy Method (NRFM) models, outputs undergo segmentation like inputs. In contrast, the Takagi-Sugeno-Kang type fuzzy model represents the output as a linear combination of input and output variables [22].

The preceding discussion highlights that the defining feature of a fuzzy system lies in its Membership Functions (MFs) [23]. Furthermore, Park *et al.* [24] noted that the nature and specifications of MF parameters within a fuzzy set are critical in dictating the performance of a Fuzzy Inference System (FIS). The heightened ambiguity, manifested as increased partitions, for instance, leads to a greater number of rules, consequently, making system responses slower. This slowdown was attributed to the augmented computational load required to process these rules prior to generate an output [21]. As such, the efficiency of a FIS is determined by various factors, including the count of partitions and the intricacies of the corresponding MFs.

Although Membership Functions (MFs) are crucial, they lack a standardized empirical approach for defining their shape, quantity, or scope. The selection of MFs typically relies on subjective criteria such as technical insight, intuition, specific application requirements, or the experience of the designer. Triangular MFs are commonly used in basic control applications, while Gaussian-shaped MFs are often favoured for tasks involving function approximation.

IV. Proposed Method

The main challenge in handling handoffs within CRN lies in their extremely dynamic environments, which demand a system adept at swiftly recognizing and adapting to changes. The fuzzy system emerges as a viable solution to this challenge, primarily because of its rapid computational capabilities that facilitate swift decision-making. This is possible in fuzzy systems as they employ a set of fuzzy rules, formulated from expert knowledge, for decision-making. With these rules established, the fuzzy system can quickly process inputs and produce decision-making outputs. This quick output generation, a characteristic of fuzzy systems, stems from their ability to directly derive outputs from established fuzzy rules, setting them apart from other methods like artificial neural networks or metaheuristic algorithms, which often require iterative processes for result generation. In making handoff decisions, the proposed fuzzy system considered three input parameters: hold time (HT), Psu, and Vsu, and generated an output, P_HO, which was then applied in handoff decision processes.

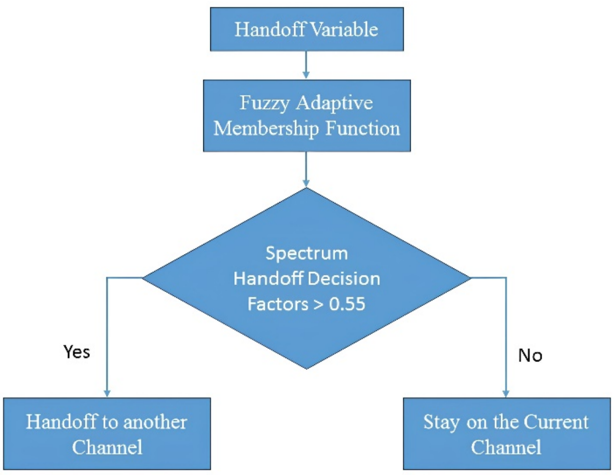

Fig. 3. The procedure for determining spectrum handoff.

Due to the highly dynamic environment of CRN, fixed membership functions are less suitable for real-world implementation. Therefore, membership functions must be adaptable to actual conditions. In such dynamic conditions, the performance of handoff decisions using a fuzzy system needs to be enhanced, through an ability to adjust to environmental conditions to produce more accurate decisions. This adaptability can be achieved by implementing an adaptive membership function. The fuzzification section of the fuzzy system employs the adaptive membership function, as depicted in Fig. 3, with the rest of the system's components maintaining their original state.

The adaptive membership function within the fuzzy system is shaped using three key parameters, as illustrated in Fig. 2 and detailed as follows.

- Adaptive Membership Function for Hold Time (HT)

HT represents the time during which the PU is not active on its channel. It indicates the anticipated time span during which the SU can use the licensed frequency band before the PU's reactivation [11]. A more extended holding time typically equates to higher quality. The decision to integrate HT as an input in the fuzzy system stems from the goal of reducing the ping-pong effect. To mitigate the frequency of handoff events, it is crucial to prevent a SU that has recently completed a handoff from immediately initiating another one. The adjustment value(Δmf_1)for the membership function is determined by calculating the difference between the current HT (HT_{now}) and the previous HT ($HT_{previous}$). This difference is then used to adjust the membership function's value. The initial step involves computing the variation between the current HT value ((HT_{now}) and the preceding HT value ($HT_{previous}$), using Eq. (1) as follows:

$$HT_{difference} = HT_{now} - HT_{previous} \quad (1)$$

Subsequently, this difference to set the value of Δmf_1, which would be used to modify the membership function was utilized. The adjustment value can be calculated by considering the difference and a predetermined adjustment factor, using Eq. (2) as follows:

$$\Delta mf_1 = f\left(HT_{difference}\right) \times HT_{adjfactor} \quad (2)$$

- $f\left(HT_{difference}\right)$ is a function that converts the HT difference into an adjustment value. A simple mathematical function, such as linear or exponential, can be used, which aligns with the characteristics of the changes wish to address.
- $HT_{adjfactor}$ is the adjustment factor that allows for controlling the extent to which the membership function will be adjusted based on the $HT_{difference}$. This factor can be set according to specific requirements.

The variation in HT is employed to modify the values of $[a, b, c, d]$ in the membership function. Mathematically stated, the modified values of $[a, b, c, d]$ are the default values plus the adjustment (Δmf_1), using Eq. (3) as follows:

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}^{\mu_{x1}}_{adjustment} = \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}^{\mu_{x1}}_{default} + \Delta mf_1 \quad (3)$$

The default values of $[a\ b\ c\ d]$ are $[0.2\ 0.4\ 0.6\ 0.8]$. The $adjfactor$ is an adjustment factor that allows for controlling the extent to which the membership function will be adjusted based on the HT difference with its value set to 0.5. μ_{x1} is the MF value of the fuzzy set input with $x1$ being the fuzzy system input of HT.

- Adaptive Membership Function for Power of Secondary User (Psu):

Psu represents an initial qualitative estimation of the distance among the SU and the PU to select an appropriate transmission power level for the SU (Psu) [25]. This helps the SU to avoid using excessive transmission power that can disrupt PU operations, despite uncertainties in distance estimation. In other words, this information aids the SU in making more informed spectrum handoff decisions and better spectrum management in the context of CRN. Psu serves as an input for the fuzzy system due to its direct relevance to data transmission quality. Consequently, Psu should be considered among the factors determining handoff decisions. To calculate the adjustment value (Δmf_2) for the membership function, the difference in Psu values was computed, and then the new MF value was set based on this difference in Psu value. First, the discrepancy the current Psu value (Psu_{now}) and the previous Psu ($Psu_{previous}$) was calculated using Eq. (4) as follows:

$$Psu_{difference} = Psu_{now} - Psu_{previous} \tag{4}$$

Subsequently, this difference was used to determine the value of Δmf_2, which would be employed to modify the membership function. The adjustment value could be calculated by considering this difference and a predetermined adjustment factor using Eq. (5) as follows:

$$\Delta mf_2 = f\left(Psu_{difference}\right) \times Psu_{adjfactor} \tag{5}$$

- $f\left(Psu_{difference}\right)$ is a function that transforms the Psu difference into an adjustment value.
- $Psu_{adjfactor}$ is an adjustment factor that facilitates control over the extent to which the MF is adjusted based on the Psu difference. This factor can be modified to suit specific needs.

The variation in Psu was employed to modify the values of $[a, b, c, d]$ in the membership function. Mathematically expressed, the adjusted values of $[a, b, c, d]$ are the default values plus the adjustment (Δmf_2), using Eq. (6) as follows:

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}_{adjustment}^{\mu_{x2}} = \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}_{default}^{\mu_{x2}} + \Delta mf_2 \tag{6}$$

The default values of $[a\ b\ c\ d]$ are $[2\ 8\ 12\ 18]$. The $adjfactor$ is an adjustment factor that enables control over the extent to which the membership function will be adjusted based on the Psu difference with its value set to 0.5. μ_{x2} is the MF value of the fuzzy set input with $x2$ being the fuzzy system input of HT.

- Adaptive Membership Function for Velocity of Secondary User (Vsu):

The velocity disparity between the current and preceding instances was computed under the assumption that the Secondary User (SU) furnished information regarding its speed at a specific moment. This variation in velocity was selected as one of the inputs for the fuzzy system owing to its association with the estimated lifespan of the connection. A higher velocity difference resulted in a shorter connection lifespan, as the SU left the channel more quickly. Conversely, a lower velocity difference would result in a longer duration of connection, as the SU could move along for a more extended period unless the Primary User (PU) is present. Therefore, the velocity difference is closely related to handoff decisions. The spectrum bands' availability underwent changes as a user transitions between different locations, posing a considerable challenge for continuous spectrum allocation in CRNs [11]. Velocity emerges as a crucial factor that initiates spectrum handoff and may contribute to challenges such as the ping-pong effect. To calculate the adjustment value (Δmf_3) for the membership function, the difference in Vsu values was computed, and then the new membership function value was set based on this difference in Vsu value. First, the difference between the current Vsu value (Vsu_{now}) and the previous Vsu ($Vsu_{previous}$), was calculated using Eq. (7) as follows:

$$Vsu_{difference} = Vsu_{now} - Vsu_{previous} \tag{7}$$

Subsequently, this difference was utilized to determine the value of Δmf_3, which would be used to modify the membership function. The adjustment value can be calculated by considering this difference and a predetermined adjustment factor using Eq. (8) as follows:

$$\Delta mf_3 = f\left(Vsu_{difference}\right) \times Vsu_{adjfactor} \tag{8}$$

- $f\left(Vsu_{difference}\right)$ is a function that transforms the Vsu difference into an adjustment value.
- $Vsu_{adjfactor}$ is an adjustment factor that allows for controlling the extent to which the membership function will be adjusted based on the Vsu difference. This factor can be tailored to suit specific needs.

The difference in Vsu was employed to modify the values of $[a, b, c, d]$ in the membership function. Mathematically expressed, the adjusted values of $[a, b, c, d]$ are the default values plus the adjustment (Δmf_3), using Eq. (9) as follows:

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}_{adjustment}^{\mu_{x3}} = \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}_{default}^{\mu_{x3}} + \Delta mf_3 \tag{9}$$

The default values of $[a\ b\ c\ d]$ were $[20\ 40\ 60\ 80]$. The $adjfactor$ is an adjustment factor that enables control over the extent to which the membership function will be adjusted based on the Vsu difference, with its value set to 0.5. μ_{x3} is the MF value of the fuzzy set input with $x3$ being the fuzzy system input of HT.

In the decision-making process for handoff, it is imperative to simultaneously consider the three parameters to derive a suitable P_HO for the handoff determination. Consequently, various conditions can be generated through the interplay of these three parameters. In this regard, an intelligent system that can factor in all three parameters for decision-making becomes essential, and the fuzzy system is considered a fitting approach, particularly when lightweight computation is favoured. To handle inputs and generate adaptive P_HO values, the fuzzy system incorporates multiple processing blocks, as depicted in Fig. 3.

V. Simulation Results and Discussion

This section will present simulation results using our proposed method, namely a fuzzy system-based approach with support from adaptive membership functions. We will compare these results with two existing fuzzy models, namely fuzzy hybrid [1] and Fuzzy MF Optimization with PSO [14]. The aim is to facilitate informed decision-making in matters of spectrum handover at CRN. The output of the fuzzy model uses five levels of linguistic variables, namely VL, L, M, H, and VH, which represent the possibility of spectrum handoff [1, 14]. Simulations were carried out using MATLAB software. The final decision to start handoff is based on fuzzy logic's output value [26]. In this research, the defuzzification process's output value exceeding 0.55 is considered a trigger to run the handoff process [8, 14]. However, if the value is equal to or less than 0.55, then no handoff will be performed, and the SU will remain connected to the current channel. Fig. 3 depicts the procedure for determining spectrum handoff.

The results achieved showed that the fuzzy system designed with an adaptive membership function succeeded in reducing the spectrum handoff frequency compared to the fuzzy system which already existed before. From these results, it can be concluded that reducing the ping-pong possible by effectively reducing the number of spectrum handoffs, which in turn increases the accuracy in the spectrum handoff decision-making process. In addition, a lower handoff frequency can prevent potentially detrimental interference to the PU.

In this section, an analysis will be conducted on the proposed method compared to previously existing systems. Firstly, the results from the fuzzy system research [1] and [14] were simulated and compared with the proposed system. In this study, we implemented scenarios to measure the performance produced by the fuzzy system with an adaptive membership function.

In this scenario, we applied the adaptive membership function model for all variables in FLC-2, as shown in Fig. 2. Based on the conducted tests, it could be observed that the model's performance with an adaptive membership function significantly reduced the number of handoffs. As depicted in Fig. 4, utilizing the threshold values outlined as in Fig. 3, it was apparent that multiple data points indicated a lower likelihood of handoff compared to the model with a fixed membership function. Therefore, the model with an adaptive membership function has a substantial impact on the decision-making process for spectrum handoff.

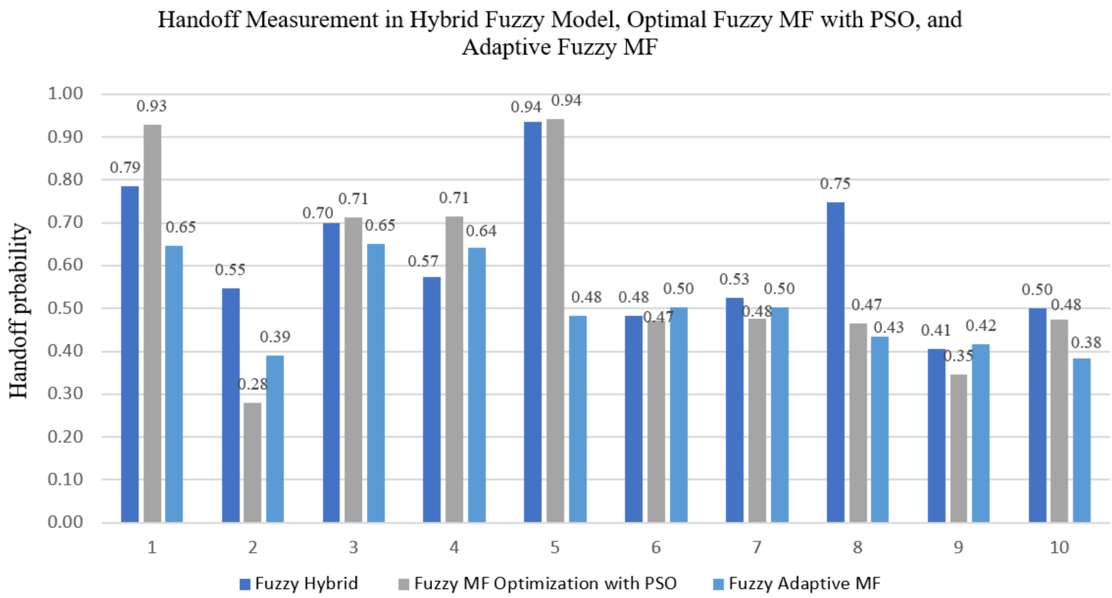

Fig. 4. Graph of handoff comparison results between hybrid fuzzy, fuzzy MF optimization with PSO, and fuzzy adaptive MF.

TABLE I. Comparison between Models with Fuzzy Fixed MF and Fuzzy Adaptive MF

Fuzzy Hybrid [1]		**Fuzzy MF Optimizatin with PSO [14]**		**F-AMF (Proposed)**	
Handoff Probabilities	**Condition**	**Handoff Probabilities**	**Condition**	**Handoff Probabilities**	**Condition**
0.79	Handoff to another channel	0.93	Handoff to another channel	0.65	Handoff to another channel
0.55	Stay on the current channel	0.28	Stay on the current channel	0.39	Stay on the current channel
0.70	Handoff to another channel	0.71	Handoff to another channel	0.65	Handoff to another channel
0.57	Handoff to another channel	0.71	Handoff to another channel	0.64	Handoff to another channel
0.94	Handoff to another channel	0.94	Handoff to another channel	0.48	Stay on the current channel
0.48	Stay on the current channel	0.47	Stay on the current channel	0.50	Stay on the current channel
0.53	Stay on the current channel	0.48	Stay on the current channel	0.50	Stay on the current channel
0.75	Handoff to another channel	0.47	Stay on the current channel	0.43	Stay on the current channel
0.41	Stay on the current channel	0.35	Stay on the current channel	0.42	Stay on the current channel
0.50	Stay on the current channel	0.48	Stay on the current channel	0.38	Stay on the current channel
Total of Handoffs	5		4		3

Table I compares values between three models: Fuzzy Hybrid, Fuzzy MF Optimization with PSO, and Fuzzy Adaptive MF. The table indicates a decrease in handoffs from 50% in the Fuzzy Hybrid model to 40% in the Fuzzy MF Optimization with the PSO model and 30% in the model with adaptive membership functions. These values are obtained from ten sets of test data results. The calculation of handoff percentage is presented as follows:

$$Fuzzy\ Hybrid = \frac{5}{10} \times 100 = 50\%$$

$$Fuzzy\ MF\ Optimizatin\ with\ PSO = \frac{4}{10} \times 100 = 40\%$$

$$Fuzzy\ Adaptive\ MF = \frac{3}{10} \times 100 = 30\%$$

$$Reduction = \frac{(5-3)}{10} \times 100 = 20\%$$

The findings above reveal significant differences in the effectiveness of reducing spectrum handoff among three fuzzy system models applied in cognitive radio networks. Using hybrid fuzzy logic, the first system recorded 5 handoffs out of ten sets of test data, resulting in a handoff rate of 50%. This indicates that half of the total test data experienced spectrum handoff. Then, the fuzzy MF optimization with the PSO model yielded a handoff rate of 40%. Meanwhile, for the proposed model, a fuzzy system with adaptive membership functions, only 3 handoffs were recorded out of ten test data sets, equivalent to a 30% handoff rate. This reduction reflects greater efficiency in spectrum management. Further analysis indicates a 20% reduction in handoff between the hybrid fuzzy model and the fuzzy model supported by adaptive membership functions, calculated from the difference in handoff frequency (5-3), divided by the total number of test data sets (10), and then multiplied by 100%. These results demonstrate that implementing adaptive membership functions in a fuzzy logic system can enhance spectrum utilization efficiency by reducing unnecessary handoff frequency, which is crucial for improving performance in cognitive radio networks. The use of ten datasets in this simulation aims to ensure that the testing of the three fuzzy models—Hybrid Fuzzy, Fuzzy MF Optimization with PSO, and Fuzzy Adaptive MF—is conducted under different input scenarios. By utilizing these varied conditions, the models can be evaluated more comprehensively in terms of their ability to efficiently manage spectrum handoff. This approach provides a more accurate picture of the models' performance in various real-world situations, allowing the results to reflect the effectiveness of reducing handoffs in different cognitive radio network.

VI. Conclusion

This research proposes adaptive membership functions in a fuzzy system designed explicitly for CRN. This approach addresses the challenges of rapidly changing environmental conditions and offers significant improvements compared to fixed membership functions. Our method significantly enhances real-time decision-making efficiency by enabling the fuzzy system to adapt dynamically to various factors, such as signal strength and interference levels.

The main achievement of this technique is a substantial reduction in unnecessary spectrum handoffs in CRN, a common cause of performance degradation. The adaptive nature of the membership functions provides an optimal balance between adaptability and stability. This balance ensures more effective spectrum handoff decision-making and reduces interference with primary users.

Empirical results from simulations are highly intriguing, demonstrating a considerable decrease in spectrum handoffs of around 30% over ten test iterations. This reduction underscores the effectiveness of the adaptive fuzzy membership function model in minimizing the frequency and potential errors in handoffs, thereby minimizing harmful disruptions to primary users, and reducing the occurrence of 'ping-pong' effects common in less accurate systems.

While the results are promising, it is important to acknowledge the limitations of this study, such as the dependency on simulated data which may not fully capture real-world complexities. Future work will focus on implementing this model in actual CRN environments to validate its effectiveness under varied and unpredictable conditions and exploring enhancements to further refine the adaptive capabilities of the fuzzy system.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Sampurna Dadi Riskiono developed the methodology, performed extensive simulations, and wrote the paper. Selo Sulistiyo and Wayan Mustika clarified and validated the problem formulation, as well as assessed the findings; all authors had approved the final version.

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