

Performance Evaluation of Radio Frequency Identification Tag Antenna for Commercial Applications

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Article Info	Abstract
Received 30/07/2024	<p>Radio Frequency Identification (RFID) has emerged as an effective technology for automatic identification across industries due to its capability to use radio signals while providing security. The most common type is the passive RFID tag, consisting of an RFID chip and an antenna. The tag's antenna plays a crucial role in determining system performance and impacting various metrics. This paper investigates different designs of commercial tag antennas. With computer processing, selecting the optimal design for business applications becomes more flexible, minimizing the need for specialized expertise. These tags are widely available at low costs, reducing reliance on antenna design tools. The procedure outlined in this paper provides a method for evaluating tag performance. Three standard Ultra High Frequency (UHF) RFID antenna models- tag 1, tag 2, and tag 3- were simulated and evaluated in the 0.6-2 GHz range using the Antenna Toolbox in MATLAB. Comparison metrics include return loss, mismatch loss, bandwidth (BW), and current distribution. The second tag design achieved the best return loss of 18 dBm and a lower Voltage Standing Wave Ratio (VSWR) of 1.4 dB, while the first design offered the longest range between the tag and the reader.</p>
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1. Introduction

Since 2008, the potential of Near Field Communication (NFC) technologies has been highlighted by the NFC Forum, discussing all issues that could be impacted by its adoption in different daily life activities. Many benefits can be achieved, especially in marketing and financial applications [1]. This led to the adoption of a low-cost, acceptable-range communication technology, besides the availability in different sizes and types, represented by Radio Frequency Identification (RFID), the new competitor technology for the next years [2]. The widely used UHF RFID technologies are grounded in UHF Electronic Product Code (EPC) standards that cater to logistics and supply chain operations, as well as NFC standards for scenarios that involve item identification by end users [1]. The high communication speed at distances up to about 10 m provided by UHF RFID makes it an efficient technology for object tracking in many applications, including localization, monitoring, and control of various items [3]. Nowadays, the large-scale and low-cost printing of RFID tags has become a competitive alternative to barcode technology because it allows quicker identification with much fewer reading errors and a long reading range [4].

From another point of view, the diverse specifications for each component of an RFID system need a thorough evaluation relative to the application requirements to select the most suitable RFID system. Consequently, the logical subsequent action is to establish guidelines for the RFID implementation process [1]. Hence, it can be concluded that the efficiency of RFID is governed by many factors. RFID tag's antenna and the propagation environment are significantly affected factors. The tag's antenna design directly affects the operating frequency and antenna gain and hence determines the power scattered back to the reader. Accordingly, the readable range, which is directly affected by the power received by the reader, the tag configuration and antenna dimensions, even that the stocked material [5]. Accordingly, understanding tag characteristics is mandatory for verifying the compliance of an RFID product in the required applications.

For people who are not specialists in the field and employ this technology for a unique aspect in their work (e.g., factory and workshop managers), they need as little information about the suitable technology they depend on and their characteristics. A variety of standard UHF RFID tags are commercially available in the market, but they are not necessarily convenient for the

target application. Each application has its specifications, including the environment, the nearby objects, the desired read range, etc. [6].

From the commercial customer side, it is difficult to make an accurate decision about choosing the appropriate tag without analyzing its performance. The variety of RFID tags makes it a hard mission to distinguish their slightly different performance. Therefore, in this work, flexible software will be introduced that analyzes the performance of standard commercial UHF RFID tags, which easily visualizes and reflects their characteristics. This program is built with the aid of image processing and antenna tools in MATLAB, offering resources and support for the selection process and empowering non-experts to make well-informed choices, while also enhancing the overall efficiency and effectiveness of RFID technology in practical applications.

The rest of this paper will be organized as follows: some of the researchers' works in the field of RFID are illustrated in Section 2. The general theoretical background about RFID technology is illustrated in Section 3. In section 4, the methodology of this research is explained with the metrics used for evaluation. The results of this work are pictorialized and discussed in section 5. Finally, the main contribution points and significant results are concluded in section 6.

2. Literature Review

Standard RFID tags are widely spread in the markets for different applications due to ease of implementation and low printing cost. Nowadays, RFID employment is involved in recent IoT network applications [7]-[10]. RFID's scientific role is extended beyond identification and packaging to a wider range of applications such as recognition, healthcare applications, etc. [11]-[13]. This stimulates researchers to investigate this powerful technology from different perspectives.

Shao [14] presented a multi-layered material based on designing broadband RFID tag antennas. The performance of the antenna in terms of impedance matching and the radiation pattern is evaluated according to the effect of different dielectric materials. Then, this antenna is fabricated and embedded in a tire, where it has been experimentally proven to be more efficient than the commercial one. The RFID system was tested by Wang and Alexander [5]. The system performance was investigated under the influence of RF attenuation, tag material, and angle orientation. Two experimental scenarios: fixed transmitting power and fixed readable range. The experimental results show that RF attenuation has a significant effect on the read range. In contrast, tag antenna orientation has the least influence on read range, while tag material may be the most effective parameter. Chen et al. [15] proposes a new ceramic material to design an RFID microstrip antenna that has the best performance values at specific operating frequencies. The simulation results by the HFSS software verify that the designed antenna meets China's UHF broad applications requirements. In a study conducted by Dobkin and Weigand [16], a comparison between two commercial antenna tag designs (I-tag and M-tag) was performed in terms of read range

and reflection coefficient at different frequencies. These two types were constructed and tested, and calibration was needed due to mismatches resulting from fabrication. The experimental results show that the read range is affected directly by the nearby materials, especially metals and liquids. The forward link and backward link are determined in terms of outage probability for a UHF RFID system, as discussed by Grosinger [17]. This study aims to quantify the appropriate power needed for reliable backscattered communication based on the link budget estimation. The experiment is conducted in a wireless body area network with custom-built monopole or patch antennas operating at 900 MHz or 2.45 GHz and for different stationary and moving body postures. The outcome of this study demonstrates that both operating frequencies are feasible for such a communication system, while the monopole acts as a more efficient antenna than the patch antenna. Mouzouna et al. [18] designed an UHF RFID antenna to be tagged to a glass bottle, and different paper substrates were studied. The design was implemented based on the meander technique, and the simulation was performed for the whole system: the glass bottle and the designed antenna. The system assessment was materialized by reading range, reflection coefficient, and radiation pattern. The dimensions of the RFID tag antenna are optimized by Jouali et al. [19]. The cost function is to reduce the effect of the capacitance introduced by the analog characteristics of the antenna by proposing an open L-shaped stub. The obtained results showed an improvement in reducing the mismatch and improving the return loss. Liu et al. [20] analyzed the performance of an RFID tag antenna designed in HFSS and visualized it using absorption rate images. Accordingly, they were able to correct the antenna parameters to overcome the mismatch problem. They concluded that the antenna can be redesigned easily based on their image analyses to meet the application requirements. Marques et al. [4] discussed the effect of printed RFID configuration and factors on the readable range. The results showed that varying the film thickness and increasing the number of layers can directly affect the readable range and hence determine the suitable application.

Rizzi et al. [1] compared an RFID inlay equipped with an innovative integrated circuit with standard tags commonly used in the EPC and NFC fields. This research provides the IT and logistics managers with useful information to understand and evaluate tag performance and which would be the best choice for a specific RFID application.

Based on the preceding discussion, it is observed that researchers often concentrate on either the design of antennas or the analysis of pre-designed antennas from a singular viewpoint. In contrast, this work seeks to offer a comprehensive analysis tool that enables users to make well-informed decisions by considering multiple factors that meet application requirements. This research presents a software package specifically developed for non-experts looking to acquire a range of pre-designed commercial RFID tags for diverse applications.

3. Aspects of RFID Technology

RFID technology was first introduced in the mid-20th century as part of war technology, and then it rapidly developed and

penetrated over a few years. The RFID system is composed of a reader, antenna, and tag. During the operation, the reader sends a query signal to the tag by its RF transceiver on the system's operating frequency. The tag responds to the reader by modulating the received signal according to the tag data and using back-scatter radiation to send the modulated signal back to the reader [21]. Fig. 1 depicts the RFID system [22].

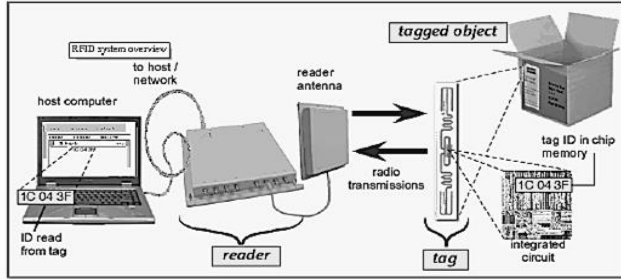


Figure 1. RFID System Overview. Reprinted from DigitalCommons@CalPoly, C. Kam, "902-928MHz UHF RFID Tag Antenna Design, Fabrication and Test", California Polytechnic State University, 2011: RFID System Overview, fig 1.1, page2, under CC BY 4 license [22]

Tags are available in two types: active and passive tags, and each type has its advantages and disadvantages. Active tags are supported by the embedded battery. Accordingly, they do not need activation from the RFID reader. Also, they have large storage capacity and strong signals, which make them less interfered with by nearby electromagnetic fields. Recently, active tags have been introduced with the new ability to be programmed and integrated with other techniques for smart self-powered [23]. On the contrary, passive RFID emits a signal when it is activated by the reader signal and is based on backscattering techniques. Also, it has the lowest cost, smallest size, short response range, and long lifetime [22]. Passive RFID tags are usually more dependent due to simplicity and low fabrication cost. It can be defined as an inactive, real-time secured mechanism [24].

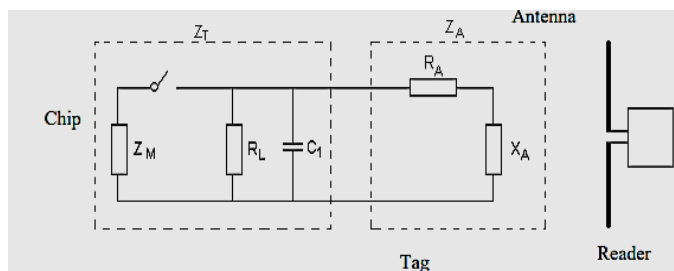


Figure 2. Equivalent circuit of RFID tag. (Reprinted from DSpace software, Z. Li, "Characterization and performance analysis of UHF RFID tag for environmental sensing applications," University of Waterloo, 2012: Figure 17: Equivalent circuit model of a typical tag, page 33, under CC BY 4 license [2])

It can be noticed that the read range of the RFID reader is determined by many factors. Besides the environmental effects, RFID tag antenna design is a significant factor that, in turn, controls the gain and operating frequency of the system. As with any other antenna, the RFID antenna must be designed accurately to achieve the required performance by reducing the

reflection coefficient, which is an indication of the matching between the tag antenna and the chip. Fig. 2 depicts the RFID tag antenna equivalent circuit [2].

As shown in Fig. 2, the impedance is modulated during the backscattering process, generating corresponding voltage variations at the reader. Z_A and Z_T are the impedance of the antenna and the RFID chip, respectively, which are mathematically expressed by the equations (1), and (2) [25]:

$$Z_A = R_A + jX_A \quad (1)$$

$$Z_T = R_T + jX_T \quad (2)$$

R_A , R_T , X_A and X_T are the real and imaginary parts of Z_A and Z_T respectively. To gain maximum power transfer, $R_A = R_T$ and $X_A = X_T$ must be verified.

4. System Model

The contribution of this work is to introduce reliable software to analyze the available designed tags. This software can be used by the vendor (before marketing) and the customer (before purchasing) to evaluate tags' performance and determine the key elements that influence implications trade-offs on the usage of these tags.

4.1. Tag Design Simulation Method

The design and evaluation of tags are usually implemented by special software like HFSS and CST programs, which can be used by electromagnetic engineers and require many precise details, while in this work the performance of the tags can be evaluated using MATLAB software, which is more widely used, and there is no need for details because it is based on the analysis of the tags' antenna images. The Morphological Toolbox supported by MATLAB is being used in this part, as explained in Fig. 3.

4.2. Readable Range

One of the key metrics that evaluate an RFID system is the read range. In order to quantify the performance in terms of maximum distance that can be achieved between the reader and the tag, the link budget formula must be used. Equation (3) represents the free space link budget, which is used to calculate the power received by the tag as below [26]:

$$P_{tag} = P_{reader_{tx}} - Loss_{sys} + G_{reader_{tx}} + G_{tag} + 10 \log_{10} \left(\frac{\sigma}{4\pi} \right) - 20 \log_{10} \left(\frac{4\pi}{\lambda} \right) - 40 \log_{10}(d) \quad (3)$$

Where $P_{reader_{tx}}$ (dB) is the power transmitted by the reader, P_{tag} (dB) is the power received by the tag, $G_{reader_{tx}}$ the gain of the reader antenna, G_{tag} the gain of the tag, σ is the radar cross section of the tag, λ is the wavelength and d is the distance (m) between reader and the tag.

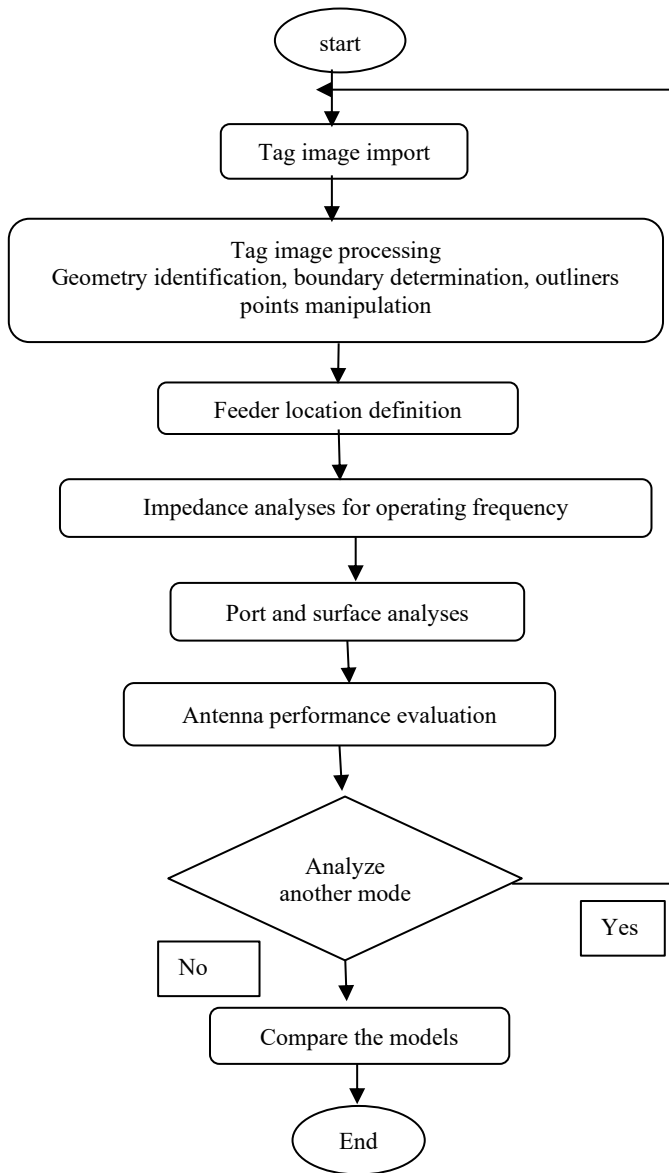


Figure 3. System Model

Radar cross section (σ) can be expressed as a function of return loss (Γ) as in below [26]:

$$(\sigma) = \frac{G_{tag}^2 \lambda^2 |\Gamma|^2}{4\pi} \quad (4)$$

It can be noted that return loss (Γ) has a significant influence on the readable range.

As mentioned above, the tag responds to the reader via backscattering mode. Accordingly, the backscattered power to the reader can be determined by equation (5) [26]:

$$P_{reader_{rx}} = P_{reader_{tx}} - Loss_{sys} + G_{reader_{tx}} + G_{reader_{rx}} + 20\log_{10}(\Gamma) + 2G_{tag} - 40\log_{10}\left(\frac{4\pi}{\lambda}\right) - 40\log_{10}(d) \quad (5)$$

Where $P_{reader_{rx}}$ and $P_{reader_{tx}}$ are the powers transmitted and received by the reader transmit and receive antennas, $G_{reader_{tx}}$ and $G_{reader_{rx}}$ are the gains of the reader transmit and receive antennas and $40\log_{10}(d)$ is the free space path loss for the two-way path. It is expected that additional loss will be added due to environmental effects, such as the material that the tag will be mounted on, and this point is out of the scope of this research and is suggested as future work.

4.3. Performance Evaluation

The performance of tags is being analyzed and evaluated, materialized by the following metrics:

1. The impedance antenna is represented by an electronic circuit and the RFID chip as in Fig. 2. Each impedance is a complex number, where the imaginary part indicates the load type (inductive or capacitive). As the impedance varied with frequency, the imaginary part fluctuated around 0 Ω . It can determine the operating frequency of the antenna, which is the point where the impedance equals zero.

2. Return Loss (Γ) is an indication of the mismatch between the tag antenna and chip as formulated below [27]:

$$\Gamma = -20\log_{10}\left(\frac{Z_a + Z_c}{Z_a - Z_c}\right) \text{ dB} \quad (6)$$

A higher value of return loss indicates a high mismatch as the power transferred to the chip is less.

3. The radiation efficiency is related to the Voltage Standing Wave Ratio (VSWR) as in 7. VSWR is an indication of the voltage standing wave pattern in the transmission line due to the phase constructive or destructive between the reflected and incident waves which reduce the power gain [28].

$$VSWR = \frac{10^{\frac{\Gamma(dB)}{20} + 1}}{10^{\frac{\Gamma(dB)}{20} - 1}} \text{ dB} \quad (7)$$

4. Mismatch Loss (ML) is a way to quantify the reflected power due to the mismatch between the load and the source and can be determined as below [29]:

$$ML = 10 \log_{10} [1 - \Gamma^2] \quad (8)$$

5. Results and Discussion

Three models of RFID tag antennas, as in Fig. 4, are adopted from internet images to analyze their characteristics with the aid of an image processing tool and the antenna toolbox in MATLAB 2020a. All three tags have the same outer dimensions (18.6x72.3 mm), feed width of 0.5 mm, and the feeder is located at the center. In contrast, the inner dimensions (the slot depth and length) present the differences in these tags' design, as obviously shown by Fig. 4 and Fig. 5.

In the first stage, the three images are processed to get binary clear images with obvious boundaries, removing all outlier points and covering all holes resulting from unclear or distorted images. Fig. 5 represents the three designs after preprocessing. In addition to this stage, the feeders' locations are identified, preparing these models for performance analyses. At first

glance, the three designs may appear similar, but the slight variation in the thickness and length of the slot affects the antenna properties. This is where antenna simulation tools play a role in highlighting these differences, as will be explained through the obtained results.



Tag 1



Tag2

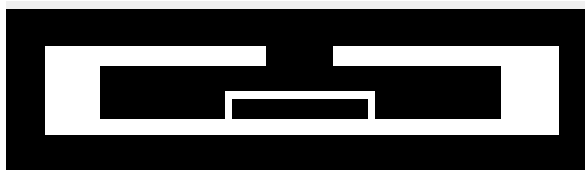


Tag3

Figure 4. RFID tags' images



Tag1



Tag2



Tag3

Figure 5. RFID tags' images after processing

The first port analyses are to compute the impedance of the three tags over a range of frequencies from 7 MHz to 2GHz, as in Fig. 6. All three types have a complex input impedance with inductive reactance that behaves normally at the selected range of frequencies. Each tag's impedance indicates a parallel

resonance frequency where the reactance equals zero and can be modeled by a parallel RLC circuit.

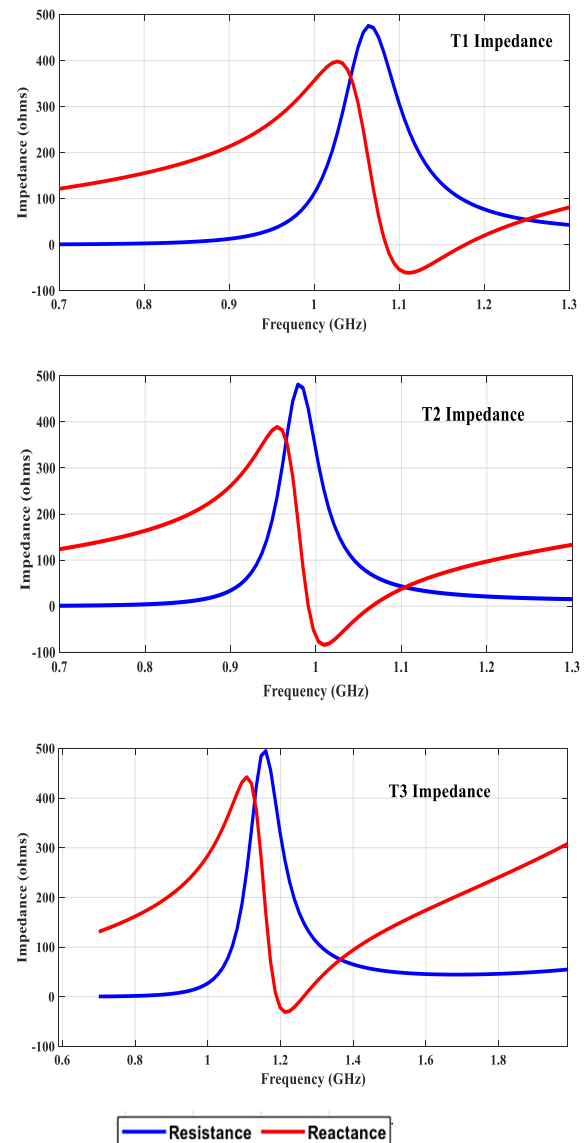


Figure 6. RFID tags' antenna impedance

Another pictorial representation is the Smith chart in Fig. 7, verifying the parallel resonance of the three models. Moreover, it can be noticed that the normalized impedance indicates a mismatch and needs to be compensated by adding a predetermined load at the feed.

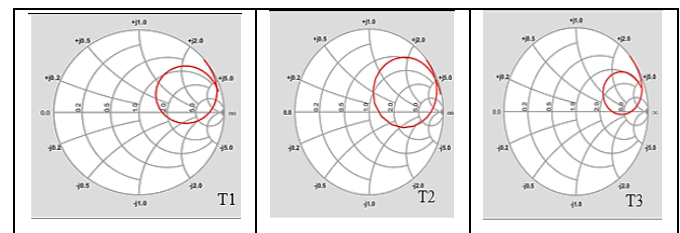


Figure 7. Smith chart of the three tags' impedance

Return loss defined is another form of analysis as in Fig. 8. Commonly, the parameter S11 is used to quantify the amount of power reflected back and not delivered to the antenna. From

the literature, it is recommended that the return loss should be less than -10dB since 90% is delivered and 10% is reflected, with an acceptable voltage standing wave ratio equal to 2. Fig. 8 shows that tags 1 and 2 provide 12dB and 18dB return loss, respectively, while only about 7.5dB return loss is generated by tag 3. According to [27], the voltage standing ratio can also be concluded from Fig. 8, as it is related directly to the return loss. Tag 2 outperforms tags 1 and 3, with a voltage standing ratio of 1.288; tag 1 has a voltage standing ratio of 1.671, and tag 3 shows performance degradation with a high voltage standing ratio of 2.4. The Bandwidth (BW) at which each antenna operates can also be determined in Fig. 8. The minimum BW gained by tag2 equals 40 MHz, which is almost equal to tag1 BW. Tag3 antenna BW is vague since the BW is usually calculated from the intersection with a 10dB which is not verified in the case of tag3.

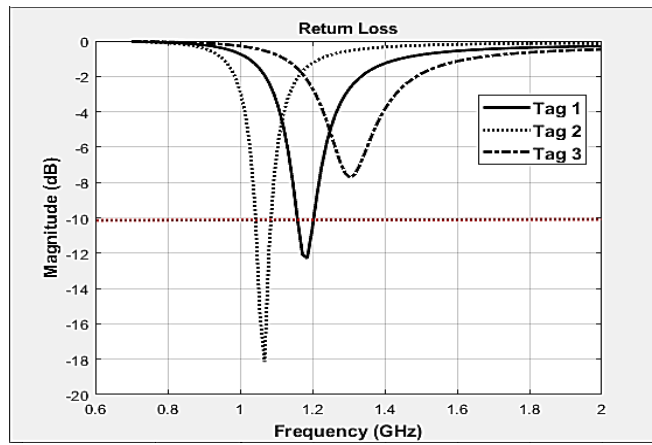


Figure 8. Return Loss

Fig. 9 clarifies the VSWR for the three tags' model. Again, it shows that tag 2 provides less VSWR equal to 1.4 dB, followed by tag1 and tag 3, where their VSWR are respectively.

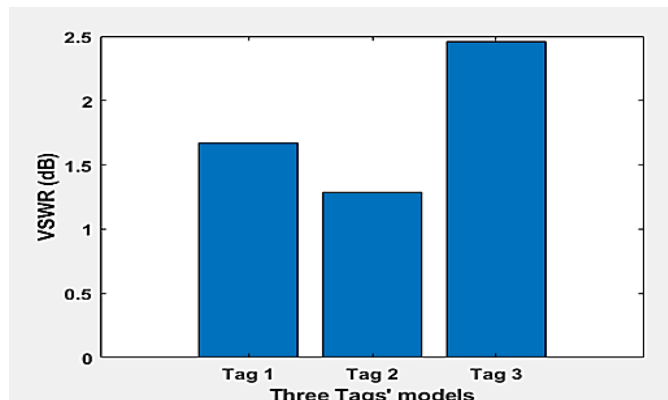


Figure 9. Voltage Standing Wave Ratio

Fig. 10 depicts the mismatch loss as calculated using Eq. (5). This figure shows the three resonance frequencies, where the power delivered to the load is maximum. The operating frequencies of tag 1, 2, and 3 are 1.186 GHz, 1.07 GHz, and 1.304 GHz, respectively.

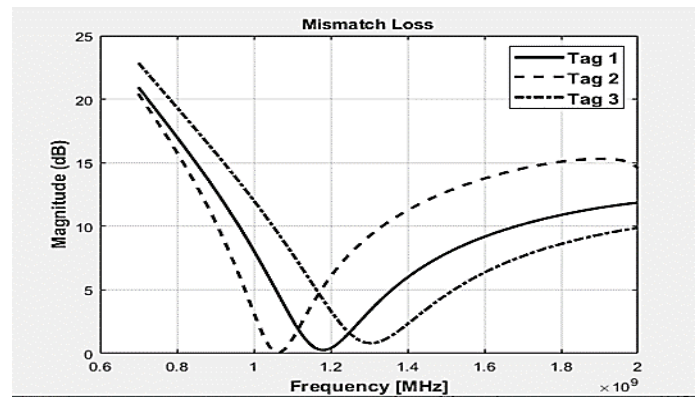


Figure 10. The mismatch loss

Finally, antenna surface performance, materialized by the current distribution investigation at their operating frequency, is conducted as in Fig. 11. All three models present an evenly low field density moving along the antenna. The three tags' current distributions behave naturally, starting with a higher value at the feeder (where the radiated power is significant) and degrading gradually towards the end segments. Tag 2 outperforms other models, where the field density at the input port equals 18 A/m, while tag 1 and tag 3 equal 14 A/m and 9 A/m respectively. Higher current distribution results in higher radiation power efficiency; however, the field variation along the tag also affects the performance. From this point of view, tag1 provides more typical field variation and hence more potential range.

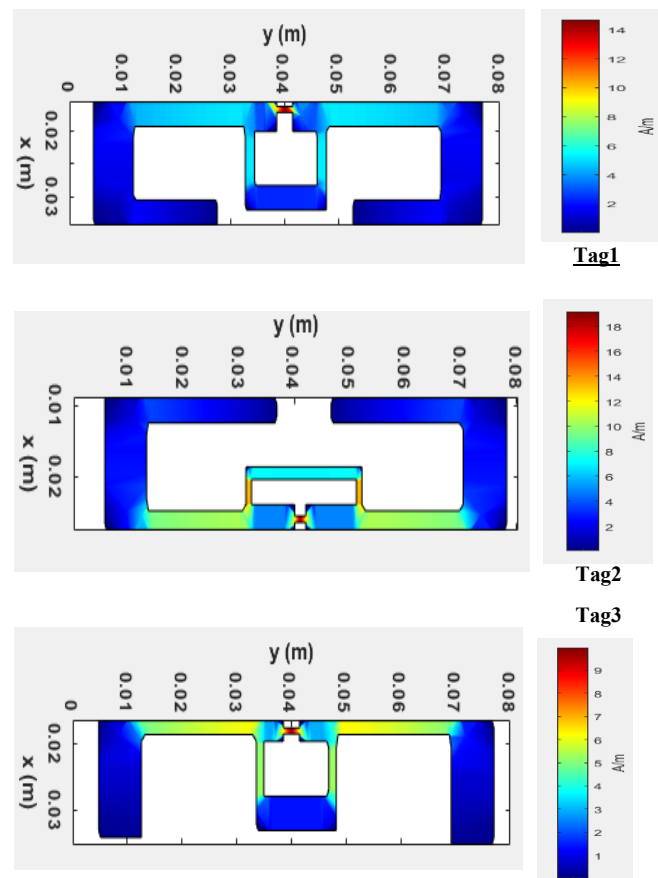


Figure 11. The three-tag model current distribution

The above results provide an in-depth analysis of each RFID tag antenna's characteristics. However, from a commercial point of view, knowing the appropriate distance between the reader and the tag also needs to be calculated for a comprehensive evaluation. Fig.12 represents the relation between the reader power received versus the distance at the operating frequency based on 5. For transmit power (5dB), reader antenna gain (3dB), and tag gain (2dB), Tag 1 has the highest range, equal to (7.5m) when the reader received power equals (-60 dB). Tag 2 range equals to (5.5m) and tag 3 range equals to (4m) at the same received power.

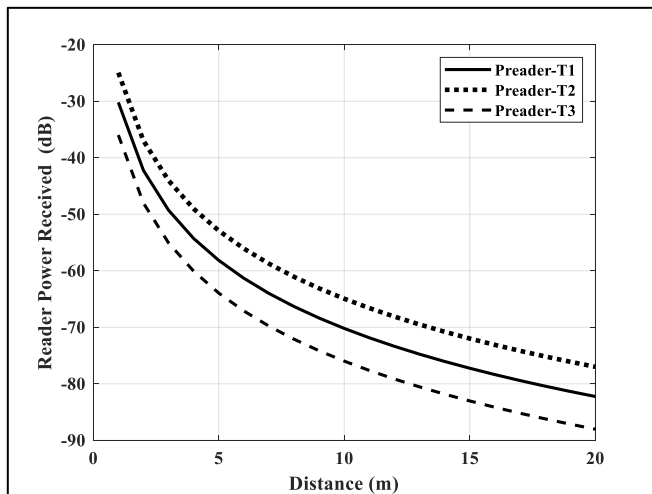


Figure 12. Reader received power vs. readable range

6. Conclusion

In this paper, three RFID antenna tag models were introduced pictorially to analyze their performance based on image processing and the Antenna Toolbox in MATLAB. The proposed procedure used for selecting the best antenna performance among candidate antenna design models facilitates the way for customers to make a judicious decision that is appropriate for their applications. Return loss, VSWR, and mismatch loss are used for antenna port analyses. Moreover, the current distribution has been examined to investigate the antenna surface analyses. The impedance test, along with the link budget assessment, contributes to a thorough evaluation of each RFID antenna. From the obtained results, it can be seen that antenna model 2 proves to be the best design. Its characteristics, concluded from the results, show (return loss of 18 dB, VSWR equal to, and a minimum 40MHz BW at a resonance frequency of 1.86 GHz), which is considered acceptable in applications in the UHF band.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. Additionally, the research was conducted without any financial support or sponsorship that could have influenced the results or interpretations.

Contribution of authors

Aseel Hameed Alnakkash conceived the study, designed the research methodology, and wrote the manuscript. Conducted the performance analyses and simulations using MATLAB.

Jumana Abdulhadi Jarallah assisted in the literature review, provided input on the design aspects of RFID antennas, and contributed to the analysis and interpretation of results.

Ali Salman Kurji provided technical guidance on RFID technology, contributed to the discussions surrounding the results, and reviewed the manuscript for coherence and completeness.

Use of LLM and AI

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Data Availability

Not applicable.

Conflict of interest

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