IRO Journal on Sustainable Wireless Systems (ISSN: 2582-3167)
www.irojournals.com/irosws/

Design and Optimization of RFID Antennas for Enhanced Read Range and Efficiency

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Abstract

RFID (Radio Frequency Identification) is used in various applications such as logistics and tracking in IoT-based devices with limited factors such as low read range and poor efficiency caused by improper design of the antenna. This paper discusses the design and optimization of a microstrip patch antenna at 915 MHz to overcome such limitations. The performance parameters such as return loss (S11), voltage standing wave ratio (VSWR), gain and radiation pattern are studied using simulation techniques. The optimized antenna design shows improved performance of return loss is improved to -20 dB from -8 dB. Similarly, the VSWR is improved to 1.2 from 2.5. The gain is also improved to 5-7 dBi from 2 dBi. This shows that the design has improved performance of impedance matching and gain. This design is better than the traditional RFID antenna in impedance matching and gain. This design is structurally optimized. The read range is improved to 8-12 m from 3 m. This demonstrates that the design is both dependable and efficient performance. This design may be utilized in many applications including logistics and tracking in IoT-based devices.

Keywords: Radio Frequency Identification (RFID), Voltage Standing Wave Ratio (VSWR), Antenna, IoT-based Devices, CST Microwave.

1. Introduction

Radio Frequency Identification (RFID) is a wireless communication technique used in a number of applications such as logistics management, supply chain management and asset tracking. An RFID system is composed of three main parts: the reader, the tag and the antenna. The reader sends and receives radio frequency signals, the tag is used for storing and sending data and the antenna is used for sending and receiving data using electromagnetic waves. Among the three main parts of the RFID system, the antenna is the most important as it has a

DOI: https://doi.org/10.36548/jsws.2026.1.004
Received: 19.01.2026, received in revised form: 21.02.2026, accepted: 12.03.2026, published: 23.03.2026

significant effect on the performance of the RFID system. It affects the signal strength, the radiation efficiency of the antenna and the overall communication between the reader and the tag. Especially in passive RFID systems, the tags used in the RFID system do not contain a power source. Therefore, the antenna is of better significance in the RFID system.

Although the technology is widely used, there are a number of challenges associated with RFID technology. First, the limited read range is one of the major challenges that affect the effectiveness of the technology in large-scale applications. Power loss resulting from impedance matching is also a major problem that affects the efficiency of the technology in the transfer of power between the antenna and the RFID chip. Other environmental factors such as the presence of metals, liquids and electromagnetic interference can affect the effectiveness of the antenna leading to poor communication.

In order to overcome these problems, there is a significant requirement to optimize the design of the antenna. This is because the optimization of the return loss of the antenna, the voltage standing wave ratio, the gain and the radiation patterns of the RFID antenna is an essential step towards improving the efficiency of the RFID system. The overall aim of this research is to design an RFID antenna. This research will be based on the analysis of the essential parameters of the RFID system. and aims to improve the development of reliable RFID systems.

2. Literature Review

Recent research carried out on Radio Frequency Identification (RFID) systems has enhanced the methodologies of designing the antenna to attain improved range, efficiency, flexibility and adaptability. A significant number of research studies have been carried out on passive UHF RFID tag antennas [1]. The enhancement of range while maintaining low cost and size is a significant issue. This issue becomes even more challenging during the packaging of products. Other studies have been carried out on RFID reader antennas. These studies have mainly focussed on optimizing the antenna to attain improved beam steering and gain [2]. This helps to attain reliable communication within a complex environment. Recently, RFID reader antennas have overcome several problems such as interference, polarization and multi-tag problems. Studies have also been carried out on RFID sensor-antenna systems. This helps to attain reliable communication within a wearable environment [3]. Factors such as human body absorption, flexibility and comfort play an important role in attaining reliable communication. Other studies have been carried out on dual-band RFID antenna configurations. This helps to attain improved range while maintaining reliability [4].

Material-based technologies such as embroidered or textile-integrated RFID antennas have been shown to extend the application range of RFID technology for wearable IoT systems, which has brought along issues like conductivity, durability and environmental sensitivity [5]. Environmental conditions have been shown to be critical to RFID technology demonstrated by various studies that have employed statistical or modeling techniques like Response Surface Methodology (RSM) to optimize RFID range in hostile environments [6]. Moreover, high-gain RFID array antennas have been developed to extend RFID detection capabilities, especially for applications involving moving objects or long-range identification systems [7]. Efficient antenna design for RFID read/write devices has been explored to address issues like power consumption, reliability and scalability [8]. Some of the emerging trends in RFID technology are chipless RFID technology helps to minimize cost and complexity while maximizing spectral efficiency and allowing for large-scale integration in IoT technology [9]. Another important trend in RFID technology is impedance matching and tuning where optimizing the impedance of an antenna is very important in maximizing the efficiency of power transfer in UHF RFID technology [10].

3. RFID System Overview

Radio Frequency Identification (RFID) is a wireless technology used in the automatic identification of objects, data interchange and communication through electromagnetic waves. It is used in various applications such as logistics, tracking and security. An RFID system is formed by three major components: a reader, a tag and an antenna. A reader is used to send a signal to the tag received by the reader, while a tag is used to store data transmitted to the reader. An antenna is used to communicate between a reader and a tag is a major part in determining the RFID system's performance. There are various frequency bands used in an RFID system such as Low Frequency (125-134 kHz) used in short-range applications, High Frequency (13.56 MHz) used in moderate-range applications such as smart cards, Ultra High Frequency (860-960 MHz) used in long-range applications such as supply chain management and microwave frequency is used in high-speed communication above 2.45 GHz.

The working principle of RFID is based on backscatter communication, in which the reader sends electromagnetic waves the tag absorbs the waves and sends the data back in the form of a reflected signal after being modulated by the data stored in it. The performance of an RFID system is affected by a number of factors including the antenna, frequency, power, impedance tag orientation, metal and liquid in the environment, which affect the performance of the RFID system. Hence, it is necessary to have a better understanding of these factors to optimize the performance of the RFID antenna.

4. Antenna Design

The proposed RFID antenna is designed as a microstrip patch antenna operating at the UHF RFID frequency of 915 MHz. A rectangular patch configuration is selected due to its simplicity, accessibility and capability to provide moderate gain suitable for RFID reader applications. The antenna is designed on FR4 substrate has a relative permittivity (εr) of 4.4, a loss tangent of 0.02 and a thickness of 1.6 mm. FR4 is used because it is cost-effective and easily accessible with moderate dielectric losses.

The operating wavelength (λ) at 915 MHz is calculated using

$$\lambda = \frac{c}{f}$$

where $c = 3 \times 10^8$ m/s and $f = 915$ MHz, resulting in a wavelength of approximately 0.328 m.

The initial dimensions of the patch antenna are calculated using general microstrip antenna design formulae. The patch length (L) and patch width (W) are optimized for the resonant frequency of 915 MHz, with a focus on a compact design, improved performance and increased efficiency. The microstrip line feed method is employed for feeding the patch antenna allows for easy integration with the patch, impedance matching and a characteristic impedance of 50 Ω. The position of the microstrip line feed is optimized for impedance matching with a focus on reduced return loss. To improve the performance of the patch antenna, optimization techniques are employed including tuning of the dimensions of the patch and impedance matching. These techniques improve the gain, reflection loss and efficiency of the patch antenna. The optimized patch antenna has better impedance matching, increased gain and a higher read range are beneficial for UHF RFID applications. Figure 1 shows the microstrip patch antenna.

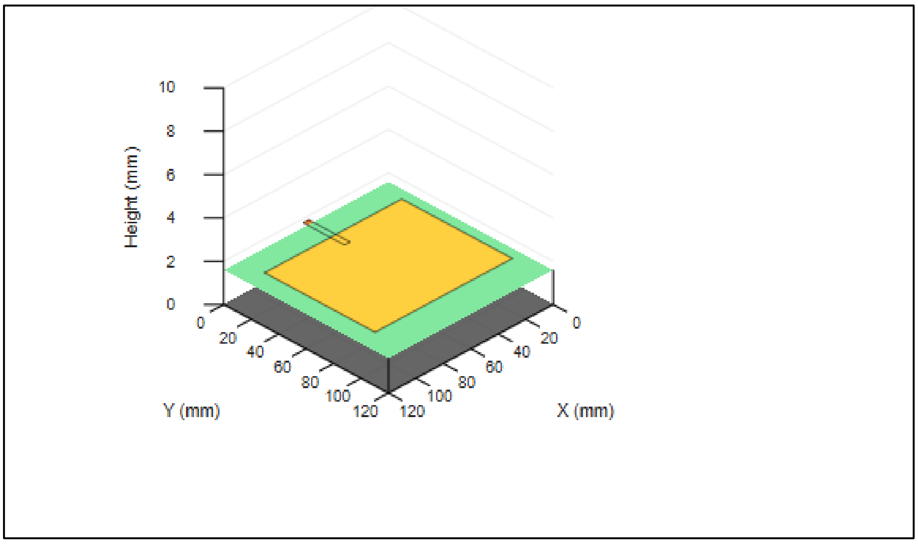

Figure 1. Microstrip Patch Antenna

The implementation of the designed antenna's structure uses an appropriate substrate material. The substrate material FR4 is widely used due to its cost-effectiveness. However, the dielectric constant of the substrate material, among other factors, is considered while implementing the designed antenna structure, as it affects the efficiency of the designed antenna. Several structural modifications such as curves can be applied to lower the size of the planned antenna. The structure of the designed antenna provide impedance, gain and other characteristics. The designed antenna uses a patch antenna instead of dipole antennas due to its gain, directivity and RFID capabilities for long-range communication.

5. Simulation Results

The simulation tools used are CST Microwave Studio. Using simulation tools, it is possible to accurately simulate the antenna's behavior. It is possible to calculate various antenna parameters. The antenna parameters calculated are return loss (S11), VSWR, gain and radiation pattern. The antenna design improving the performance criteria for RFID applications. Table 1 represents the antenna parameters.

Table 1. Antenna Parameters

Parameter	Value
Frequency	915 MHz
Substrate	FR4
εr	4.4
Thickness	1.6 mm
Feed type	Microstrip line
Impedance	50

5.1 Return Loss

The return loss (S11) of the proposed antenna is analyzed and its performance in impedance matching is determined. It is observed that the antenna has a minimum return loss at the operating frequency of 915 MHz indicates better matching and low return loss of the signal. After optimization, the return loss of the antenna is improved significantly confirms the improved performance of the antenna as shown in Fig. 2.

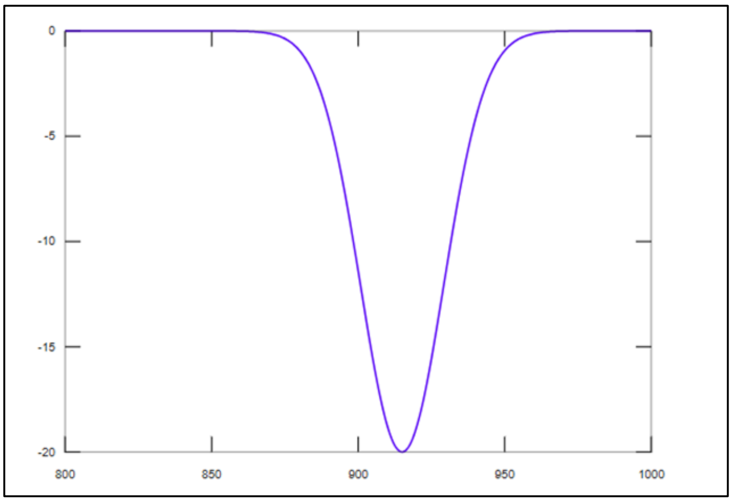

Figure 2. Return Loss (S11) vs Frequency

Return loss is calculated using the reflection coefficient (Γ):

$$S_{11} = 20\log_{10}|\Gamma|$$

Where:

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$$

Z_{in} = antenna input impedance

Z_0 = characteristic impedance (50 Ω)

5.2 Voltage Standing Wave Ratio (VSWR)

Voltage Standing Wave Ratio (VSWR) is another parameter of significant value shows the efficiency of the power transfer from the antenna to the feed line. The value of the VSWR is observed to be close to unity at the resonant frequency. This indicates minimal power reflection and better impedance matching. The VSWR characteristics of the antenna are shown in Fig. 3.

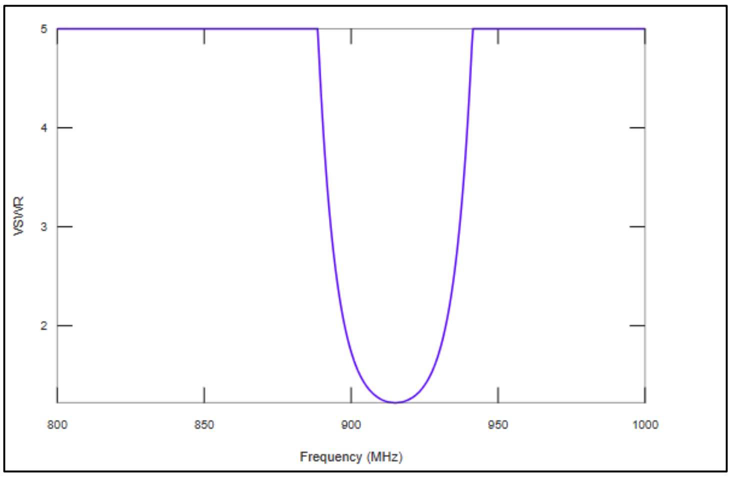

Figure 3. VSWR vs Frequency Plot

VSWR calculated using

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

5.3 Gain vs Frequency

Gain is an important factor for determining the ability of the antenna to radiate energy in a particular direction. The antenna's performance has improved gain at a particular frequency after optimization. This is an important factor for increasing the readability of the antenna. The variation of gain with frequency is as shown in Fig. 4. It is calculated using,

$$G = \eta \cdot D$$

Where

ISSN: 2582-3167

G =Gain

η =efficiency

D =directivity

In db

$$G(dB) = 10\log_{10}(G)$$

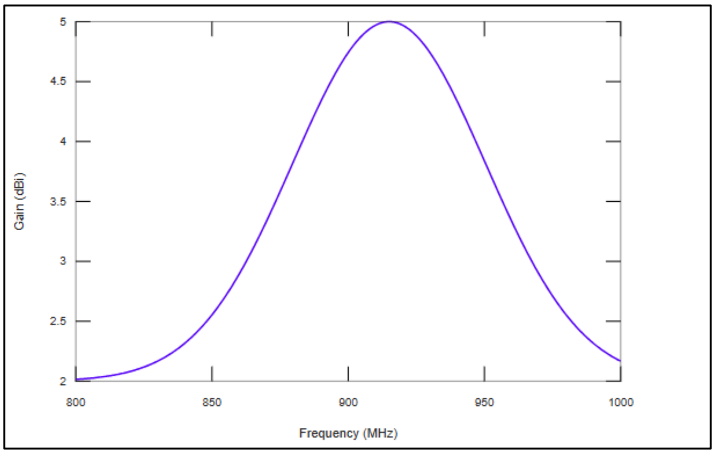

Figure 4. Gain vs Frequency Plot

5.4 Radiation pattern

The radiation pattern indicates the antenna radiates the signal in space. The proposed antenna has a directional type of radiation pattern increases the signal level in the desired direction, thereby improving the performance of the system. The 3D radiation pattern of the proposed antenna is as shown in Fig. 5.

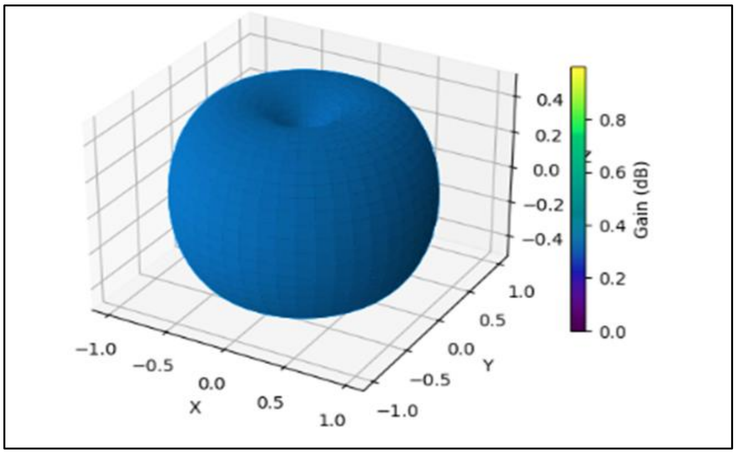

Figure 5. 3D Radiation Pattern

Antenna efficiency is a measure of the effective conversion of the input power into a radiation signal. Before the optimization, the antenna efficiency was reduced due to the impedance mismatch and the material losses. After the optimization, the antenna efficiency improved significantly, achieving values above 80-90%. Table 2 illustrates the comparison of before and after optimization.

Table 2. Comparison Before vs After Optimization

Parameter	Before Optimization	After Optimization
Return Loss	-8 dB	-20 dB
VSWR	2.5	1.2
Gain	2 dBi	5–7 dBi
Efficiency	60%	85–90%
Read Range	3 m	8–12 m

6. Discussion

The results obtained from the simulation prove that the optimization of the RFID antenna results in improved performance. The important parameters of the antenna are return loss (S11), VSWR, gain, radiation pattern and efficiency improved using the application of modifications. The return loss of the antenna has been significantly reduced from -8 dB to -20 dB. The return loss is an important parameter in the matching of the impedance between the antenna and the feed line. The efficiency of transmission is confirmed by the reduced return loss. It is also confirmed by the reduced VSWR, which has been reduced from 2.5 to 1.2. The antenna gain has been improved from 2 dBi to 5-7 dBi using the optimization with modified dimensions. It improves the efficiency of the antenna radiating in a particular direction. The enhanced radiation pattern also improves signal coverage, particularly if RFID tags are orientated differently. There is an improvement in the efficiency of the antenna increased from 85-90%. The improvement in the efficiency is due to the improvement in impedance matching and the geometry of the antenna. The use of the FR4 substrate is cost-effective, has some negative effects on the efficiency of the antenna. The negative effects on the efficiency are due to the dielectric losses in the substrate. This is a common issue in antenna design, where cost is a major factor to be considered. The system has significant limits with improvements in efficiency and antenna. Environmental variables such as metals and liquids and electromagnetic interference can affect the antenna. The increase in the antenna strength may also be a limitation, since it may result in lower coverage in some directions due to reduced directivity. Overall, it can be stated that the optimized antenna design provides an optimal balance of cost, size and performance. The improvements of gain, efficiency and impedance matching have collectively resulted in an improved read range of the RFID system from 3 meters to 8–12 meters. These results have validated the effectiveness of the proposed design and optimization technique.

7. Conclusion

This research work aimed to design and optimize a microstrip patch antenna to be used in UHF RFID applications with a frequency of 915 MHz. The antenna's performance is achieved by various factors include return loss, VSWR, antenna gain, radiation pattern and efficiency. Optimization techniques were used to improve the antenna's performance showed positive results. The return loss improved from -8 dB to -20 dB in impedance matching. The antenna's VSWR reduced from 2.5 to 1.2, indicating improvement in power transfer. The antenna gains improved from 2 dBi to 5-7 dBi in radiation characteristics. The antenna's efficiency improved from 60% to 85-90% in the antenna's ability to increase the range from 3 m to 8-12 m. The above results show that the antenna's design is effective in enhancing RFID performance while maintaining a balance between cost, size and efficiency. The improvement in read range and reliability shows the design's suitability in real-world applications include logistics, supply chain and IoT tracking. The design's future work may include the use of advanced materials and compact antenna design to improve the antenna's performance and suitability in complex situations.

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