A novel reverse design method of tag antenna based on image analysis

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Abstract
Since the working efficiency of the entire radio frequency identification system depends on the performance of the radio frequency identification tag antenna, the research and design of the tag antenna have received attention, especially for radio frequency identification tags applied to special scenes. We mainly studied the effect of antenna bending on the performance of ultra-high frequency radio frequency identification systems, and combined the bent antenna with the impedance matching loop to achieve impedance matching between the chip and the antenna in the ultra-high frequency band. We analyzed the variation of tag antenna performance with antenna parameters by the simulation software High Frequency Structure Simulator (HFSS). At the same time, we propose a novel antenna reverse design method. Through the analysis of the antenna-specific absorption rate image, the antenna performance intensity is visually reflected. According to the image analysis result, the antenna parameters are corrected to improve the antenna matching performance. This design method is simpler and faster than other methods.

Keywords
Radio frequency identification, image analysis, impedance matching, return loss, reverse design

Introduction
Radio frequency identification (RFID) technology is a non-contact identification technology, which has the advantages of large information capacity, strong adaptability, and high precision. RFID technology is widely used in daily life and gradually penetrated all fields of people’s study, life, and work. In order to meet the needs of people’s ever-changing and rapid growth of information, RFID technology has been recognized by more and more people and has become a hot research field.

Ultra-high frequency (UHF) RFID technology is widely used due to its long reading range and low cost. The RFID system includes an antenna, a reader, a tag, and a management system. The most important part is the RFID tag. The tag antenna receives the RF signal from the reader and transmits the chip data to the reader through backscattering. So, the tag performance depends mainly on the antenna. In UHF RFID tags, not only conjugate matching of chip impedance and antenna impedance is required but also the antenna has good directivity.

The design of the tag antenna is based on the application requirements of the antenna, and the different requirements are derived from the actual application environment of the tag. At present, the main research contents of UHF RFID tags are focused on RFID system application design,¹ tag chip research, and antenna optimization design. In terms of antenna design, it mainly focuses on the improvement of antenna performance,² ³ such as antenna and chip impedance matching,⁴ increasing the tag bandwidth and...
reducing the return loss. Although there are many UHF antenna structures, the main research object is the dipole tag antenna.

UHF antennas are basically designed to miniaturize or resist metal interference on the basis of dipole antennas or to improve antenna performance. Yang proposes a polarization diversity antenna composed of two dual-planar inverted-F antennas. The antenna can work with a linearly polarized antenna with any polarization direction and the antenna can operate normally on a metallic medium. However, the return loss of the antenna is very low, which requires high antenna incident power. Hamani designed a new UHF antenna that covers the entire UHF band and achieves good read and write distances when working on metal plates. The current research mainly focuses on the performance analysis of the antenna in practical applications, less research on the design method of the antenna and summarizing the basic model of the antenna. Multiple performances should be considered when designing the antenna, but the antenna performances cannot be fully improved.

The basic model used in this paper is a half-wave dipole antenna, and an impedance matching loop is added to the antenna. This model has a simple structure and strong applicability. Antenna performance can be varied by adjusting the basic antenna geometry. The antenna can quickly adjust the impedance value of the tag antenna by changing the parameters of the center impedance matching loop to achieve the purpose of matching with the tag chip. Through the changes and analysis of the antenna parameters, the key factors affecting the antenna performance indicators can be summarized. Referring to the existing analysis results, the tag antennas that meet the requirements of different applications can be obtained through corresponding parameter optimization.

In this paper, the dipole antenna model was analyzed theoretically, and the important parameters that affect the antenna performance were found out. Taking the bent dipole antenna as an example, this paper analyzed the parameters of the dipole tag antenna combined with the impedance matching model and studied the influence of each parameter on the antenna, which provides the direction for the optimization of the antenna design. The antenna model has relatively independent performance changes, so it is easy to adjust the parameters to make the antenna meet certain application requirements.

At the same time, combined with optical, electromagnetic, and scientific computing visualization technology, the electromagnetic field radiation intensity of the tag antenna is more intuitively express. The image processing method is used to optimize the interference factors of the electromagnetic radiation field around the tag antenna, and the antenna is reverse designed. Therefore, the RFID tag is designed with minimal limits to optimize the spatial electromagnetic field strength and electromagnetic wave receiving capability. The research method in this paper provides a novel method for antenna design. The motivation of the paper is to simplify the complexity of the antenna design algorithm. Compared with the traditional method, the method reduces the calculation difficulty and simplifies the parameter selection of the antenna design.

The content of this study is as follows: the second part introduces the antenna structure, analyzes the influence of the main parameters of the antenna on the antenna performance, and introduces the reverse design method of the RFID antenna. The third part simulates and analyzes the test results of the influence of antenna parameters on performance, and inversely designs the antenna. The fourth part introduces the conclusion and significance of this paper.

Design of UHF RFID dipole tag antenna

RFID antenna reverse design method

Figure 1 is a half-wave dipole antenna model with impedance matching loop. $l$ is the length of the dipole antenna; $a, b, w, w'$ are the length, width, and line width of the impedance matching loop; $w$ is the width of the dipole antenna.

![Figure 1. Half-wave dipole antenna model.](image-url)
The length of the half-wave dipole antenna is determined by equation (1)

\[ L = \frac{\lambda}{2} = \frac{c}{2f\sqrt{\varepsilon}} \]  

(1)

Among them, \( c \) is the propagation velocity of light in vacuum, \( f \) is the center frequency of the antenna, and \( \varepsilon \) is the relative dielectric constant.

The impedance value of the dipole antenna can be expressed as \(^2.15\)

\[ Z_{in} = \frac{2Z_t(1 + x)^2Z_A}{2Z_t + (1 + x)^2Z_A} \]  

(2)

\[ Z_{in} = \frac{1}{(1+x)^2Z_A + \frac{1}{Z_t}} \]  

(3)

The size of antenna impedance can be known \((1 + x)^2Z_A\) and \(Z_t\) determined by equation (3). The impedance between the antenna and the chip is \(Z_t\) and the impedance between the impedance loop and the antenna is \(Z_{in}\). The size is

\[ Z_t = jZ_0 \tan \left( \frac{ka}{2} \right) \]  

(4)

According to equation (5), the matching impedance loop width \(b\), the line width \(w\), and the antenna line width \(w'\) all affect the coefficient \(x\); thus, they can change the antenna impedance. The influence of \(b\) on the coefficient is limited, and the change of the \(w\) and \(w'\) will also have a certain effect on \(x\), but the coefficient of \(w'\) is 8.25 and the coefficient of \(w\) is 0.25, so the impact of \(w\) on antenna impedance is greater than that of \(w'\). Therefore, the main parameters affecting impedance matching are the length, width, and line width of the impedance matching loop.

Since the half-wave dipole operates in the UHF and the total length of the tag antenna reaches 16 cm, this size of the antenna is very difficult to use in most scenarios. In order to reduce the size of the label while working in the UHF band, the dipole antenna is bent. According to Figure 1, an antenna model diagram is drawn. The dipole antenna is bent and the left and right radiators are bent into three equal length sections to obtain the antenna model shown in Figure 2. The simulation experiment mainly studies the effect of antenna geometric parameters on the antenna impedance and antenna performance. The parameters of the bent dipole antenna are consistent with the half-wave dipole, except for the antenna arm length, as shown in Figure 2.

**RFID antenna reverse design method**

The specific absorption rate (SAR) describes the absorption characteristics of the medium to the electromagnetic field energy. SAR is defined as the rate of absorption of electromagnetic energy by a medium in the same environment. The medium can be regarded as a conductive medium with a dielectric constant of \(\varepsilon\). When the effective amplitude of the electric field strength in the medium is \(E\), the power loss value of
the microwave in a unit volume of biological tissue can be expressed by equation (6)

\[ P = \sigma \frac{E^2}{2} \] (6)

The SAR image can visually display the intensity of the radiant energy of the antenna in a certain direction. Its intensity is related to antenna loss and gain. By observing and processing the antenna SAR image, the antenna tag can be reverse engineered to optimize the antenna radiation capability. By processing the SAR images, some important parameters of the radiation performance of the RFID antenna are obtained. These parameters can provide a basis for antenna design.

The general process of antenna SAR image processing is as follows. The SAR images of the tag antenna in a vacuum environment are extracted and binarized. Most of the original images are converted into binary information, thereby reducing unnecessary information in the image. The images are average filtered to eliminate image noise.

Among them, when the original images are relatively clear, the SAR images can be directly converted into a binary image, and a sharp contour can be formed after extracting the edge. However, some SAR images are generally not particularly clear. They need to be converted to a grayscale image, which is then filled with grayscale and then converted into a binary image.

Threshold segmentation is used to the preprocessed image. Determining a gray threshold \( T \), the divided image can be expressed by

\[ g(x, y) = \begin{cases} 1, & f(x, y) \geq T \\ 0, & f(x, y) < T \end{cases} \] (7)

where \( f(x, y) \) is the input image and \( g(x, y) \) is the output image. If the pixel in \( f(x, y) \) is greater than the set threshold, the region is considered to be the target image region. Otherwise, it belongs to the background area.

After the image is edge-detected, the feature value of the image is extracted. The eigenvalues can better express the main features and attributes of the target area. In this paper, the area, center of gravity, perimeter, and eccentricity are selected as the features of the image.

The image feature value is calculated as follows. Suppose the image size is \( M \times N \), the coordinates of a certain point are \((x, y)\), \( f(x, y) \) represents the gray value of the SAR image at the coordinates, \( O(x, y) \) represents the coordinate information located in the target area, \( O(x, y) = \begin{cases} 1, & f(x, y) \in O \\ 0, & otherwise \end{cases} \), and the area of the image area is calculated by the following equation

\[ A = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} O(x, y) \] (8)

The calculation formula for the position of the center of gravity of the image is

\[ \begin{aligned} \bar{x} &= \frac{1}{A} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} xO(x, y) \\
\bar{y} &= \frac{1}{A} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} yO(x, y) \end{aligned} \] (9)

The perimeter is represented by an eight-way chain code, which is a method of describing a curve or boundary using the coordinates of the starting point of the curve and the direction code of the boundary point. The eccentricity is the ratio of the distance between the focal points to the length of the long axis.

According to the requirements of the antenna performance in the experimental application, the selection range of the eigenvalues of the antenna SAR image can be determined, and the structural parameters of the antenna are reversely derived.

### UHF RFID tag bent dipole antenna analysis

The basic parameters of the bent dipole antenna are shown in Table 1. The parameters of the antenna include the lengths \( L_1 \), \( L_2 \), \( L_3 \) of the bent dipole; the length \( a \), width \( b \), and line width \( w \) of the impedance loop; and the antenna line width \( w' \). We adjust a certain parameter of the antenna model and use HFSS simulation to analyze the change of antenna performance. We observe and analyze the specific effects of each parameter on antenna performance.

| Table 1. The bent dipole model antenna parameters. |
|---------------------------------------------------|
| Parameters | Reference value (mm) |
|-----------|----------------------|
| \(L_1\)   | 20                   |
| \(L_2\)   | 35                   |
| \(L_3\)   | 25                   |
| \(w\)     | 1                    |
| \(a\)     | 20                   |
| \(b\)     | 10                   |
| \(w'\)    | 1                    |
Antenna performance change analysis

Analysis of the influence of antenna length $L_3$ on antenna performance. When the length of the bent dipole antenna $L_3$ is 20, 25, 30, and 35 mm, the total length of the antenna is equivalent to 150, 160, 170, and 180 mm. As can be seen from Figure 3, the center frequency of the bent dipole antenna is significantly shifted to the right compared to the basic half-wave dipole antenna. Taking a length $L_3$ of 35 mm as an example, the theoretical center frequency of the half-wave dipole antenna is 833 MHz, which is smaller than 920 MHz in the figure.

Because the antenna is bent, the mutual inductance between the antenna arms causes the antenna impedance to change. The antenna does not match the impedance of the chip at the original frequency, causing the center frequency of the antenna to shift. Since the UHF is mainly used in the 920–925 MHz band, the following studies take $L_3$ as 35 mm.

Analysis of the influence of the impedance matching loop length $a$ on antenna performance. As shown in Figure 4, when the impedance matching loop route is continuously increased, the return loss value generally increases, and the center frequency shifts to the right. The standard impedance of the tag chip is 50 Ω. From Figure 5 (a) and (b), it can be seen that when the antenna is operating at the center frequency, the impedance of the antenna is close to 50 Ω, and the antenna and chip impedance are matched. When $a$ is 16 mm, the antenna impedance is closest to 50 Ω, so the return loss is minimal at this time. As $a$ increases, the real part of the impedance increases in turn, while the imaginary part gradually decreases. It can be inferred that when $a$ is less than 16 mm, the antenna does not match the impedance of the chip, and the return loss will increase instead. Therefore, when the impedance matching loop length $a$ is 16 or 18 mm, the antenna performance is superior.

As can be seen from Figure 5, the values of the real and imaginary parts of the impedance change significantly. When the impedance matching loop length is determined, the antenna impedance curve will always approach the conjugate matching condition at a certain frequency, which is also the reason why the antenna center frequency shifts. However, the degree of impedance matching is different, so the return loss of the antenna does not increase as the length of the impedance matching loop increases. When $a$ is 20 mm, the return loss value is relatively large.

The antenna gain visualization images are shown in Figure 6. The red part represents a high antenna gain and the green part represents a low antenna gain. As can be seen from Figure 6, the gain of the five images is basically the same. This shows that the antenna parameter changes the return loss but has no effect on the antenna gain. In antenna design, when changing the impedance loop length, it is no longer necessary to consider the antenna gain. When changing the other parameters of the antenna impedance matching loop, the simulation results show that the antenna gain is also unchanged. This shows that the antenna gain is not affected by the antenna parameters, but it is affected by the antenna structure.

Analysis of the influence of the impedance matching loop width $b$ on antenna performance. Changing the size of the impedance matching loop width $b$, the result is shown in Figure 7. The center frequency of each antenna works slightly changed, but the return loss changes.
Figure 4. Changes of return loss with impedance loop length.

Figure 5. Changes of impedance with impedance loop length. (a) The real part of the impedance; (b) The imaginary part of the impedance.
When $b$ is 12 mm, the loss is minimal. When $b$ changes, the loss slightly changes, but the center frequency is basically unchanged. The performance of the antenna changes relatively little.

**Analysis of the influence of the impedance matching loop line width $w$ on antenna performance.** When the line width $w$ of the impedance matching loop is increased from 0.8 to 1.6 mm, the center frequency of the antenna is shifted slightly to the right, and the return loss increases, as shown in Figure 8. When $w$ is 0.8 mm, the antenna and the chip achieve a good match.

**SAR image analysis**

In this paper, the antenna electromagnetic field radiation intensity images are represented as Figure 9, where $L_3$ is, 32, ..., 35, 36 mm. Except for the antenna parameters mentioned, other antenna parameters are unchanged. The antenna center frequency selected for this simulation is 920 MHz. Among them, the closer the color is to the blue portion, the lower the SAR. It shows that the radiant energy intensity of the antenna in this direction is smaller.

The SAR images in Figure 9 are binarized to obtain the image results in Figure 10. The radiation capability
of the antenna can be visually seen from Figure 10. As can be seen from the figure, when \( L_3 = 35 \text{ mm} \), the area of the image is large, that is, the antenna performance is excellent. Moreover, when the length of \( L_3 \) changes, the performance of the antenna changes significantly. The feature values of the images are extracted, and the data are as shown in Table 2.

A certain rule can be obtained from the image and data results. The larger the area of the SAR image, the greater the energy radiated by the RFID antenna. The position of the center of gravity of the image can represent the position where the radiation energy of the antenna is the strongest. There is basically no change in the position of the center of gravity in the image, indicating that the direction of the radiant energy of the antenna does not change. The eccentricity and perimeter can reflect the shape of the SAR image. When the eccentricity is small, the graph is close to a circle. In the case where the image areas are substantially equal, the pattern of the long perimeter is more irregular.

By changing the size of the antenna line width \( w' \), a series of SAR images can also be obtained. The characteristic data of the SAR image are shown in Table 3. The area in Table 3 shows the intensity of the radiation of the antenna on that face. Compared to Table 2, the change in area is not very obvious. This shows that the
Table 2. Specific absorption rate image feature value of \( L_3 \).

| Eigenvalues | Area   | Centroid | Eccentricity | Perimeter |
|-------------|--------|----------|--------------|-----------|
| \( L_3 = 32 \text{ mm} \) | 58,071 (271.9, 282.3) | 0.4828 | 894 |
| \( L_3 = 33 \text{ mm} \) | 81,661 (282.8, 284.7) | 0.4059 | 1041 |
| \( L_3 = 34 \text{ mm} \) | 96,767 (278.9, 279.8) | 0.3577 | 1136 |
| \( L_3 = 35 \text{ mm} \) | 104,257 (279.4, 278.8) | 0.2964 | 1180 |
| \( L_3 = 36 \text{ mm} \) | 96,020 (275.7, 279.9) | 0.3169 | 1123 |

Table 3. Specific absorption rate image feature value of \( w' \).

| Eigenvalues | Area   | Centroid | Eccentricity | Perimeter |
|-------------|--------|----------|--------------|-----------|
| \( w' = 0.8 \text{ mm} \) | 100,412 (273.3, 281.8) | 0.3390 | 1153 |
| \( w' = 1.0 \text{ mm} \) | 104,257 (279.4, 287.8) | 0.2964 | 1180 |
| \( w' = 1.2 \text{ mm} \) | 103,448 (273.2, 279.6) | 0.3563 | 1178 |
| \( w' = 1.4 \text{ mm} \) | 102,356 (275.8, 280.8) | 0.3805 | 1168 |
| \( w' = 1.6 \text{ mm} \) | 101,344 (271.5, 284.1) | 0.3837 | 1154 |

Table 4. Specific absorption rate image feature value of \( L_2 \) and \( L_3 \).

| Eigenvalues | Area   | Centroid | Eccentricity | Perimeter |
|-------------|--------|----------|--------------|-----------|
| \( L_2 = 30 \text{ mm}, L_3 = 40 \text{ mm} \) | 85,881 (275.5, 282.7) | 0.4360 | 1076 |
| \( L_2 = 35 \text{ mm}, L_3 = 35 \text{ mm} \) | 104,257 (279.4, 287.8) | 0.2964 | 1180 |
| \( L_2 = 40 \text{ mm}, L_3 = 30 \text{ mm} \) | 90,906 (273.2, 284.4) | 0.2875 | 1087 |
| \( L_2 = 45 \text{ mm}, L_3 = 25 \text{ mm} \) | 73,493 (274.3, 279.0) | 0.3551 | 979 |
| \( L_2 = 50 \text{ mm}, L_3 = 20 \text{ mm} \) | 63,339 (270.4, 281.6) | 0.4338 | 918 |

The bending length of the single arm on the antenna is changed, and the obtained antenna characteristic data are shown in Table 5. It can be seen that not only does the area of the image change significantly but also the center position changes, which gradually moves in one direction. This shows that the radiation direction of the antenna is also changing.

The position of the impedance matching loop is shifted, and the data of the SAR image feature values are shown in Table 6. The antenna position does not move and only the impedance matching loop is translated as a whole. When the impedance loop moves in the positive direction of the y-axis, its moving distance is a positive number. The data shows that there is no obvious trend in SAR changes, and the difference in the changes is not very large. This shows that the main influencing factor of SAR is the length of the antenna arm, and the impedance loop does not affect the radiation performance.

Contrast and discussion

From the above simulation results, it can be seen that the center frequency of the bent dipole antenna is mainly determined by the total arm length of the antenna, but it deviates from the basic half-wave dipole antenna theory. Due to the mutual inductance between the antenna arms, the impedance variation of the bent dipole antenna is not the same as the theoretical model, but the influence degree of the parameters estimated from the antenna theory on the impedance is consistent with the simulation result. Changing the impedance
loop length can significantly change the center frequency and return loss of the antenna. Relatively speaking, the width and line width of the impedance loop have less effect on the performance of the antenna. At the same time, when the antenna parameters are changed, the antenna gain is substantially unchanged. Only one of the real or imaginary parts of the antenna impedance changes, and the center frequency of the antenna generally does not change much.

Through the calculation of SAR image features, we can get that when the antenna parameters satisfy \( L_2 = 35 \, \text{mm}, \, L_3 = 35 \, \text{mm}, \, w' = 1 \, \text{mm}, \, w = 0.8 \, \text{mm} \), the performance of the antenna is the best. Several features of the antenna SAR image can clearly reflect some of the performance of the antenna. The area of the image can reflect the radiation intensity of the antenna, which is related to the loss and gain of the antenna. The radiation intensity is related to the antenna signal propagation distance, so the antenna SAR image area can intuitively reflect the antenna transmission distance. The center position of the SAR image can reflect the main radiation direction of the antenna. The eccentricity and perimeter can reflect the radiation range of the antenna. In general, the smaller the eccentricity and perimeter, the easier it is for the antenna to cover the signal in one direction. The simulation results show that the SAR image analysis results can correctly reflect the antenna performance.

At present, the methods of antenna optimization design mainly include electromagnetic simulation calculation methods\textsuperscript{11,12} and neural network optimization methods.\textsuperscript{13} In the electromagnetic calculation method, it is necessary to compare the effects of different antenna parameters on the antenna. Then, modify the antenna parameters one by one to make the antenna meet the design requirements in a certain frequency band. Electromagnetic calculation methods require iterative calculations and take a long time. Since the performance is affected by different parameters, the adjustment parameters are more complicated and the calculation workload is huge. Compared with other electromagnetic calculation methods, this method can acquire a large number of images in a short time. The image method can quickly determine the antenna parameters, and the real-time performance is good. Under the same antenna structure, the antenna parameters can be changed according to the design requirements without more calculations. The neural network optimization method has high precision. However, it is a complicated job, and some parameters of the neural network need to be adjusted according to different prediction work.

The antenna design process is relatively simple by the antenna reverse design method of SAR image analysis. Moreover, the radiation intensity and distribution information of the antenna can be discriminated by image information and feature values, and the result is more intuitive and real-time.

**Conclusion**

According to the practical application requirements of the UHF antenna, a bent dipole antenna is designed and combined with an impedance matching loop. The structure of the antenna is simple, and the structural parameters are easy to adjust to achieve a good impedance matching effect between the antenna and the chip. On this basis, through the analysis of SAR images, the antenna can be reverse engineered according to the actual application requirements of the antenna, so that the antenna design can meet the application requirements. The reverse design method is simple and more intuitive to reflect the gap between design and application. This paper provides guidance and direction for the design of RFID antennas.

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