The Role of Impedance Matching for Power Transfer Efficiency in HF RFID Systems

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***Abstract*-An important aspect that should be taken into consideration when we talk about RFID systems is the antenna impedance matching. When a mismatch occurs in the antenna circuit, the power transferred from the RFID reader to its antenna is reflected, causing drastically decreasing of the tags reading distance. In this paper are analyzed some matching impedance circuits for an HF RFID reader antenna and are proposed few methods to achieve the desired impedance. The obtained results confirm that when a standard RFID reader antenna is used and the impedance isn't matched, the maximum reading distance decreases up to 60% towards when is well matched.**

Keywords: RFID systems, impedance matching, metallic environment, power transfer efficiency, HF antenna

I. INTRODUCTION

RFID or Radio Frequency Identification technology is a widespread object identification technology that uses radio waves for collecting data and doesn't need physical contact or LOS (Line-Of-Sight) with the objects that need to be identified. This technology is becoming increasingly used in various fields and applications due to the continued need for data flows optimization and due to reduced time needed for achievement [1-3].

Generally speaking, an RFID system consists of three main components: a reader used for interrogation process, a tag that is attached to the object that need to be identified and a data processing unit that can be a PC or other device that has a microcontroller, needed for processing the collected data. The reader communicates with the tag through radio waves. Scanning of the RFID tags with radio waves doesn't imply a precise positioning between the reader and the tagged object because the radio waves can easily penetrate all non-metallic materials, offering good results in the identifying process.

An RFID tag contains circuits that can control the communication with the reader and are integrated into a small package, called chip. This chip has attached an antenna, which in most cases gives the tag shape and covers almost all its surface. The chip contains a part used for radio communication and a part used for memory, which will store the received data's from the reader. The stored data are transmitted back to the reader when are requested, but only after is initiated a secured communication link.

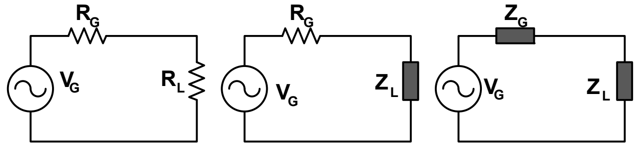
The performances of the RFID systems are given especially by the identification range of the tags. Even if the systems work in LF, HF, UHF or MW frequency band, achieving the maximum reading range implies transferring enough power from the reader antenna to the area where tags must be identified [4]. If the tag isn't matched in impedance and the resonance frequency is different from the reader's frequency, a power loss will occur and the power transfer efficiency will drop significantly [5]. This is also true for the reader's antenna. When the antenna is mismatched, the reader's output power will be reflected back and into the identification field will be only a part of the total transmitted power. This will cause a small identification rate of the tags located in the identification field.

II. THEORETICAL APPROACH FOR A CIRCUIT IMPEDANCE

There are three different situations regarding the impedance when we connect a power source and a load through a transmission line [6].

a) Both, the power source and the load are resistive, with different values;
b) The source is resistive and the load has a complex value;
c) Both, the power source and the load have complex values.

These situations are depicted in Fig. 1. Here V_s is an RF power source with an internal resistance R_G or complex impedance Z_G. This source has connected a load R_L or a complex impedance Z_L.



a) pure resistive b) resistive-complex c) pure complex

Fig. 1. Circuits with different type of impedances

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The first case (Fig. 1.a) needs an impedance matching circuit that will adjust the load resistance R_L to be equal to the source resistance R_G. This is the simplest situation because the matching can be easily implemented using an adequate resistor connected in series or in parallel with the load resistance. When we talk about the situations presented in Fig. 1b and Fig. 1c respectively, we need to take more attention to the matching circuit between the power source and the load.

The case presented in Fig. 1b is commonly used for the RFID reader antenna. Because the load has a complex value (which is the reader antenna) and the power source is resistive (RFID reader), we need to use an additional circuit that will cancel the reactance from the load and will match the resistances from the source and from the load.

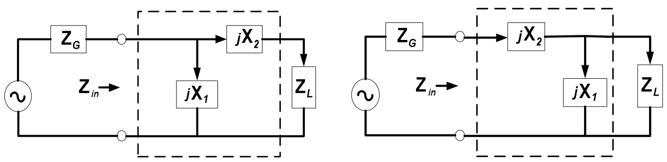
The case from Fig. 1c is commonly used when we analyze the RFID tags. The IC used in an RFID tag (which in our case is the load) has a complex value and must be matched in impedance with the antenna, which is the power source.

In most cases, the impedance matching circuits have only reactive components (capacitors and/or inductors), to avoid losses from the circuits where are placed. We can meet, depending on the complexity, two types of these matching circuits:

- Matching circuits with two elements – L type network
- Matching circuits with three elements – T or π network

A. Matching circuits with two elements - L type network

The two elements networks are the most used in an impedance matching circuit. Using series or parallel configuration can be made 8 different circuits, in normal or reverse configuration (Fig. 2) [7].



a) normal configuration ($R_G > R_L$) b) reverse configuration ($R_G < R_L$)

Fig. 2. Two elements network (L type network)

In case when both input and output impedances have a complex value, the network can be modeled with (1).

$$Z_L = R_L + jX_L$$
$$Z_G = R_G + jX_G \tag{1}$$

Z_{in} is the input impedance and depending on the configuration can be expressed with (2).

$$Z_{in} = \frac{Z_1(Z_2 + Z_L)}{Z_1 + Z_2 + Z_L} \quad \text{(normal configuration)}$$
$$Z_{in} = Z_2 + \frac{Z_1 Z_L}{Z_1 + Z_L} \quad \text{(reverse configuration),} \tag{2}$$

where $Z_1=jX_1$ and $Z_2=jX_2$.

The values for the circuit reactance X_1 and X_2 can be expressed with (3).

$$X_1 = \frac{X_G \pm R_G Q}{\frac{R_G}{R_L} - 1} \qquad X_1 = \frac{X_L \pm R_L Q}{\frac{R_L}{R_G} - 1}$$
$$X_2 = -(X_L \pm R_L Q) \qquad X_2 = -(X_G \pm R_G Q) \tag{3}$$
$$Q = \sqrt{\frac{R_G}{R_L} - 1 + \frac{X_G^2}{R_G R_L}} \qquad Q = \sqrt{\frac{R_L}{R_G} - 1 + \frac{X_L^2}{R_G R_L}}$$

(normal configuration) (reverse configuration),

where Q is the quality factor and can be expressed as the ratio between the stored energy and the dissipated energy from that circuit (4).

$$Q = 2\pi \frac{stored\_energy}{disipated\_energy} \tag{4}$$

When both source and load impedances are resistive (X_L=0 and X_G=0) then the results for the reactance will be:

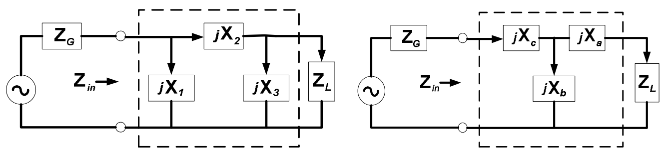
$$X_1 = \pm\frac{R_G}{Q} \qquad X_1 = \pm\frac{R_L}{Q}$$
$$X_2 = \mp R_L Q \qquad X_2 = \mp R_G Q \tag{5}$$
$$Q = \sqrt{\frac{R_G}{R_L} - 1} \qquad Q = \sqrt{\frac{R_L}{R_G} - 1}$$

(normal configuration) (reverse configuration)

If X_1 and X_2 must have real values, then a real value for the Q factors are also needed, or the expression under the square root must have a positive value.

B. Matching circuits with three elements - T or π network

We can make matching circuits with three elements in T or π configuration (Fig. 3). These kinds of configurations allow having control over the circuit bandwidth comparative with two elements circuit where the bandwidth cannot be controlled. Using these types of circuits the bandwidth can be made as narrow as desired.



a) π network b) T network

Fig. 3. Three elements network

Because Z_1, Z_2 and Z_3 are pure reactive, we will have (6) for the π network and (7) for the T network type.

$$Z_1 = jX_1, \quad Z_2 = jX_2, \quad Z_3 = jX_3, \tag{6}$$

$$Z_a = jX_a, \quad Z_b = jX_b, \quad Z_c = jX_c. \tag{7}$$

For easily determination of the circuit reactance's we need to split the three element network into 2 different L type networks. As an example, in Fig. 4 is taken a π network with X_4 and X_5 as a split reactance from X_2. In the circuit will be a new impedance $Z=R+jX$. In this case we will have 2 new impedances that can be expressed with (8).

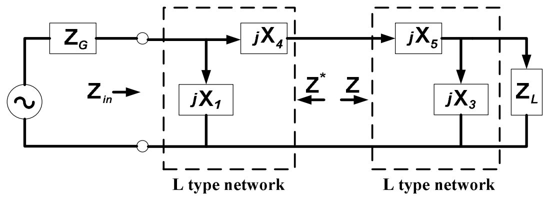


Fig. 4. Equivalent π network

$$Z_4 + \frac{Z_1 Z_G}{Z_1 + Z_G} = Z^*, \qquad Z_5 + \frac{Z_3 Z_L}{Z_3 + Z_L} = Z \tag{8}$$

Because Z_1 and Z_4 are pure reactive, the conjugate values will be $Z_1^* = - Z_1$ and $Z_4^* = - Z_4$. Thus, Z^* can be expressed with (9).

$$Z_{in} = \frac{Z_1(Z_4 + Z)}{Z_1 + Z_4 + Z} = Z_G^*. \tag{9}$$

This is the essential matching condition that must be satisfied by the network. Thus, if this condition isn't true, Z will have a random value. Because we split the circuit, we will have 2 different Q factors that will characterize Z^* and Z.

$$Q_G = \sqrt{\frac{R_G}{R} - 1}, \qquad Q_L = \sqrt{\frac{R_L}{R} - 1}. \tag{10}$$

The maximum value for the Q factor will be when both R_G and R_L will have maximum values. Thus, the relation for Q factor will be:

$$Q = \sqrt{\frac{R_{max}}{R} - 1}, \qquad R_{max} = \max(R_G, R_L). \tag{11}$$

Q factor can be expressed as a parameter that has a direct effect over the circuit bandwidth [8].

$$Q = \frac{f_0}{BW} \tag{12}$$

If we know the exact bandwidth we can depict the value of the Q factor and also the value for R from (11), using (13).

$$R = \frac{R_{max}}{Q^2 + 1}. \tag{13}$$

After we know the Q factor, we can easily calculate the values for Q_G and Q_L.

$$Q_G = \sqrt{\frac{R_G}{R_{max}}(Q^2 + 1) - 1}, \qquad Q_L = \sqrt{\frac{R_L}{R_{max}}(Q^2 + 1) - 1} \tag{14}$$

The analytical values for the circuit reactance can be expressed with (15).

$$\begin{aligned} X_1 &= -\alpha_G \frac{R_G}{Q_G} \\ X_2 &= \frac{R_{max}(\alpha_G Q_G + \alpha_L Q_L)}{Q^2 + 1}, \\ X_3 &= -\alpha_L \frac{R_L}{Q_L} \end{aligned} \tag{15}$$

where α_G and α_L have values equal with ±1[9]. $\alpha_G = \alpha_L = 1$ are the most common used because they will give X_1 and X_3 as capacitive elements and X_2 as an inductive element.

The total Q factor of the circuit is expressed with (16) and is a sum of Q_G and Q_L.

$$Q_{total} = Q_G + Q_L = \sqrt{\frac{R_G}{R} - 1} + \sqrt{\frac{R_L}{R} - 1} \tag{16}$$

The R value can be expressed with (17).

$$R = \frac{(R_G - R_L)^2}{(R_G + R_L)Q_{total}^{\ 2} - 2Q_{total}\sqrt{R_G R_L Q_{total}^{\ 2} - (R_G - R_L)^2}}, \tag{17}$$

Q_G and Q_L became:

$$\begin{aligned} Q_G &= \frac{R_G Q_{total} - \sqrt{R_G R_L Q_{total}^{\ 2} - (R_G - R_L)^2}}{R_G - R_L} \\ Q_L &= \frac{R_L Q_{total} - \sqrt{R_G R_L Q_{total}^{\ 2} - (R_G - R_L)^2}}{R_L - R_G}. \end{aligned} \tag{18}$$

Thus, the final values for the circuit reactance will be expressed with (19).

$$\begin{aligned} X_1 &= -\alpha_G \frac{R_G}{Q_G} \\ X_2 &= R(\alpha_G Q_G + \alpha_L Q_L). \\ X_3 &= -\alpha_L \frac{R_L}{Q_L} \end{aligned} \tag{19}$$

III. Results and Discussions

Using simple configuration of the impedance matching circuits presented above, we intend to match in impedance an HF RFID reader antenna. The antenna pattern is presented in Fig. 5. The physical dimensions and the performance characteristics aren't the subject of this paper and are related in [10] and [11].

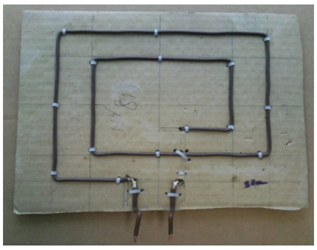


Fig. 5. RFID antenna pattern [11]

This antenna must have 50Ω input impedance, which is the output impedance of the RFID reader. We can match the impedance of the antenna in several ways:

- Analytical determination of the matching circuit component values using references from section II;
- Experimental determination using physical components and a vector network analyzer (VNA);
- Using simulations with specialized EM simulator software (Ansoft HFSS).

The first solution assumes choosing a matching circuit like in Fig. 6.

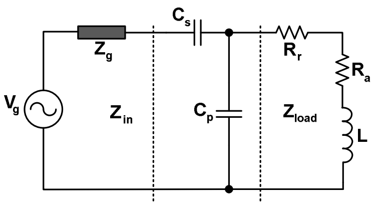


Fig. 6. L type antenna matching circuit

In this circuit the impedance matching can be made with C_s and C_p that are connected into an L type network. R_a and R_r are the resistances of the antenna wire and antenna radiation, respectively. L is the antenna inductance. The Q factor of the circuit can be expressed with (20).

$$Q = \frac{2\pi f_0 L}{R} \tag{20}$$

O higher Q factor leads to a higher output power transmitted to the reader antenna. If we use a high value for the Q factor, the bandwidth of the circuit decreases according to (12). The RFID systems must ensure enough bandwidth in order to identify tags that have technological dispersion. 450 kHz is enough for the circuit bandwidth if we take into consideration tags that have 3-5% dispersion in the operating frequency [10].

A higher value of the Q factor can be damped using an additional resistor connected in series with the antenna. If we take a look at (20), the value of this resistor is relatively small and can be a problem achieving it in a real environment. Thus, we can replace this series resistor with a parallel one as in Fig. 7.

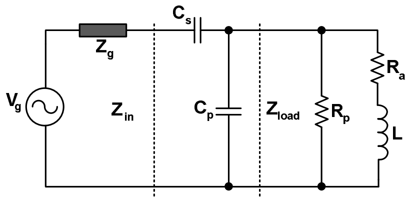


Fig. 7. Matching circuit with parallel damping resistor

This time the value of the Q factor can be expressed with (21) and we can see that the value is higher and is much easier to obtain in a real environment.

$$Q = \frac{R}{2\pi f_0 L}. \tag{21}$$

The circuit from Fig. 7 is the optimal structure for the simplest impedance matching circuit that can be used for the antenna pattern described above. This circuit can also be used for any type and shape of an antenna connected to an HF RFID reader. Below is presented the theoretical approach. The input impedance can be expressed with (22).

$$Z_{in} = \frac{1}{j\omega C_s} + \frac{1}{j\omega C_p + \frac{1}{R_a + j\omega L} + \frac{1}{R_p}}. \tag{22}$$

From this circuit the inductance of the antenna is measured using a VNA, or can be calculated from the antenna geometry [11]. The measured value for this parameter is 1.8µH (Fig. 8).

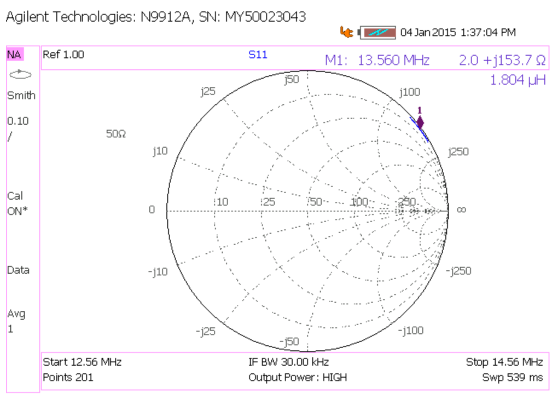


Fig. 8. Smith chart with the antenna inductance

After this value is calculated or measured, we need to find out the values for the rest of the components from the circuit. If we analyze the equation (22) we can see that the input impedance has a complex value. The output reader provides an impedance that is (50+0j)Ω. Thus, if we want to obtain the maximum power transfer between the reader and its antenna we need to separate the real part and the imaginary part from Z_{in}. The equation (22) will be spitted in (23) and (24), respectively.

$$\frac{R_p\left(\omega^2L^2 + R_pR_a + R_a^2\right)}{\left(R_p + R_a - \omega^2C_pLR_p\right)^2 + \left(\omega C_pR_pR_a + \omega L\right)^2} = 50 \tag{23}$$

$$\frac{R_p\left(\omega^2C_sL^2 + 2C_pR_pR_a + 2L + C_sR_pR_a + C_sR_a^2\right)}{C_s\left(R_p + R_a - \omega^2C_pLR_p\right)^2 + \left(\omega C_pR_pR_a + \omega L\right)^2} = 0 \tag{24}$$

The series and parallel capacitors can be expressed with (25) and (26), respectively. These equations are obtained from (23) and (24).

$$C_p = \frac{10R_p\omega L - \sqrt{2}\sqrt{\left(R_pR_a + R_a^2 + \omega^2L^2\right)\left(\left(R_p - 50\right)R_a^2 - 50R_pR_a + \omega^2L^2\left(R_p - 50\right)\right)}}{10\left(\omega^2L^2 + R_a^2\right)R_p\omega} \tag{25}$$

$$C_s = \frac{-2\left(C_pR_pR_a + L\right)}{R_pR_a + R_a^2 + \omega^2L^2} \tag{26}$$

Thus, if we take 13.56MHz as the operating frequency of the RFID system, we can depict the values needed to match the antenna impedance. The obtained values are presented in Table I.

TABLE I
VALUES OF THE IMPEDANCE MATCHING CIRCUIT COMPONENTS

Parameter	Value
L	**1.8µH**
R_a	**1.84Ω**
R_p	**1.3kΩ**
C_p	**372pF**
C_s	**118pF**

The second method to express the values for the matching circuit components assumes using a VNA and the Smith chart (Fig. 9).

This method uses a physical circuit and variable capacitors. Knowing the antenna inductance and the damping resistor (that is chosen in the way of maximizing the *Q* factor of the circuit), we can adjust manually the series and parallel capacitors in the circuit until the antenna impedance has the desired value. In Fig. 9 we can see that when the antenna is matched, at 13.56MHz the impedance has a value of (50+j0.2)Ω. In this way the signal losses are avoided and the power transfer is maximized.

The main disadvantage of this method is the using of VNA for achieving the desired impedance. This type of measurement equipment is expensive being used especially in research centers and for teaching purpose. For this method cannot be achieved a desired quick impedance matching circuit for an antenna without using a specialized measurement tool, like the VNA.

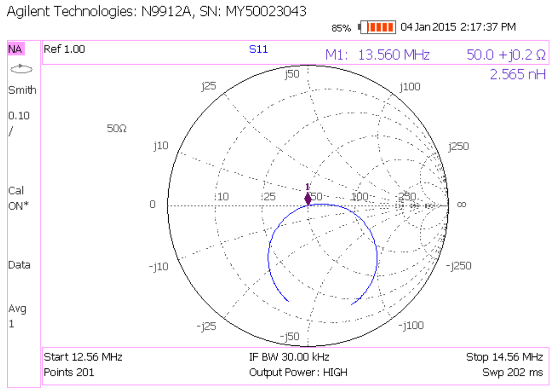


Fig. 9. Impedance matching using Smith chart

The last method implies using an electromagnetic simulator software. The results obtained in this part are made with a software package from Ansoft that has Ansoft HFSS and Ansoft Designer. The antenna is modeled and simulated using HFSS. From the obtained results we can extract the antenna impedance (Fig. 10).

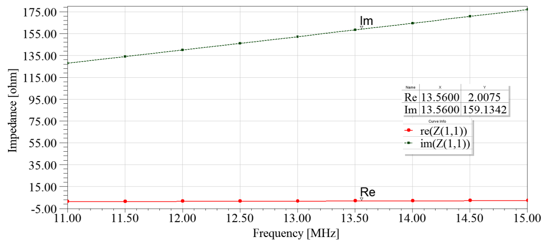


Fig. 10. Impedance of the simulated antenna

At 13.56MHz the antenna impedance is Z_L=(2+j159)Ω. Using the equation (27), we can express the antenna inductance, which is 1.86µH.

$$X_L = 2\pi f_0 L \tag{27}$$

This simulated antenna is imported in Ansoft Designer where the matching circuit is made. Using the same Smith chart (Fig. 11) like in the previous method, we can adjust the components from the circuit in order to achieve final circuit impedance.

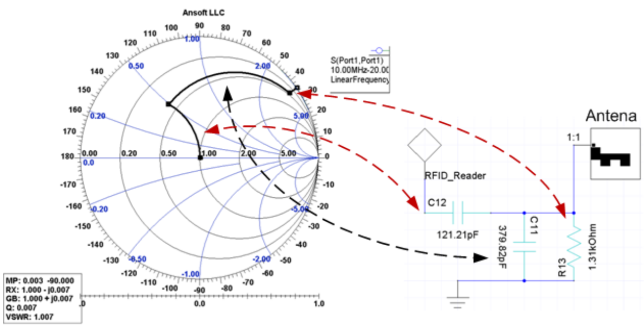


Fig. 11. Impedance matching using Ansoft Designer

The obtained values are depicted in Table II. These values can be compared with the values obtained using analytical method.

TABLE II
VALUES OBTAINED FROM THE SIMULATED METHOD

Parameter	Value
L	**1.86μH**
R_a	**2Ω**
R_p	**1.31kΩ**
C_p	**379pF**
C_s	**121pF**

In order to verify the importance of the antenna impedance matching, is used a standard HF RFID reader with an output power of 1W. First the antenna is tuned and matched at 50Ω. To achieve the mismatch is used a 2mm thickness conductive plate placed under the RFID antenna. This plate will detune the antenna because of the effects caused by a metallic plate in the close proximity of an antenna [10]. The experimental setup is presented in Fig. 12.

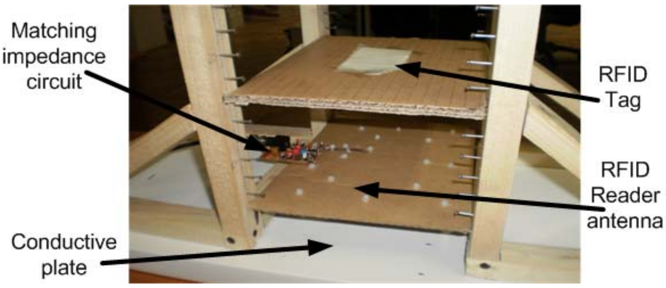


Fig. 12. Experimental setup for testing variation of the antenna impedance

The distance between the antenna and the conductive plate is changed from 2mm to 35mm, causing the changing of the antenna inductance. In this way for changing the antenna impedance only one circuit component is changed. In Table III are depicted few values for the antenna impedance.

TABLE III
ANTENNA IMPEDANCE VALUES OBTAINED FROM THE EXPERIMENTAL SETUP

Distance between the antenna and the conductive plate [mm]	Antenna impedance [Ω]	Reading distance [cm]
2	**28.1-j18.3**	**16**
4	**32.4-j15.1**	**24**
6	**36.3-j10.4**	**30**
10	**39.7-j8.3**	**40**
15	**42.8-j6.7**	**44**
25	**48.3-j3.2**	**47**
35	**50.3+j0.1**	**50**

When the distance between the antenna and the conductive plate is small (2mm) we can observe a drastically changing of the impedance.

This will cause a small reading range, in this case only 16cm. When the distance between the antenna and the conductive plate increases, the mismatch will disappear and the antenna will transfer the maximum power to the identification field. In this case the reading range will increase, until will reach the maximum value of 50cm.

IV. CONCLUSIONS

The impedance matching of an antenna used for RFID systems is very important and has a powerful impact over the entire system. If between the antenna and the reader will be an impedance mismatch, then the power transfer efficiency will decrease, affecting directly the identification range of the tags.

In this paper are related some methods of matching the impedance of a standard antenna and the results obtained will conclude that when the RFID reader antenna is mismatched in impedance the reading distance can decrease up to 60% towards when is well matched.

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