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High Frequency RFID Module Design and Performance Comparison between Different Antenna Geometries for TV Applications

Heba YÜKSEL[*1]

[1]Bogazici University, Department of Electrical and Electronics Engineering, 34342, Istanbul, Turkey

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NFC

Abstract: This paper examines the design of a 13.56 MHz Radio Frequency Identification (RFID) reader that is used in secure TV access applications. It also presents the performance analysis between different geometry and sizes of the reader's antennas in order to achieve the optimum operational excellence. Four different antenna geometries and sizes are designed and analyzed; square (4 loop and 6 loop), rectangular, and circular antennas. In order to find the best way for achieving the optimum performance, simulations, calculations, and measurements have been implemented by comparing the antennas in terms of gain, read distance, and cost performances with the availability of proximity of metals and smart cards, considering accuracy and reliability. The reader design for secure TV access is aimed to work with a passive tag. The rectangular antenna operated at the 13.56 MHz of frequency level with a return loss of -27 dB. The 6 loop square antenna and circular antenna operated with frequencies different than the optimum frequency of 13.56 MHz for the desired application, so the adjustments and other tests were not necessary for such antennas. It has been observed that for such TV applications, the best performance in terms of read range and gain, is achieved for a read distance up to 5 cm using the 4 loop square antenna operating at the 13.56 MHz of frequency level with a return loss of -30 dB. Some enhancement techniques to optimize system performance against the capacitive effects of close proximity to metals and smart cards are also discussed like detuning the capacitor values in the matching circuit. This paper aims to fill the gap in literature in observing RFID systems' performance with comparison of different size and geometry antennas by setting forth the best antenna geometry with metal and smart card effects.

TV Uygulaması için Yüksek Frekans RFID Modüllerinin Farklı Şekil ve Geometrideki Antenler ile Performans Karşılaştırılması

Anahtar Kelimeler
RFID Okuyucu,
HF Antenler,
Okuyucu Antenler,
NFC

Özet: Bu makalede, güvenli TV erişim uygulamaları için kullanılan 13.56MHz Radyo Frekansı Tanımlama (RFID) okuyucunun tasarımı incelenmektedir. Ayrıca, optimum operasyonel mükemmellik elde etmek için okuyucu antenlerinin farklı geometri ve boyutları arasındaki performans analizini sunar. Kare (4 döngü ve 6 döngü), dikdörtgen ve dairesel antenler olmak üzere, dört farklı geometrili ve boyutlu antenler tasarlanmış ve analiz edilmiştir. Optimum performansa ulaşmanın en iyi yolunu bulmak için, antenleri kazanç, okuma mesafesi ve maliyet performansları açısından, simülasyonları, hesaplamaları ve ölçümleri yapılıp, metaller ve akıllı kartların yakınlığı göz önünde bulundurularak, doğruluğu ve güvenilirliği karşılaştırarak yapılmıştır. Güvenli TV erişimi için tasarlanan okuyucunun pasif bir etiketle çalışması amaçlamaktadır. Dikdörtgen anten 13.56 MHz ile çalışırken, geri dönüş kaybı -27 dB olarak tespit edilmiştir. İstenen uygulamada, 6 döngülü kare anten ve dairesel anten optimum 13.56MHz frekanstan farklı çalışmaktadır. Bu sebeple ek test ve ayarlamalar, konusu geçen antenler için gereksiz ön görülmüştür. Bu tür TV uygulamaları için en iyi sonucunu ise, 4 döngülü kare anten kullanarak, 13.56MHz çalışma frekansında dönüş kaybı -30 dB olarak ölçerek tespit etmiş olduk. Ek olarak sistem performansını, metal yakınlıklarından ve akıllı kartlardan kaynaklanan kapasitif etkilerin ortaya çıkardığı problemlere karşı optimize etmek için; eşleştirme ve kapasitans ayarlamak gibi teknikler tartışılmış, sunulmuştur. Bu makale, RFID sistemlerinin performansını, metal ve akıllı kart etkileri ile farklı boyutlu ve geometrili antenleri karşılaştırmayı, en iyi anten geometrisini ortaya koyarak da literatürdeki boşluğu doldurmayı amaçlamaktadır.

*Corresponding author: heba.yuksel@boun.edu.tr

1. Introduction

RFID technology allows people to achieve a contactless identification of an item, an animal or a person by using radio waves. A basic RFID system usually includes two main devices; a reader and a transponder or tag. The reader initiates the communication with the tag and enables the identification operation. The reader includes an antenna as a component which can operate at frequency ranges from 125 KHz to 5.8 GHz. The reader's antenna generates the interrogating electromagnetic field which makes communication with the tag possible. The transponder, or tag, is located in the item that is required to be identified. The tags can be passive or active and they can have different geometry and material. Passive tags don't have their own power source, so they are powered and the communication is achieved by the incoming Radio Frequency (RF) communication signal from the reader. They have the shortest read range but they are also the cheapest at the same time. Another positive feature of such tags is they are the easiest when it comes to integrating into products and their life time is almost indefinite [1, 2].

RFID technology is commonly used in tracking products or any kind of goods, control of access by integrating the RFID technology to the ID cards, inventory management, and supply chain management. RFID is used not only in industry but it is also available for personal use such as, credit cards, and tickets for public transportation [3, 4]. The main advantages of the RFID technology are, shortening the transaction time, preventing the loss of information, improving the quality of data capture, and achieving higher productivity. The RFID technology offers functionality similar to the barcode, with additional advantages such as higher data capacity, larger readout distances and higher robustness.

The designed RFID reader in this paper allows users secure access into their personal menus in TVs, computers or e-boards with passive tags. This secure control of electronic devices is mainly used in offices, schools, hospitals etc. When a user operates the remote control to control the TV, the remote control unit's unique ID number is transmitted by the device's RFID tags and enables stand by voltage of electronic devices. However, the usage of RFID can lead to additional technological challenges. The most technological challenge for the aimed design is the proximity of metal. With locating any metal close to the system, some decays and unwanted bouncing of the radio waves occur. System accuracy and selectivity are highly important because wrong or missed readings will affect the system reliability in applications of secure control for electronic circuits. Therefore, optimization and trade off are required both for the standards and obtaining maximum performance [5].

Several studies have underscored the fact that the performance of RFID systems in the proximity of metals and liquids was affected [6-15]. Also, some studies describe the effects of geometry of loop antennas on system performance [16]. However, very few literature studies are available about design selection considering functional performance and the effect of varying size and geometry of reader's loop antenna for high frequency (HF) RFID readers in metal environment and capacitive smart card effects. This paper aims to fill this gap in the literature through observing RFID systems' performance with comparison of different size and geometry antennas and setting forth the best antenna geometry with metal and smart card effects.

The RFID reader antenna and reader circuit for the desired secure TV access application is designed to fit inside the TV unit 1 cm inside the front cover. By locating the antenna there, minimum communication range would be greater than 1 cm. Like all other RFID applications, the maximum reading range is aimed for this work. For such designs, the cost and the size should be as minimum as possible while maintaining the accuracy. When the read distance increases, the accuracy rate of the systems decreases. The system accuracy is prior for such design, which requires the read distance to be minimized. The RFID system design that is defined in this paper allows communication up to 5 cm.

In this paper, we aim to achieve the most effective matching between the tag's antenna and the designed reader in a wide frequency band with a high level of accuracy. Also, factors that are affecting the performance of the reader's loop antenna such as, sizes and geometry, as well as the main considerations that are needed to be taken for choosing the right reader antenna are discussed. Four different antenna geometries and sizes are designed and analyzed; square (4 loop and 6 loop), rectangular and circular antennas. In order to find the best way for achieving the optimum performance, simulations, calculations, and measurements have been implemented by comparing the antennas in terms of gain, read distance, and cost performances with the availability of proximity of metals and smart cards, considering accuracy and reliability.

RFID designs face some challenges such as following communication protocols, EMC limitations, and obtaining long read range with small size antenna at high system accuracy. After simulations and measurements have been implemented, the optimum results imply the usage of the 4 loop square antenna design with a return loss of -30 dB and a frequency level of 13.56 MHz. Such design is in the limits of the regulation while having the most efficient operational excellence.

2. Material and Method

2.1. RFID reader design

RFID systems consist of a reader (interrogator) which includes an RF transmission system, a receiver, data decoding and antenna transmit sections. Another main component of RFID systems is the tag (transponder) which consists of a microchip and an antenna. The last main component of RFID systems is a computer or a database. Those main elements are shown in Figure 1 [17].

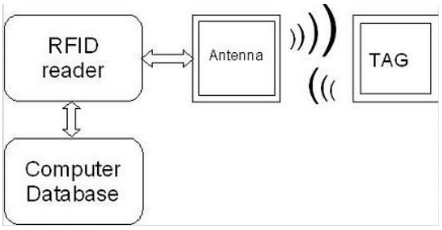

Figure 1. Sample RFID system

The system is aimed to operate with a frequency of 13.56 MHz which is classified as HF RFID system. Communication and power of the HF RFID system are achieved through electromagnetic coupling between the reader and the tag. The tag consists of an antenna coil and a silicon chip that includes basic modulation circuitry and non-volatile memory. Passive RFID tags need an induced antenna coil voltage for operation from the reader. The reader antenna coil produces a time-varying magnetic field to energize the tag.

For such TV authorization application at 13.56 MHz, the NXP PN531 transmission module, which puts together the modulation and demodulation for contactless communication, is the optimum module. By using different transfer speeds and modulation protocols, the PN512 transmission module supports the Read/Write mode for ISO/IEC 14443 A/MIFARE and ISO/IEC 14443B [18, 19].

There are some factors that the operating distance of NXP contactless NFC reader ICs depends on:

- Antenna matching.
- Receiver sensitivity.
- Size of the antenna in the reader system.
- Antenna size of the communication partner.
- External parameters (e.g. metallic environment and noise).

The example application circuit of the PN531 transmission module is shown in Figure 2 [19].

With the usage of a proper antenna and other system components, the main IC should be tuned to a center frequency of 13.56 MHz with impedance of 50 ohms. The Voltage Standing Wave Ratio (VSWR) should be less than 1.2 to achieve the optimum performance.

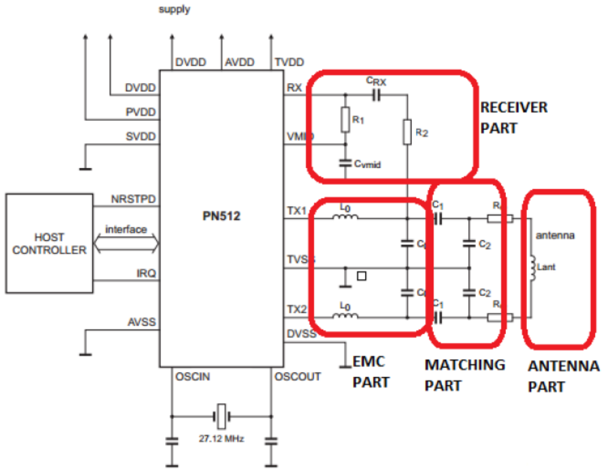

Figure 2. Sample application diagram of PN531 (Philips Semiconductors, 2004) [19]

Figure 3 gives the circuit diagram for the Antenna, matching circuit and EMC filter which will be designed in the next subsections [20].

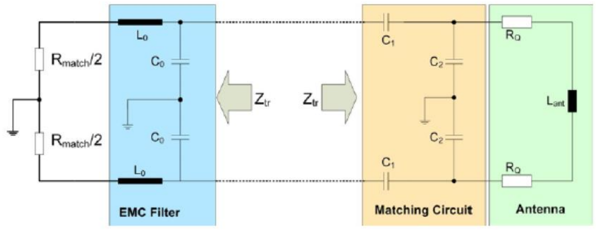

Figure 3. Circuit diagram showing the EMC filter, matching circuit and antenna [20]

2.2. Antenna design

Main functions of the antenna can be defined as, storing charge as capacitance, resisting to the changes in current as inductance and radiating power as resistance. The antenna type should be taken under consideration while doing the configurations of the circuit. In the resonance frequency that is in use, the series resonant circuit results in minimum impedance. For that reason, it gets the maximum current at the resonance frequency. The series equivalent model of the antenna is shown in Figure 4 [20].

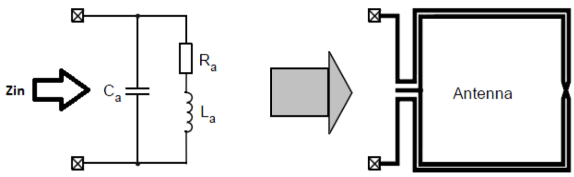

Figure 4. Series equivalent model for the antenna (NXP Semiconductors, 2010) [20]

Having a parallel resonant circuit gives the maximum impedance at the resonance frequency. For that reason, maximum voltage can be obtained at the resonance frequency. For the desired application, the use of double loop antenna coil which includes two parallel antenna circuits would give the optimum performance. Figure 5 shows the parallel equivalent model of the antenna [20].

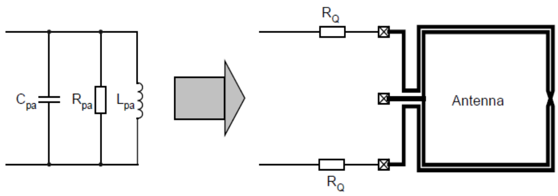

Figure 5. Parallel equivalent model for the antenna (NXP Semiconductors, 2010) [20]

The inductance for the loop reader antenna at the frequency of 13.56 MHz is in the range of a few microhenries. Matching the low inductance numbers gets significantly difficult while the margin for error becomes smaller. When the bandwidth increases, the Q factor gets lower. The reader antenna windings and the path to the antenna can be defined as the ratio of the total reactance of the resistance. Voltage amplification have to be given for the required bandwidth due to the reason that Q's magnitude is about twice as the voltage amplification factor. Antennas with large reactance and low numbers of resistance can be used to match the tag at one frequency, with sufficient power transfer and voltage multiplication, but this would cause the performance to go lower in the usage of other frequencies [21, 22].

For low cost applications, the most commonly used dielectric material is FR4 which is also used for the desired application. Figure 6 and Table 1 show the physical dimensions of the antenna.

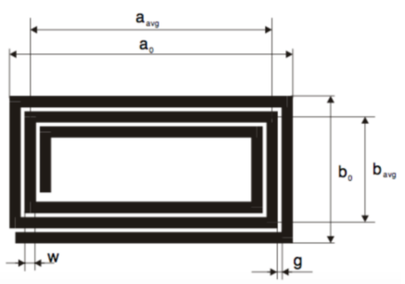

Figure 6. Modelling rectangular planar antenna [23]

Table 1. Physical dimensions of the rectangular reader antenna.

a_0 (Overall dimension of the coil) [mm]	b_0 (Overall dimension of the coil) [mm]	t (Track width) [mm]	w (Track width) [mm]	g (Gap between tracks) [mm]	N_a (no. of turns)
61	34	35	0.38	0.25	6

Table 2 shows the properties of the substrate material and Figures 7 and 8 show the model and layout of the 6-loop rectangular antenna.

Table 2. Properties of the dielectric material.

Dielectric Material	Permittivity	Thickness of dielectric	Conductor	Thickness of conductor
FR4	4.6	1.55 mm	Cu	35µm (top and bottom)

Figure 7. Reader antenna model of the rectangular antenna

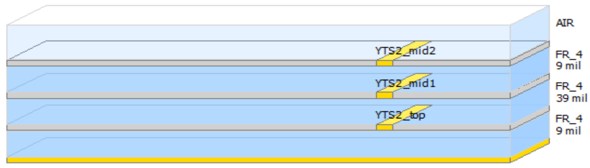

Figure 8. Layout of the rectangular reader antenna

There are 4 different size and geometry antennas designed and their performances are analyzed: 4-loop square antenna (dimensions: 8x8cm, area: 64 cm^2, length of coil: 243.36 cm), 6-loop square antenna (dimensions: 8x8cm, area: 64 cm^2, length of coil: 346.56 cm), 6-loop rectangular antenna (dimensions: 6.2x3x5 cm, area: 21.7 cm^2, length of coil: 136.68 cm), and circular antenna (dimensions: r_{out} = 3 cm, r_{in} = 2.8 cm, area: 18.85 cm^2, length of coil: 72.848 cm).

The 6-loop rectangular antenna is modelled using the Advanced Design System (ADS) Momentum analysis software and its input impedance simulation results can be seen in Figure 9.

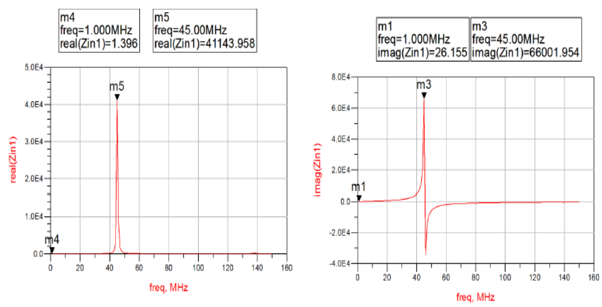

Figure 9. Simulated input impedance results using ADS

The results of the loop antenna by the values of series inductance (L_a) and series resistance (R_s) are well below the self-resonance frequency of the antenna, but they are sufficient enough for good measurement accuracy. Those values can be measured or adjusted by using the following formulas evaluated at 1 MHz frequency [20];

$$L_a = \frac{imag(Z_{in})}{2\pi f} = 4.15\mu H \quad (1)$$

$$R_s = real(Z_{in}) = 1.38\Omega \quad (2)$$

The location in the simulation input impedance figure where the imaginary part of the input impedance crosses the positive axis to negative, the self-resonance frequency of the coil can be determined. The results of the modelled antenna which is measured in ADS gives;

$$f_{res} = 46.2 \text{ MHz}$$

The series equivalent resistance R_a of the antenna is measured taking into account the parallel and series resistances of the antenna. Those calculations can be seen in the Figure 10.

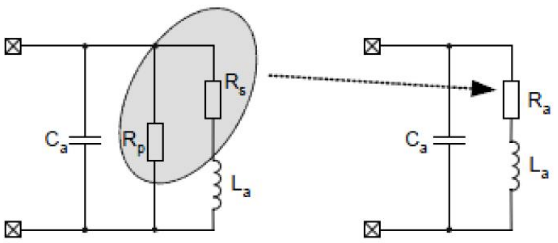

Figure 10. Antenna series equivalent resistance calculation

The parallel resistance at the self-resonance frequency is calculated as R_p= 41.2k. This result is caused by the skin-effect. For the desired application, the antenna is designed to operate at the frequency of 13.56 MHz. For that reason, the value of the resistance has to be corrected according to the frequency dependency of the skin effect. The correction factor is modelled in Equation 3 [23];

$$R_p(13.56 \text{ MHz}) = \sqrt{\frac{f_{res}}{f_0}} \times R_p = 76.05 \text{ k}\Omega \quad (3)$$

Calculations of the antenna's series equivalent resistance and parallel equivalent resistance give:

$$R_a = R_s + \frac{(2\pi f_0 L_0)^2}{R_p(13.56 \text{ MHz})} = 3.03 \ \Omega \quad (4)$$

$$R_{pa} = \frac{(2\pi f_0 L_0)^2}{R_a} = 11.06 \text{ k}\Omega \quad (5)$$

Calculation of the capacitance of the antenna gives;

$$C_a = \frac{1}{(2\pi f_{res})^2 L_a} = 2.9 \text{ pF} \quad (6)$$

2.3. Quality factor

The sharpness or selectivity of the resonant circuit is determined by the quality factor. High Q factor causes the antenna to radiate more energy. The reason which makes the quality factor having a significant role in determining the constraints is, high Q factor would result in a limited bandwidth and long-time constants which causes defects in the signal during the test setup. The Quality factor of the antenna is calculated as;

$$Q_a = \frac{w_{res} L_a}{R_a} = 116.93 \quad (7)$$

and the value of R_Q resistor is calculated as;

$$R_Q = 0.5\left(\frac{w_{res} L_a}{35} - R_a\right) = 4.38\Omega \quad (8)$$

2.4. EMC filter design

One of the functions that the EMC filter circuit, shown in Figure 2, offers is the filtering of the signal as well as the impedance transformation block. To obtain the broadband receiving characteristics, the EMC filter resonance frequency (f_{r0}) has to be close to the upper side band frequency determined by the highest data rate (848 kHz sub carrier) in the system. L_0 is chosen as 560nH and f_{r0} is calculated as;

$f_{r0} \geq$ 13.56 MHz + 848 MHz = 14.408 MHz and chosen as f_{r0} = 14.4 MHz.

C_0 is calculated as,

$$C_0 = \frac{1}{(2\pi f_{r0})^2 L_0} = 221.2 \text{ pF} \quad (9)$$

The values of the EMC circuit parameters are given in Table 3.

Table 3. EMC matching circuits parameters

Parameter	Value	Comment
L_0	560 nH	EMC filter inductance
C_0	221.2 pF	EMC filter capacitance

2.5. Matching circuit design

The antenna should be matched to 50 Ohms and has to be tuned to radiate with a quality factor of 35. Therefore, the load at 13.56 MHz should match the 50 ohms driver impedance, R_{match}. The capacitances are used to match the inductive load and to build a resonator [24, 25]. A serial capacitor, C_1, and a parallel capacitor, C_2, are used as a matching network as given in Figure 3 [20].

EMC filter and matching circuit must transform the antenna impedance to the required TX matching resistance $Z_{match(13.56MHz)}$. The following equations are needed to calculate the matching components [23],

$$Z_{TR}=R_{TR}+jX_{TR} \quad (10)$$

where;

$$R_{tr} = \frac{R_{match}}{(1-w^2 \times L_0 \times C_0)^2 + \left(w \times C_0 \times \frac{R_{match}}{2}\right)^2} = 216.7 \ \Omega \quad (11)$$

$$X_{tr} = 2w\frac{\left(1-w^2\times L_0\times C_0\right)^2\times L_0-\left(\frac{R_{match}}{4}\right)^2 C_0}{\left(1-w^2\times L_0\times C_0\right)^2+\left(w\times C_0\times\frac{R_{match}}{2}\right)^2} = -57.83\ \Omega \quad (12)$$

Series and parallel capacitances can be calculated using the following equations,

$$C_1 = \frac{1}{w\left(\sqrt{\frac{R_{tr}\times R_{pa}}{4}}+\frac{X_{tr}}{4}\right)} = 16.02\ \text{pF} \quad (13)$$

$$C_2 = \frac{1}{w^2\frac{L_a}{2}} - \frac{1}{w\left(\sqrt{\frac{R_{tr}\times R_{pa}}{4}}\right)} = 45.2\ \text{pF} \quad (14)$$

The resistor R_1 in combination with R_2 in the receiving part as shown in Figure 2 is a voltage divider which regulates the voltage level at the receiver (RX) pin. The voltage level should not exceed 3 Vpp, but should be maximized for optimum Read/Write (R/W) performance. The measurement of the voltage level at the RX pin needs to be done with a low capacitance probe. Furthermore, those measurements need to be done in the final housing/position as well as with different loads (targets) which detune the antenna and detects the RX signaling [23].

The receiver's components are defined by the experimental results. Maximum write distance is obtained where the voltage at the RX pin is 2.8V with components;

- C_{RX} = 1nF (DC blocking capacitor),
- C_{vmid} = 100nF (decoupling capacitance),
- R_1 = 1k (voltage divider part),
- R_2 = 2.7k (voltage divider part).

Figure 11 shows our reader design with the rectangular antenna. Using the calculated component values in our experiment, the desired carrier frequency (f_0=13.56 MHz) was not achieved. With calculations based on simplified equations, it is hard to determine the equivalent circuit values with 100% accuracy. For that reason, fine tuning of the matching circuit is a necessary process. For tuning, simulations using the ADS software is an effective software to use. For the designed system, in order to achieve the optimum performance, the proper values of the matching components, C_1 and C_2, should be found accordingly.

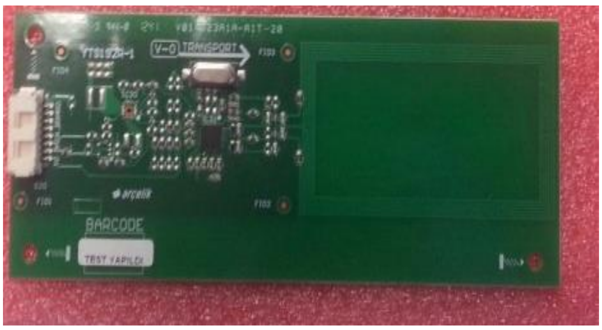

Figure 11. Built prototype with the rectangular antenna

2.7. Measurements in ADS Software

The basic model of the system is shown in Figure 12. On the right side, the antenna components exist. The box contains the necessary data for the simulation and it is possible to change these data or values, which allows us to make simulations with various data and values. Those values are saved through the Network Analyser.

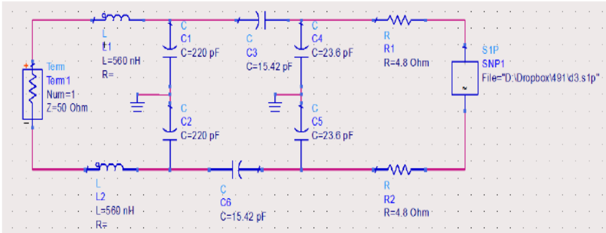

Figure 12. Main schematic of reader design

For our design, inductance (L) and the capacitance (C_1) values which exist on the left side of the model are taken constant; those values are L= 560 nH and C_1= 220 pF. To make the simulation simpler, the values of capacitances are taken as; $C_1 = C_2$, $C_3 = C_6$ and $C_4 = C_5$. Considering those changes and assumptions, the new model is represented in Figure 13.

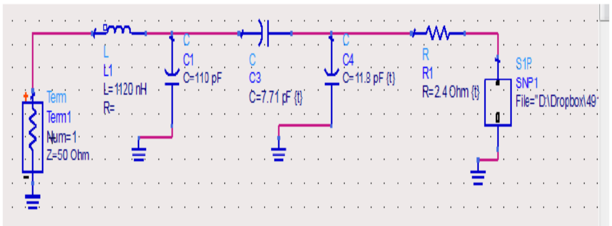

Figure 13. Simplified schematic of reader design.

Determining the optimum values of the matching circuit capacitance is the most vital factor for this schematic. By using the ADS software, these capacitor values are optimized, in order to optimize our antennas.

The Quality factor is also another factor that affects the performance of the antenna. Quality factor of 30 should be obtained after the calculations of these two capacitors.

3. Results

The system design for a TV application can have square, rectangular, and circular loop antennas for the reader. Each of these antenna designs have different return loss, sensitivity, accuracy and read-range. In this section, the comparison results are presented. There can be external and internal effects that can change the operating frequency and the return loss such as proximity of metal and matching circuit capacitor values. Those factors can be used for adjusting the frequency and return loss values.

3.1. Experimental results with proximity of metal and capacitor value effects

3.1.1. Rectangular antenna

Figure 14 shows the ADS impedance measurements of the rectangular antenna.

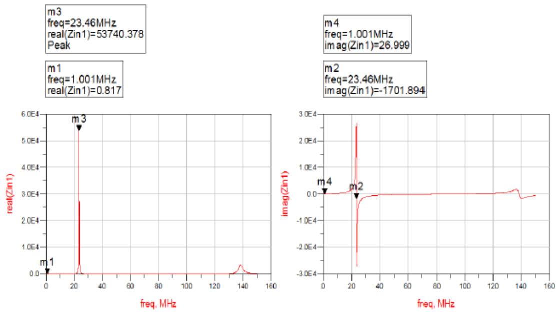

Figure 14. Impedance measurements of the rectangular antenna

Using Equations (1), (2), (3) and (4), the following circuit parameters are calculated;

L_a = 4.33 μH, R_s = 0.82, R_p (13,56 MHZ) = 70.71 kΩ, and R_a = 2.72 Ω.

Such antenna operates at 11.87 MHz and the return loss is -17 dB. Using equation (7), the value of the quality factor is;

$$Q = 135\ (f \times \frac{Hz}{\Omega})$$

Those values depend on the proximity of a metal. Figure 15 shows the rectangular antenna with a distance of 1 cm from metal. When the metal comes closer, it increases the operating frequency and initially increases the absolute value of the return loss then decreases it as shown in Table 5.

Table 5. Operating frequency values and absolute value of return Loss with respect to metal separation from the reader for the rectangular antenna.

Metal Separation from Reader (cm)	Operating Frequency (MHz)	Absolute Value of Return Loss (dB)
2	12.2	17.91
1	13.34	22.9
0.1	15.23	15.19

Figure 15. Metal effect with distance of 1 cm from the rectangular antenna

Another factor that affects the frequency and the return loss is the matching circuit's capacitor values. Table 6 shows the resonance frequency changes with the matching circuit capacitor values for the rectangular antenna.

Table 6. ADS and measured resonant frequency values with respect to capacitor values.

Example	C_3 (pF)	C_4 (pF)	ADS result frequency (MHz)	Measured frequency (MHz)
1	46.00	30.00	15.27	14.33
2	20.00	12.60	15.91	14.61
3	22.00	15.00	15.37	14.30
4	30.00	15.00	14.68	13.52
5	22.00	22.00	14.49	13.40
6	22.00	18.00	14.97	13.89
7	27.00	18.00	14.56	13.42

The main reason for the difference between the frequencies obtained with ADS and the measured ones is that the Q-factors of lumped elements used in ADS simulation are not included in the real measurements. The frequency of 13.56 MHz is the optimum to operate such TV application. Values of C_3 = 30 pF and C_4 = 15 pF are capable of increasing the frequency value up to 13.52 MHz which is close enough to the optimum frequency.

For measurements of the return loss and real and imaginary impedance of the design, an SMA connector is attacted to the TX1 and TX2 inputs of the PN531 transmission module. Figure 16 shows the measurement setup.

Figure 16. Measurement Setup to determine the return loss of the design

Tunning process is applied on the C1 and C2 values of the matching circuit given in Figure 3 to achieve the intended return loss. The best return loss is achieved when C1 = 33.8 pF and C2 = 15 pF. The measurement results show that the input impedance is obtained as 52.36 while the reactance level of 3.8 is achieved. At the frequency level of 13.56 MHz, the return loss value is obtained as -27 dB.

Figure 17. Return loss and Smith Chart measurements with optimized design

3.1.2. 4 Loop square antenna

Figure 18 shows the built prototype of the 4-loop square antenna.

Figure 18. Built Prototype of the 4-loop square antenna

Figure 19 shows the impedance measurements of the 4 loop square antenna.

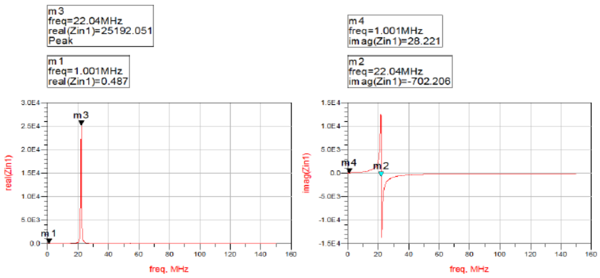

Figure 19. Impedance measurements of the 4 loop square antenna

Using Equations (1), (2), (3) and (4), the following circuit parameters are calculated;

L_a = 4.53 μH, R_s = 0.49 Ω, R_p (13,56 MHZ) = 32.11 kΩ, and R_a = 5.13 Ω.

Such antenna operates at the frequency of 11.5 MHz and the return loss is -19.32 dB. Using Equation (7), the value of the quality factor is;

$$Q = 75\ (f \times \frac{Hz}{\Omega})$$

When the metal gets closer to the antenna, it increases both the operating frequency and the absolute value of the return loss, but if the metal is too close, for example 1mm or less, the absolute value of the gain loss begins to decrease as shown in Table 7.

Table 7. Operating frequency values and absolute value of return loss with respect to metal separation from the reader for the 4 loop square antenna.

Metal Separation from Reader(cm)	Operating Frequency (MHz)	Absolute Value of Return Loss (dB)
2	11.73	20.69
1	12.24	25.00
0.1	14.45	23.14

Table 8 shows the resonance frequency changes with the matching circuit capacitor values for the 4 loop square antenna.

Table 8. ADS and Measured resonant frequency values with respect to capacitor values

Example	C_3 (pF)	C_4 (pF)	ADS result frequency (MHz)	Measured frequency (MHz)
1	23.00	13.00	14.92	13.21
2	22.00	11.00	15.29	13.50
3	23.00	15.00	14.66	13.00
4	18.00	13.00	15.42	13.63

An increase in any of the capacitor values causes a decrease in the operating frequency. Capacitor values $C_3 = C_6$ = 22pF and $C_4 = C_5$= 11pF give the optimum resonant frequency of 13.50 MHz.

For measurement of the return loss, tunning process is applied on the C1 and C2 values of the matching circuit given in Figure 3, to achieve the intended return loss. The best return loss is achieved when C1 = 22 pF and C2 = 11 pF. At the frequency level of 13.56 MHz, the return loss value is obtained as -30 dB. At the frequency of 13.56 MHz, the resonance performance and return loss value that is proper for the design application are achieved.

3.1.3. 6 Loop square antenna

It was not possible to match the 6 loop square antenna since it has a resonant frequency of 13.21 MHz that is lower than the operating frequency of 13.56 MHz. In addition, multiple frequency peaks were noticed for such an antenna. Accordingly, the adjustments and other tests were not necessary for such an antenna. The operating values can be seen in Figure 20.

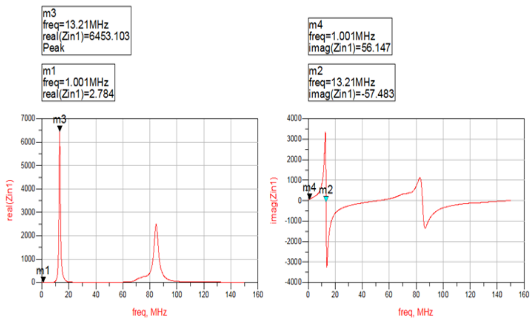

Figure 20. Impedance measurements of the 6 loop square antenna

3.1.4. Circular antenna

Figure 21 shows the built prototype of the 4-loop square antenna.

Figure 21. Built Prototype of the circular antenna

As Figure 22 shows, this type of antenna operates with a frequency which is much higher than the optimum frequency (13.56 MHz) for the desired application, so the adjustments and other tests are not necessary for such antenna.

$$Q = 330(f \times \frac{Hz}{\Omega})$$

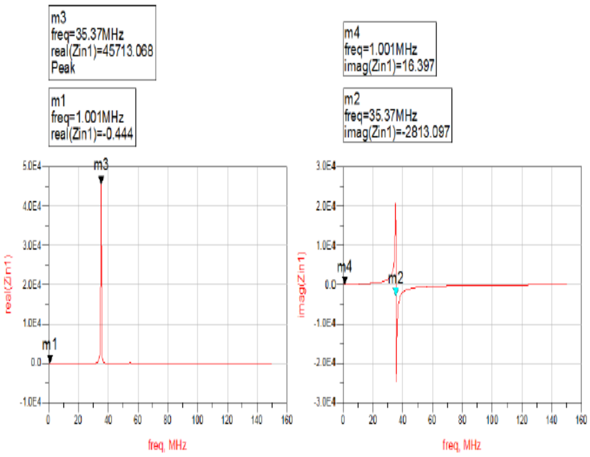

Figure 22. Impedance measurements of the circular antenna

3.2. Measurements for read range

For measuring the read distance, a special software is installed on a TV system which does not allow the usage of any menus in the TV without the reader circuit reading the signal coming from the passive tag. A notification saying "READ RFID CARD" appears on the screen when the TV is turned on. After the card is read, a notification saying "RFID CARD IS READ" shows up on the screen and the system allows the user to use menus on the TV. If the desired communication is not obtained, a notification saying "RFID CARD ISN'T READ" shows up on the screen and the system does not allow the user to use the menus until the reader can read the signal coming from the tag successfully. Figure 23 shows the measurement setup for measuring the read range.

Figure 23. Measurement setup for range measurement

Optimum reading was obtained with a distance of 4.5 cm using the rectangular antenna and 5 cm using the 4-loop square antenna. The 4-loop square antenna gave the highest read range with optimum gain performance when compared with other antenna geometries.

3.3. Smart card effect

When passive smart cards are located close to the antenna of the reader, as a result of the capacitive effect, there is a decrease in the performance of the reader antenna. Therefore, the loop antenna's resonant frequency also decreases and the field intensity is reduced at the operation frequency of 13.56 MHz. To achieve the optimum performance for such a system which will operate a TV application, locating the smart card in a fixed position with a distance of 3 cm from the reader antenna and to obtain the resonance frequency of 13.56 MHz, matching elements should be detuned.

Best results for the rectangular antenna are experienced with those values;

C_1= 18 pF, C_2= 53.8 pF.

Figure 24 shows the measurement setup based on measuring the card effect

Figure 24. Measurement setup for measuring smart card effect

At the frequency level of 13.56 MHz, the return loss value is seen as -17 dB. The maximum read range of 3.6 cm achieved, which is a smaller value than the previous measurements. The reason for that is that the measurements for the last calculations were done by using detuned values of components. For calculating the system accuracy, an experiment is performed 100 times, where a passive card is read in the x, y, and z coordinates from a distance of 3 cm and no misreading is experienced

4. Discussion and Conclusion

Considering the read range and gain performance of the antennas, the 4 loop square antenna type enables higher absolute value of the return loss and higher read range with given capacitor values, which gives us the best antenna geometry for the intended RFID design. The read range also increases as the size and number of turns increase in the antenna. When the distance of the read range increases, the accuracy gets lower. For an RFID technology operating a TV application, the accuracy is more important than the read range. To keep the system at low cost and accurate, the final design for the reader is able to initiate communication with a distance of up to 5 cm. On the other hand, bigger sizes and higher number of turns increase the cost as well. Therefore, circular and rectangular antennas have better cost performance than the 4 loop and 6 loop square antennas. In terms of the performance of the matching impedance which should be 50 ohms, with the lowest imaginary part, the 4 loop square antenna performs well. When observing frequency band performance, all have operating frequency of 13.56 MHz except the 6 loop square antenna as well as the circular antenna. It is not possible to match the 6 loop square antenna since it has a resonant frequency of 13.21 MHz that is lower than the operating frequency of 13.56 MHz. In addition, multiple frequency peaks were shown for such an antenna. The main reasons for this are the high inductance and capacitance values of the 6 loop square antenna. The circular antenna also operates with a frequency which is much higher than the optimum frequency for the desired application, so the adjustments and other tests were not necessary for such antenna.

Metal has a vital effect on the operating frequency. It shifts the operating frequency to higher values. On the other hand, metal has also an effect on the return loss, but it is not a linear effect. Metal increases both the operating frequency and the absolute value of the return loss, but when it is too close like 1 mm, the absolute value of the gain loss begins to decrease.

Passive smart cards placed in proximity to the antenna of the reader affect the reader antenna performance due to the capacitive effect. Resonant frequency of the loop antenna is shifted downwards and the circuit needs detuning. At the frequency level of 13.56 MHz, the return loss value is seen as -17 dB. The maximum read range of 3.6 cm is achieved. For calculating the system accuracy and reliability, an experiment is repeated 100 times, where the passive smart card is read in x, y, and z coordinates from a distance of 3 cm and no misreading is experienced.

In conclusion, a 13.56 MHz HF RFID reader has been designed to allow users secure access into their personal menus in TVs. Even though there are lots of literature studies and publications about assessing RFID systems' operational performance, EMC, and RF considerations with metal and liquid effects, there are only few articles observing RFID systems' performance with comparison of different size and geometry antennas by setting forth the best antenna geometry with metal and smart card effects. Four types of antennas, 4 loop square, 6 loop square, rectangular, and circular, have been simulated and measured. In order to get the desired operating frequency, the capacitor values in the matching circuit have been changed accordingly. Different types of antennas showed different resonant frequencies and return losses. Considering the read range and gain performance of the antennas, the 4 loop square antenna type enables higher absolute value of the return loss and higher read range with given capacitor values, which gives us the best antenna geometry for the intended RFID design. Such design is in the limits of the regulation while having the most efficient operational excellence.

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