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Artificial intelligence based on fuzzy logic for a long-range radio frequency identification reader antenna

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ABSTRACT

The radiation pattern of radio frequency identification (RFID) antennas is influenced by various factors such as design, operating frequency, and polarization, which determine characteristics like directionality, omnidirectionality, beam width, and gain. Achieving precise readings over extended distances is crucial for the effectiveness of RFID systems, enabling faster item retrieval and delivery. The read distance, a critical aspect of RFID system performance, depends on factors like transmitted power, frequency, and antenna gain. Passive backscatter RFID setups particularly benefit from optimizing read distance for efficient operation. Fuzzy logic, as a soft computing technique, addresses uncertainties inherent in RFID systems effectively. This paper presents a novel approach to RFID antenna design, utilizing fuzzy logic to dynamically adjust frequency and power transmission. By enhancing field distribution, polarization, and received signal strength, this approach aims to optimize tag readings at extended distances, thereby improving overall system effectiveness. The methodology involves implementing algorithms in a C program to control the long-range distance aspects of the RFID system. Incorporating fuzzy rule algorithms into the RFID system's control logic enhances its ability to respond intelligently to changes in the operating environment, contributing to improved performance and reliability in long-range RFID applications.

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1. INTRODUCTION

The swift evolution of radio frequency identification (RFID) technology has significantly advanced automated identification and tracking of objects in warehouse [1], industry, supply chain [2], and commerce. Presently, there is notable interest in mobile ultra high-frequency RFID technology due to its cost advantages [3]. Utilizing the ultra high frequency (UHF) band in RFID systems, operating between 860 and 960 MHz, provides several advantages, such as high tag handling rates and contactless operation, which allows for an extended reading distance [4], [5].

Despite its increasing adoption, designing UHF RFID reader antennas remains challenging. Communication between readers and tags can occur through near-field (inductive coupling) or far-field (electromagnetic coupling) operations, depending on the application. Numerous studies have aimed to optimize the read range for specific use cases [6]-[9].

Recent advancements in RFID antenna design have addressed significant challenges in performance and adaptability. For instance, reflect array (RA) antennas designed for chipless RFID systems demonstrate enhanced ultra-wideband (UWB) performance, achieving up to a 1-meter reading range indoors while minimizing environmental reflections [10]. Similarly, wearable RFID systems benefit from innovative patch-type antennas that offer durability, flexibility, and long-range reading capabilities (up to 5 meters), making them ideal for human identification and tracking applications [11]. These developments highlight the ongoing efforts to improve RFID system performance for diverse applications, which align closely with the objectives of our study.

In the realm of RFID systems, the integration of artificial intelligence (AI) techniques has gained significant attention for addressing challenges such as distinguishing between static and moving tags in complex environments. For example, a recent study proposed a low-cost UHF-RFID portal enhanced with AI to classify tag movements in anti-theft systems for fashion stores, employing support vector machines (SVM) and long-short-term memory (LSTM) neural networks for data processing and validation through experimental analysis [12]. This highlights the potential of intelligent systems in improving RFID-based applications, motivating our approach to utilize fuzzy logic for enhanced control and classification in similar contexts.

However, creating RFID reader antennas that effectively perform in both near-field and far-field modes, while operating at the same frequency, remains a significant challenge [13]. Current designs, as seen in US patents [14], [15], often separate near-field and far-field functions into different frequency bands, which limits their versatility in various environments. There is a growing need for RFID reader antennas that support both short-range and long-range operations to accommodate diverse objects and applications [16].

Historically, scientific disciplines have used mathematical equations as a fundamental tool to model natural processes and predict the behavior of artificial systems with precision. While these models offer structured frameworks for analyzing complex systems, they often fall short when dealing with uncertainties or non-linear dynamics [17]. In RFID systems, the interaction between the reader and the tag can be accurately described using mathematical equations. However, by incorporating fuzzy logic, we introduce a more dynamic and adaptable method that adjusts the system's behavior in real time, particularly in scenarios where uncertainty plays a significant role.

Although the application of fuzzy logic in RFID antenna systems remains an emerging area, earlier foundational studies in RFID systems have laid the groundwork for exploring innovative approaches to address challenges such as signal interference and uncertainties. For instance, a study published in 2009 introduced a fuzzy antenna model and proposed two fuzzy logic methods for passive RFID tag localization. The first method facilitated the accurate localization of passive tags and the creation of an RFID-augmented map. In contrast, the second estimated the bearing of a tag relative to the robot. These methods demonstrated the effectiveness of fuzzy reasoning in addressing issues such as signal interference, reflections, and uncertainties in RFID systems, paving the way for subsequent research [18]. Building on this foundation, our work applies fuzzy logic to optimize RFID antenna performance for dynamic and long-range applications.

In this study, we introduce a novel approach to RFID reader antenna design by incorporating fuzzy logic to optimize frequency and power transmission. By adapting these parameters in real time, our method enhances field distribution and polarization without altering the antenna's dimensions or structure. This dynamic control of the RFID antenna's operational settings improves the received signal strength and optimizes the reading distance between the reader and the tag antenna.

The fuzzy logic system, implemented through a C program, converts crisp values of frequency and power transmission into fuzzy variables, allowing for the optimization of system performance. This adaptive framework effectively manages the uncertainties and imprecisions inherent in RFID systems, resulting in more reliable long-range operations. After implementing the fuzzy logic algorithm in C, the data results were plotted using MATLAB to visualize system performance and validate our approach. Our methodology models complex relationships by leveraging fuzzy rule-based systems and optimizes RFID performance across extended distances.

The paper is structured as follows: section 2 outlines the basic components of RFID antennas and discusses the impact parameters of the antenna on reading range distance. In section 3, we delve into the novelty of our RFID reader antenna design, highlighting the application of fuzzy logic in the antenna model. Section 4 presents the study's results, comparing the performance of conventional control methods with fuzzy logic and discussing the findings in detail. Finally, section 5 offers the conclusion and summarizes our study's key findings and implications.

2. THE RADIO FREQUENCY IDENTIFICATION ANTENNA SYSTEM

RFID is a technology that uses radio waves to transfer data wirelessly between a tag and a reader [19]. RFID technology consists of three components as shown in Figure 1: RFID tag, RFID reader, and antenna. RFID tags are compact devices comprising an electronic microchip encased within and accompanied by an antenna.

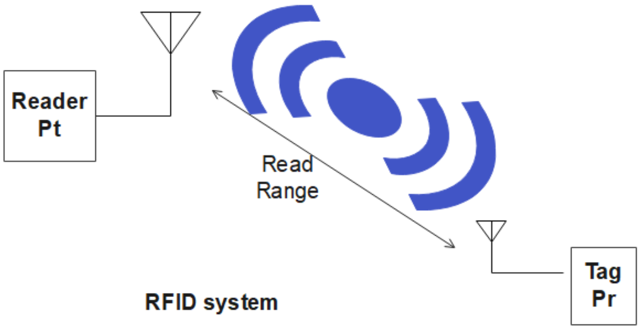


Figure 1. RFID system

An RFID reader is a key hardware element within the RFID infrastructure. It is responsible for retrieving data from RFID devices or tags and linking with the network to transmit this data to the database. The antenna is tailored to function at a designated frequency corresponding to the specific application it serves within the system.

The radiation pattern of an RFID antenna is influenced by factors such as the antenna's design, operating frequency, and polarization. This pattern can exhibit characteristics like being directional, omnidirectional, or having a specific beamwidth and gain in particular directions. Understanding the concept of the Friis transmission equation, formulated by Danish engineer Harald T, is crucial for optimizing the operational efficiency of RFID systems. The equation is depicted as (1):

$$d = (\frac{c}{4\pi f}\sqrt{\frac{P_t G_r G_t}{Pr}}) \tag{1}$$

where f is the frequency of the antenna, c is the speed of light, P_t is the transmission power, P_r is the receiver power, G_t is the transmission gain, and G_r is the receiver gain. This equation plays a pivotal role in determining the communication distance between RFID antennas.

The distance between the reader antenna and the tag antenna significantly affects the read range in RFID systems, which refers to the maximum distance at which the RFID reader can communicate with the tags. Improving the read range involves optimizing various factors to enhance signal strength and reliability. Strategies include utilizing higher gain antennas for longer read range and lower gain antennas for shorter read range or proximity scanning, increasing power transmission while complying with regulatory limits to avoid interference [3], and considering the frequency's influence on operational range, transmission speed, penetration capability through materials, and resistance to electromagnetic background noise [20].

Figure 2 illustrates the adjustments of power and frequency for achieving optimal reading range distance in traditional transmissions. The adjustments were programmed using a C program, while the results were plotted and visualized in MATLAB. The figure shows that while higher power transmission can increase the range, higher frequencies might reduce it. Proper calibration of power and frequency is essential for optimizing the read range in RFID systems.

Typically, RFID readers come with a base transmit power of either 0 or 10 dBm, with an upper limit ranging from 30 to 33 dBm. While various factors contribute to read range, including those discussed by [5], elevating the transmit power of an RFID reader generally enhances the potential read range of the system. The majority of RFID readers offer customization options for transmitting power within the specified range, allowing users to precisely adjust the power according to their application requirements.

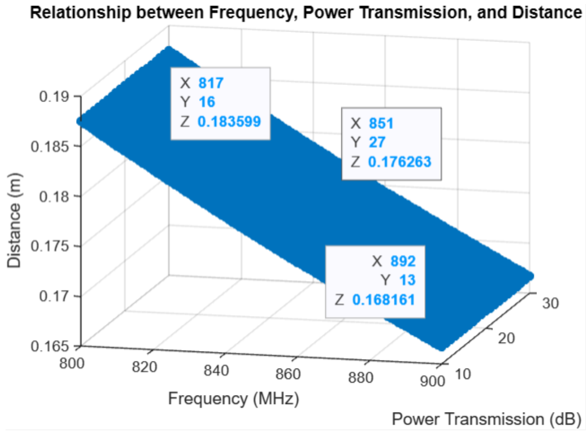


Figure 2. Adjusting power and frequency for a reading range distance

2.1. Path loss transmission

The attenuation of radio signals is a critical factor in shaping the architecture of radio communication and wireless systems. It influences various aspects of the system, including the transmitter power [21], antenna characteristics (such as gain, height, and placement), receiver sensitivity requirements, transmission format, and environmental factors. The surrounding environment, including obstacles and materials, can affect the propagation of electromagnetic waves and contribute to path loss.

In RFID systems, adjusting the transmission power and frequency is crucial for several reasons. By optimizing transmit power and frequency, you can extend or limit the communication range based on the specific requirements of the RFID application. Frequency selection is also crucial to avoid interference with other wireless systems operating in the same or adjacent frequency bands.

The path loss between the two antennas involved in communication is significantly influenced by the propagation environment, a subject that has undergone a thorough examination in wireless communication studies [22], [23]. The path loss for each frequency in the range is calculated using the Friis transmission (2).

$$PathLoss = (\frac{4\pi f d}{c})^2 \tag{2}$$

Figure 3 visualizes how path loss varies with frequency based on the Friis transmission equation. The plot helps to understand the relationship between frequency and path loss, which is crucial in the design and analysis of communication systems [24]. Higher frequencies generally result in higher path loss because of increased absorption and scattering in the environment. Furthermore, as the distance between the RFID reader and the tag increases, the path loss also increases. The relationship is often modeled considering the transmit power of the RFID reader, as a higher transmit power can compensate for the increased path loss to some extent.

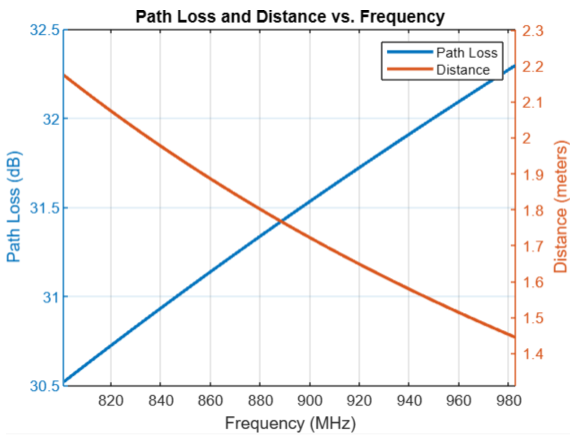


Figure 3. Path loss and distance vs frequency

Considering path loss is essential when increasing frequency and power transmission, as it directly affects the range, coverage, and overall performance of wireless communication systems. Engineers and designers must carefully analyze path loss to optimize system design, ensure reliable communication, and comply with regulatory requirements.

3. FUZZY LOGIC METHOD

AI is a synthetic form of intelligence that relies on human direction and decision-making to achieve optimal results. Despite its limitations, incorporating AI into adaptive and reconfigurable arrays holds potential advantages, as it allows for dynamic adjustments under human supervision to prevent errors [25]. To address these challenges in RFID antenna design, our study leverages fuzzy logic, a component of AI, to provide a more flexible and adaptable solution. Fuzzy logic provides a mathematical framework for reasoning and decision-making in uncertainty, ambiguity, and imprecision [26]. It enables the representation and manipulation of vague concepts where clear boundaries between categories are not defined [27], [28]. Fuzzy logic has found successful applications in various AI domains, including expert systems, control systems, pattern recognition, and decision support systems, particularly for modeling complex systems with uncertainty and subjective assessments [18].

Recent advancements in AI-driven RFID systems have demonstrated the potential of integrating AI for enhanced sensing and decision-making capabilities. For instance, machine learning algorithms, such as the NARX neural network, have been applied to RFID-based multi-sensing systems for food product quality assessment and sensing (QAS). This integration has enabled low-cost, real-time, and flexible quality assessment, demonstrating the significant role of AI in improving RFID system performance [29]. Building on this trend, our study focuses on the application of fuzzy logic to dynamically optimize RFID system parameters, addressing challenges related to long-range performance and environmental uncertainties.

In the context of adaptive control, fuzzy logic controllers can dynamically adjust parameters within antenna systems, such as power levels or frequency tuning, in response to changing environmental conditions [25]. For example, when disturbances or interference occur in the frequency spectrum, a fuzzy logic controller can adaptively modify transmission parameters to optimize performance. This study proposes employing a fuzzy logic approach to enhance the approximation of the extended range of the reader antenna in RFID systems. We demonstrate that fuzzy logic is well-suited for addressing uncertainty in RFID systems by employing a fuzzy inference system with two inputs (frequency and power transmission) and one output (distance read range), programmed in C for computational simplicity. The fuzzy logic approach to determine the distance involves several key steps, as Figure 4 illustrates. The process begins with the input variables, frequency, and power mapped to their respective membership functions. These inputs are then fuzzified, converting crisp values into fuzzy sets. The fuzzy inference engine applies the defined fuzzy rules to generate fuzzy output sets. Finally, the defuzzification process converts these fuzzy outputs into a crisp output value, representing the estimated distance.

In our study, we explore the representation of distance between short and long ranges using a membership function—a tool that captures the inherent vagueness in distance measurements. Employing a fuzzy logic approach introduces flexibility and adaptability into our representation of this spatial distinction, acknowledging and navigating the inherent imprecision in defining boundaries [25]. We opt for a fuzzy logic approach to provide a nuanced understanding of distance within our research scope. Figures 5 and 6 depict the trapezoidal membership functions, where the variable x represents distance, and parameters a and b determine the shape and transition points. These functions allow experts to effectively apply fuzzy logic principles in characterizing the boundary between short and long ranges.

Figure 6 illustrates the membership functions μ_{short} in Figure 6(a) and μ_{long} in Figure 6(b) concerning distance, including the transition region represented by μ_{exp}. The μ_{short} function begins with a membership value of 1 and decreases linearly to 0 as the distance increases. Conversely, the μ_{long} function starts with a membership value of 0 and increases linearly to 1. This setup allows for a clear transition between short and long distances, with μ_{exp} representing the intermediate values where the membership functions overlap.

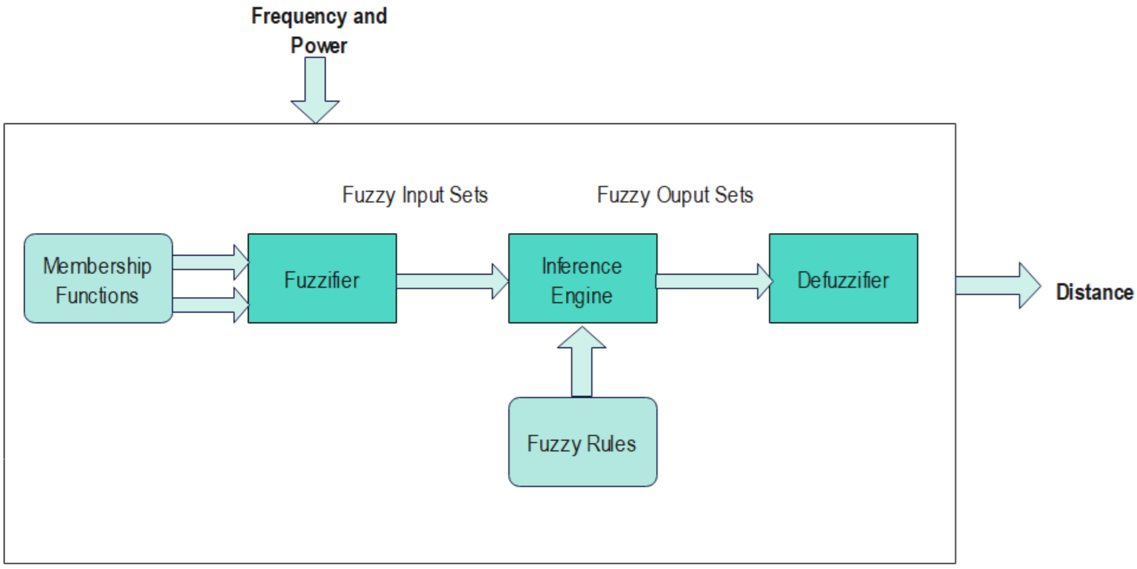


Figure 4. Fuzzy logic system

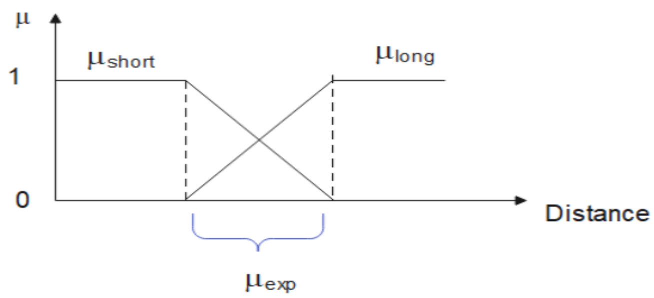
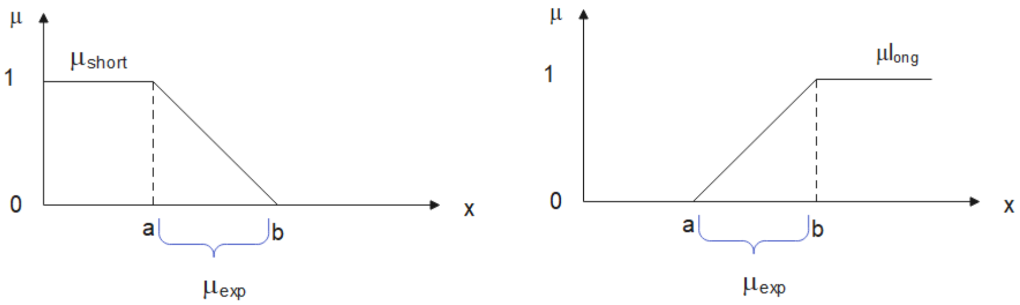


Figure 5. Trapezoid membership function



(a) (b)

Figure 6. Membership function; (a) short distance and (b) long distance

The trapezoidal membership function is mathematically defined as follows:

$$\mu_{short}(x) = \begin{cases} 1 & \text{if } x \leq a_{sh}, \\ \frac{b_{sh}-x}{b_{sh}-a_{sh}} & \text{if } a_{sh} \leq x \leq b_{sh}, \\ 0 & \text{if } x \geq b_{sh}. \end{cases}$$

$$\mu_{long}(x) = \begin{cases} 0 & \text{if } x \leq a_{long}, \\ \frac{x-a_{long}}{b_{long}-a_{long}} & \text{if } a_{long} \leq x \leq b_{long}, \\ 1 & \text{if } x \geq b_{long}. \end{cases}$$

The trapezoidal membership functions defined above $\mu_{short}(x)$ and $\mu_{long}(x)$ are essential components of our fuzzy logic approach for modeling the RFID reading range. C programming language can easily implement these functions to handle crisp frequency and power transmission values.

In a C program, we define a function to calculate these membership values based on the input values x, a, and b.

The fuzzy inference rules, summarized in Table 1, employ heuristic principles to model the RFID reading range, utilizing inputs such as frequency and power to determine the distance output. To compute the minimum and maximum operations, we utilize the following mathematical expressions:
Minimum (AND) operation:

$$\mu_{\min}(x) = \min\left(\mu_{\text{short}}(x), \mu_{\text{long}}(x)\right)$$

Maximum (OR) operation:

$$\mu_{\max}(x) = \max\left(\mu_{\text{short}}(x), \mu_{\text{long}}(x)\right)$$

Table 1. Fuzzy rules for modeling the RFID reading range

Rule	Input 1: frequency	Input 2: power	Output: distance
1	Low	High	Long range
2	High	High	Long range
3	Low	Low	Medium range
4	High	Low	Short range

Incorporating the AND operator into our fuzzy logic rules is pivotal in refining the decision-making process regarding distance characterization between short and long ranges. By utilizing the AND operator, we establish conditions that require simultaneous satisfaction for the rules to contribute to the overall inference. Unlike the OR operator, which results in a more inclusive condition by taking the maximum value. In the context of our membership functions for short and long ranges, the AND operator enables a nuanced assessment of situations where both memberships hold simultaneously. Mathematically, this is represented as the minimum operation. This approach enhances the precision of our fuzzy logic system, providing a more accurate representation of the ambiguous distance scenario between short and long ranges as seen in Figure 7.
For example, if:

$$\mu_{\text{Short Range}}(x) = 0.7 \quad \text{and} \quad \mu_{\text{Long Range}}(x) = 0.4$$

applying the AND operation would yield:

$$\min(0.7, 0.4) = 0.4$$

indicating the joint membership strength.

Two inputs are defined for each low and high, respectively. The output consists of three values labeled short range, medium range, and long range. The if-then rules for fuzzy inference are reported in Table 1, which consists of heuristic rules, such as:

IF frequency is low AND power is high THEN distance is long range.

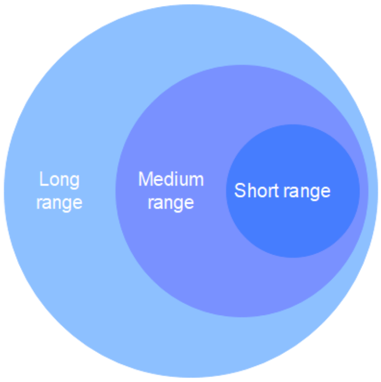


Figure 7. Illustration of ambiguous distance

3.1. Fuzzy parameters boundaries

The fuzzy inference system utilizes membership functions for the input variables, frequency, and power, as well as for the output variable, distance read range, as illustrated in Figures 8 and 9. Figure 8 illustrates the trapezoidal membership functions for the two inputs in Figure 8(a) frequency and Figure 8(b) power. In the realm of fuzzy logic design, these membership functions play a crucial role in gauging the level of uncertainty and establishing the extent to which an element is affiliated with a set, as expressed by its degree of membership [30].

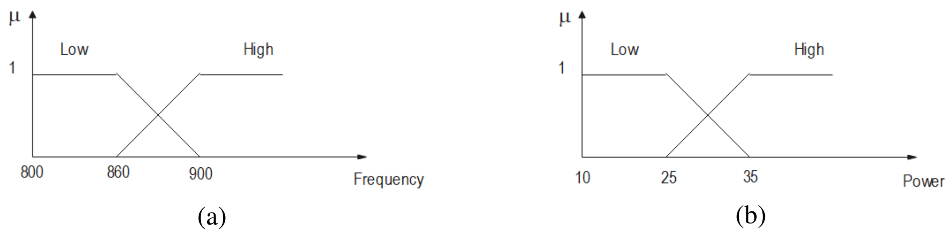


Figure 8. Fuzzy inference for; (a) frequency and (b) power transmission

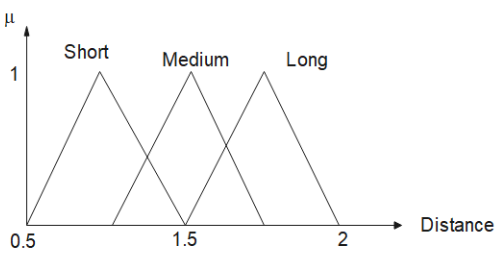


Figure 9. Fuzzy inference for distance

3.1.1. Frequency input 800-900 MHz

The frequency range was selected based on typical operational bands for UHF RFID systems, which commonly operate within the 860-960 MHz range according to EPCglobal standards. The selected 800-900 MHz boundary covers both lower and higher operational limits, ensuring compatibility with RFID systems in various regions [24].

3.1.2. Power input 10-35 dBm

The power input range reflects typical transmission power levels used in RFID systems. The lower limit (10 dBm) ensures sufficient signal strength for short-range communication, while the upper limit (35 dBm) is designed for long-range RFID applications, maximizing reading distance without exceeding regulatory power limits.

3.1.3. Distance output 0.5-2 m

The distance boundary reflects the typical range of RFID systems, where the minimum (0.5 m) corresponds to close-range identification, and the maximum (2 m) aligns with standard passive RFID tag reading distances, ensuring accurate fuzzy logic control for both short and long-range identification scenarios.

4. RESULTS AND DISCUSSION

This section presents a comparative analysis of conventional control and fuzzy logic-based systems in frequency, power transmission, and reading distance for long-range RFID applications. The system algorithms were implemented in C programming language, allowing precise control over frequency and power adjustments. The data results were then plotted using MATLAB to visualize the performance metrics effectively. The results are summarized in Table 2, which provides an overview of key performance metrics such as frequency, power transmission, and the corresponding reading distances.

Table 2. Performance comparison of conventional control and fuzzy logic in RFID systems

Frequency (MHz)	Power transmission (dBm)	Reading distance (m)	
		Conventional	Fuzzy logic
817	16	0.183	1.25
892	13	0.168	1.52
895	35	N/A	2.00

As shown in Figure 2, conventional control demonstrates a fixed relationship between power transmission, frequency, and reading distance. For example, at 817 MHz with a transmission power of 16 dBm, the reading distance achieved is 0.183 meters. However, this distance reduces as frequency and power increase due to system limitations and environmental factors. By contrast, fuzzy logic control introduces dynamic adjustments that enable the system to optimize reading distances over a wider range of conditions. Figure 10 illustrates how fuzzy logic mitigates the non-linearities and uncertainties present in real-world environments, resulting in more consistent performance. For instance, at 895 MHz and 35 dBm, the fuzzy system achieves a reading distance of 2 meters, compared to a maximum of 0.183 meters in the conventional system.

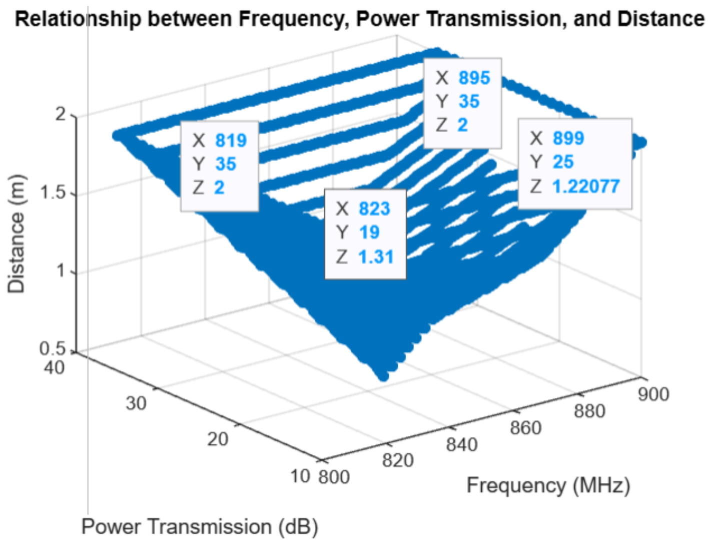


Figure 10. Enhanced control of frequency and power for long-range distance with fuzzy logic

The results indicate that fuzzy logic significantly enhances the performance of RFID systems in environments with variable conditions. Fuzzy logic allows the system to adjust dynamically to changes in power and frequency, leading to improved reading distances. In particular, fuzzy systems excel at handling non-linearities, ensuring that optimal performance is maintained even at higher frequencies and power levels. These findings suggest that fuzzy logic control is more effective than traditional systems for RFID reader antenna optimization, particularly in long-range applications.

The effectiveness of the proposed fuzzy logic control system can be further appreciated by comparing its performance with benchmarks in the literature. For instance, the work by [10] introduces a RA antenna for chipless RFID systems, achieving a reading range of 1 meter within an UWB frequency range of 4–6 GHz in a real-world indoor environment using a Universal Software Defined Radio Platform (USRP). While the RA antenna significantly improves gain and reduces sidelobe levels, it primarily targets UWB chipless RFID applications with specific hardware requirements.

In contrast, the proposed fuzzy logic system demonstrates its effectiveness within the UHF band (800–900 MHz), commonly used for RFID systems, achieving a simulated reading range of 2 meters. While this represents a substantial improvement compared to the RA benchmark, which achieves a 1-meter range, it is important to note that the comparison is based on differing conditions—our results are derived from simulations using a C-programmed algorithm, whereas the RA benchmark relies on experimental measurements with specialized hardware. Despite this distinction, the fuzzy logic approach offers notable advantages, including computational efficiency and flexibility, dynamically optimizing performance within a narrower frequency band without requiring complex hardware like RA antennas.

The proposed system is particularly well-suited for applications where cost-effectiveness, simplicity, and adaptability are critical. For example, in inventory management and logistics, where passive RFID tags are widely used, the extended reading range could significantly enhance the efficiency of tracking systems. Similarly, in anti-theft systems for retail environments, such as fashion stores, the ability to achieve a 2-meter reading range using a computationally efficient fuzzy logic system provides an appealing alternative to more complex or hardware-intensive solutions.

While the fuzzy logic control system demonstrates notable improvements, certain limitations must be acknowledged. The effectiveness of the system heavily depends on the design and tuning of the fuzzy membership functions and rules. The current implementation is tailored to a specific range of frequency and power values, limiting its adaptability to broader operating conditions. Additionally, external factors such as interference, tag orientation, and material properties were not fully explored in this study. These factors can significantly influence RFID performance in real-world scenarios.

Future work could focus on refining the fuzzy control model to address these limitations. Adaptive fuzzy controllers could be integrated to dynamically adjust membership functions based on environmental factors. Furthermore, a comprehensive investigation into the effects of interference, tag orientation, and material properties on reading distance would provide valuable insights and further enhance the system's robustness. Finally, experimental validations in diverse real-world scenarios are essential to confirm the practical applicability of the proposed approach.

5. CONCLUSION

This study demonstrates the practical advantages of applying fuzzy logic to enhance RFID system performance, particularly in optimizing power transmission and frequency for extended reading distances. By effectively managing non-linearities, fuzzy modeling overcomes the limitations of conventional control methods, resulting in more robust and efficient RFID systems that operate reliably under varying real-world conditions. This work significantly contributes by introducing a novel AI-driven approach for RFID antenna systems. By employing fuzzy logic to dynamically adjust system parameters, this study provides a computationally efficient and adaptable solution for applications such as inventory management, supply chain optimization, and anti-theft systems. This approach sets a new benchmark for precision and flexibility in RFID system design.

The findings underscore the potential of advanced AI techniques, like fuzzification, in improving the reliability and scalability of RFID systems, making them better suited for modern industrial demands. Additionally, this research provides valuable insights for industries where RFID technology plays a central role, highlighting its practical implications for improving operational efficiency. Looking forward, this study establishes a foundation for integrating fuzzy logic with machine learning techniques to enable real-time decision-making and further enhance system intelligence. Future research could focus on experimental validation in diverse environments and explore adaptive fuzzy controllers to dynamically address external factors such as interference, tag orientation, and material properties. By bridging theoretical modeling with practical applications, this work paves the way for advancing RFID technology and other wireless systems requiring effective uncertainty management.

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C : **C**onceptualization
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I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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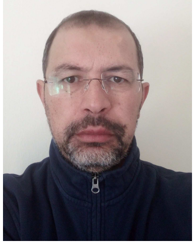

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