IMPROVING SYSTEM RELIABILITY OF HF RFID READER AND COMPARISON BETWEEN DIFFERENT ANTENNAS FOR TV APPLICATIONS

by

Nuray Türksever

B.S., Electrical and Electronics Engineering, Boğaziçi University, 2012

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Electrical and Electronics Engineering
Boğaziçi University
2019

ACKNOWLEDGEMENTS

I would like to thank my thesis supervisor, Assist. Prof. Heba Yüksel for her continuous support and motivation throughout my study. Without her assistance and excessive tolerance, the thesis could not have been accomplished. So, I am deeply grateful to her.

I would also like to thank PhD student, Özgür Özen, for his support, help and contributions throughout the process.

I would like to thank to Arçelik A.Ş.- Electronics Plant for providing the laboratory, equipment and materials.

Last but not least, I would like to thank my wife, Yıldız Türksever who supports and encourages me at every moment and my children, Emir Gökay Türksever and Ayça Türksever who do not spare their love from me.

ABSTRACT

IMPROVING SYSTEM RELIABILITY OF HF RFID READER AND COMPARISON BETWEEN DIFFERENT ANTENNAS FOR TV APPLICATIONS

Developments in Radio frequency identification (RFID) technology in the recent history, has increased significantly. With such developments and improvements RFID technology provides many advantages. RFID allows none-LOS and contactless operations to be done, it has features such as, multiple tag identification, long read range and tag re-programmability. With the increased usage of the smarts phones, the need and the demand for the RFID technology has also increased in the area of consumer applications.

In this thesis, design steps of a 13.56 MHz RFID reader and antenna that used in a RFID TV application has examined, performance comparisons between different types and sizes of antennas has been made aiming to get the most accurate and reliable system with determining the best reader antenna geometry.

By examining the results, it has seen that optimum return loss and impedance have been achieved in all types of antennas. Additionally, the best antenna geometry and size has been observed for RFID TV application. On the other hand, results of the experiments also show that metal proximity which is caused by the metal shieldings of TV unit and capacitance effect of the passive card have significant effects on the return loss and the read range.

ÖZET

ÖZEL TV UYGULMASINDAKİ RADYO FREKANSI TANIMLAMA TEKNOLOJİSİNİN GÜVENİRLİLİĞİNİ ARTIRMA VE FARKLI ANTENLERLE PERFORMANSINI KARŞILAŞTIRMA

Radyo frekansı tanımlama teknolojisi (RFID) hızla gelişen bir alan olmak ile beraber günlük yaşantımıza birden çok avantaj sağlamaktadır. Bu avantajlardan bazıları; temassız işlem olanağı sunması, birden fazla kart tanımlama olanağı ve sistem kartının tekrar programlanabilir olmasıdır. Son on yılda akıllı telefon kullanımın önemli ölçüde artması, RFID teknolojisinin kullanıcı uygulamalarının da popülerleşmesine neden olmuştur.

Bu tezin amacı, özel bir televizyon uygulaması için kullanılacak anten ve 13.56 MHz frekanslı okuyucu tasarımını yapmak, sistem tutarlılığını artırmak ve farklı tip ile boyutlardaki antenlerin performans karşılaştırmalarını göstermektir. Bu sonculların elde edilmesi, arzu edilen uygulama için doğru geometri ve boyuttaki okuyucu döngü anteninin seçilmesine yardımcı olacaktır.

Elde edilen sonuçlar gösteriyor ki, yeterli seviyede geri dönüş kaybı ve empedans bütün anten çeşitlerinde elde edilmiştir. Ayrıca, mevcut uygulama için en iyi anten çeşidinin seçimi konusunda öneride bulunulmuştur. Ancak, deneysel sonuçların incelenmesi ile TV ünitesindeki metal kaplamalar ve pasif kartlardaki kapasitans etkisinin geri dönüş kaybını ve antenin okuma mesafesini önemli ölçüde etkilediği gözlemlenmiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

B_0	Magnetic field strength
d	Distance
E	Electric field
f	Frequency
g	Gap between tracks
N_a	Number of turns
Q	Quality factor
S	Area
S_{11}	Return loss
t	Track thickness
w	Track width
Z	Impedance of a medium
α	Relative angle of the signal
ϵ	Permittivity of a material
λ	Wavelength
μ	Permeability of a material
σ	Conductivity of a material

LIST OF ACRONYMS / ABBREVIATIONS

AC	Alternating Current
ASK	Amplitude Shift Key
DC	Direct Current
EMC	Electromagnetic Compatibility
EPC	Electronic Product Code
FDTD	Finite Difference Time Domain
FEM	Finite Element Method
HF	High Frequency
ISO	International Organization for Standardization
LF	Low Frequency
LOS	Line-of-Sight
MoM	Method of Moment
NFC	Near Field Communication
PCD	Proximity Coupling Devices
PSK	Phase Shift Key
RFID	Radio Frequency Identification
SHF	Super High Frequency
SRD	Short Range Devices
UHF	Ultra High Frequency
VSWR	Voltage Standing Wave Ratio

1. INTRODUCTION

Over the space couplings, radio frequency identification, or RFID technology identifies the objects by using radio waves. Such technology can provide any kind of information that are necessary for people. With the rapid development of the technology in the 21st century, RFID technology also developed and its area of usage has increased significantly. In the industry automatic identification technology has started to bring many benefits especially in the areas of purchasing, logistics, and manufacturing [1].

Most common and basic RFID systems have the components as digital section, small tags and readers. It can be said that the tag and the reader are the main parts of RFID technology. The microchip called as "tag" which is associated with an antenna and also it keeps the identification information of the product in it. The tags don't have any power supply for themselves, they get the necessary RF power from the reader. The communication link between tag and reader is obtained with using the reader circuit. This circuit transfers a carrier signal to the tag's loop antenna then, with the tag to modulate the backscattered signal, reader receives and functions these signals or waves as information [2, 3].

Recently, there have been dramatic increases in RFID application demands in the area of access control of electronic equipment because of simplicity of using RFID technology. With that design, users can log in their personal menus in TV, computer or e-board with passive tags. That kind of application brings secure control of electronic devices in the place of office, school, hospital 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 enable stand by voltage of electronic devices. However, the usage of RFID can lead to additional technological challenges.

RFID designs face some challenges such as the following communication protocols, EMC limitations, and obtaining long read range with small size antenna at high system accuracy. Since the passive tag is remotely powered by the reader's RF signal, it works with very small power. Thus, the read range is typically limited within a proximity distance. The antenna should be tuned and made resonant in order to have a strong current flowing through the conductors and increase the emitted field strength from a limited reader output power. Therefore, the current and emitted magnetic field strength (H-field) increase using a higher quality factor (Q) [4]. However, the designed system must be compliant with the ISO 14443 standard; some specifications such as sub-carrier and data rate are limited [1,5]. Also, the radiated power by the reader and limitations on spurious emissions are limited by EN300330 regulation [6]. Moreover, system accuracy, and selectivity is 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 the standards and obtaining maximum performance.

Several studies have underscored the fact that, the performance of RFID system in the proximity of metals and liquids was affected [7]. Also, some studies describe operational considerations on system performance. However, very few literatures are available about design selection considering system reliability and accuracy of high frequency (HF) RFID readers with the effects of geometry and size of loop antennas by discussing metal environment and capacitive smart card effect.

The design goal of the thesis is to achieve good matching between tag antenna and reader in a wide frequency band with good accuracy and reliability. Also, the main considerations which need to be taken into account in choosing the right sizes and geometry of loop antenna of the reader for the desired range of application are discussed. This thesis focus on the improvement of reliability and accuracy of different sizes, turns and geometry of antennas.

In the thesis, first we introduce RFID fundamental principles and all parameters to design an antenna circuit. Later, calculation of all values of components used, analysis of return loss and read range by ADS simulation tool and experimental results are explained. Finally, experimental results are stated and a performance comparison between different sizes and geometry of loop antennas is presented with the improvement in system accuracy and reliability by choosing the right sizes and geometry of loop antenna for the application.

1.1. RFID History

When the radio waves started to be used more and more and the radar technology has developed, the first steps towards the RFID technology were also taken. Radars function by radiating energy into space and this energy or signal reflects back when it encounters any identified object. Especially in the beginning of 1940s and during the World War II the radar technology improved significantly. People started to be able to get more information about the objects from the signal that is reflected [1]. In 1970 first RFID with a passive tag started to be used. With people realizing that RFID technology could bring many benefits by decreasing the loss or transection time in the areas of access control, maritime and transport, improvements for RFID technology have grown rapidly [8]. Near field communication (NFC) has also increased the function availabilities of RFID technology when it first started to be used in 2002. With NFC it was possible to reach the information in the RFID card by a mobile phone. Nowadays, RFID has large usage area in the industry and personal lives of the people [9].

1.2. Application Areas of RFID

The main purpose of RFID is to higher the life standards of people as the same as all other technologies. RFID is commonly used in tracking the 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 the industry but it is also available for the personal use such as credit cards and tickets for public transportation [4, 10]. Benefits that RFID technology brings to those areas are [11] :

- Shortening the transection time.
- Preventing the loss of information.
- Improving the quality of data capture.

- Higher productivity.

1.3. RFID Fundemantal Principles

RFID system consist of readers (interrogators) which includes RF transmission system, receiver, data decoding and antenna transmit sections. Another main component of RFID system is tag (transponder) which consists of a microchip and antenna. The last main component of RFID systems is computer or database. Those main elements are shown in Figure 1.1 [2].

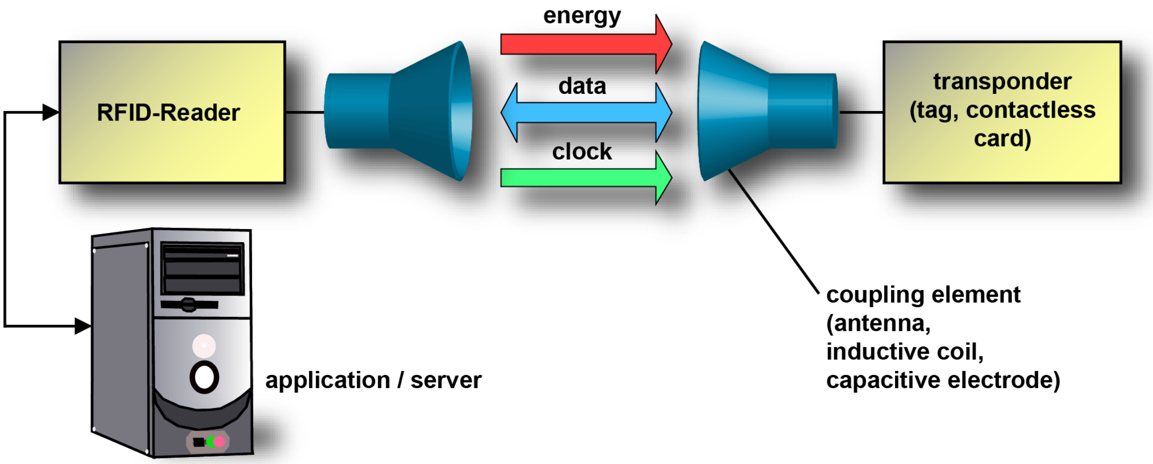

Figure 1.1. Main Elements of RFID System.

Communication and power of the HF RFID system are achieved through electromagnetic coupling between the reader and the tag. First the reader sends a carrier signal to activate the tag's chip. Then the tag processes that signal according to the data stored in tag and sends the signal with necessary data back to the reader. Finally, the signal that arrived to the reader gets decoded and transferred to a host computer or stored in a database [2, 3].

1.3.1. Tags

As mentioned before, tag includes a microchip and antenna. The chip is attached to the antenna. The tag cannot supply its own power, so it receives the power supply from the reader with the antenna. In order to keep the magnetic coupling between the reader's and tag's antennas maximum, the tag antenna circuit must be faced to reader's carrier frequency and within the international policy limitations, the tuned circuit must be maximized. Depending on the required application or the area of usage, the antenna size should be maximum within the physical limits in order to have the maximum efficiency [4].

Choosing the right kind of tag based on the required application is a vital factor. There are many types of tags having different functionalities. They can have different power sources or different frequencies of operation. Due to the fact that tags don't have their own power supply or energy source, the power source is an important factor for the tags. The power supplies determine tag's read range, lifetime, cost, and the variety and types of the functions it can offer. The three main power sources for tags are; active, semi-passive and passive.

Active tags have their own power source such as battery. Without depending on reader to initiate the communication, active tags can start the communication which makes them more reliable. They have the longer read range than the passive tags and the main reason that makes this possible is they have their own power source. They have relatively short life time due to the decay of the battery life. Those kind of tags are mostly used in livestock tracking [12].

Semi-passive (or semi-active) tags also have their own power source, so the battery powers the tag's chip but they are not able to initiate the communication. They need the reader to initiate the conversation. They also have longer read range than the passive tags while they are more expensive in return. With having the option of saving power while on the idle time, they have long life time. Semi-passive tags are used mostly in electronic tollbooths [12].

Passive tags don't have their own power source, so they are powered and the communication achieved by the incoming 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. The most common passive tags are EPC tags and smart cards.

Passive tags do not have an internal power supply and they are powered by the incoming RF communication signal from the reader. Even though passive tags have the shortest read range, they are the cheapest to manufacture and the easiest to integrate into products. Also, their lifetime is almost indefinite because they don't need battery. EPC tags and smart cards are generally passive.

Features and comparisons between the different types of tags can be seen in Table 1.1 [12].

Table 1.1. Comparison of passive, semi-passive, and active tags.

Tag Types	Passive	Semi-Passive	Active
Power Source	Harvest the RF energy	Battery	Battery
Communication	Responses only	Responses only	Responses or initiates
Max Range	1 m	>100 m	>100 m
Relative Cost	Least expensive	More expensive	Most expensive
Example Application	EPC, proximity cards	Electronic tolls, tracking	Large asset tracking, livestock tracking

1.3.2. Readers

Readers, also known as interrogators, are the components of the RFID system that provide a connection between tag and computer. The readers supply RF energy to the passive tags and process the information that is coming from the tag. Then transfer that information to a host computer since they have the ability to communicate with the computer. The main parts of the readers are RF transmission, data decoding, and data receiving. The reader is mostly functions as read-only device which can be understood from its name. It is called interrogator when it reads and writes.

The RF transmission part has components as RF carrier generator, antenna and a tuning circuit. The reader antenna is necessary for the reader to initiate the communication or allow reader to communicate with tag's antenna. The processes of getting the information from the tag and transferring it to the computer occurs in the reader's antenna. Reader's antenna is a determining factor for the read range [4].

After receiving the signal from the tag, microcontroller processes data decoding. The algorithm in the microcontroller allows reader to transmit the RF signal, process the incoming data and transfer the information or communicate with the host computer [4].

1.3.3. Antennas

Antenna is the key part of RFID system due to transmitting and receiving RF power. By having that feature, antenna performance is a significant effecting factor for the whole system's functionality. There are two different antennas in the RFID system, and those are the reader and the tag antennas. Tags get the energy from the reader with their antennas. After getting the energy, tag transfers the energy to the chip to turn it on. For the tag antenna, when the area of the antenna is bigger, it can collect more energy which would allow it to work with further range. The same fact goes with the reader's antenna, when the antenna gets larger area, read range become higher. Reader antenna's functions are to supplying power, sending the driving signal to the tag and receiving the signal that is carrying the data coming from the tag [3].

To be able to produce the largest induced voltage, available flux near the reader's antenna coil should be in the maximum level. When the bandwidth of the antenna coils is not wide enough, it interrupts the data carrier signal. To prevent this situation, antenna coils should be as wide as possible without leading negative effects on the efficiency.

To be able to get the maximum antenna current flow, the reader and tag antenna must match. As it is mentioned before, to activate the desired tag, an inductive coupling should occur. In a case of incorrectly designed reader and the tag antennas, the inductive coupling would not occur, so this would lead the RFID system into a failure [2].

1.3.4. Operating Frequency

Differences between tags and antennas in general were mentioned before. Each one of the differences creates a veraity in radio frequencies that the systems use. Different radio frequencies may be required for different read range, power requirement and the performance of the operation. And, it is important to choose the right operating frequency because those frequencies affect the read range and reader cost directly.

As it was mentioned before, reader sends a carrier signal to the tag, which is a transmitted radio signal. The energy that tag needs is supplied by this signal. The RFID systems having different carrier signal frequencies can be classified into several frequency bands [1]. The most common RFID carrier signal frequencies are [4]:

- 125 kHz
- 13.56 MHz
- 900 MHz
- 2.45 GHz
- 5.8 GHz

It can be seen that there is high variety on the frequencies that are used by different RFID systems. The classification of those frequencies is based on their sizes as below:

- Low Frequency (LF)
- High Frequency (HF)
- Ultra-High Frequency (UHF)
- Microwave and Ultra-Wide Band (UWB)

Some of the specifications and characteristics of the classified frequencies which are obtained from different RFID cards can be seen in Table 1.2 [12].

Table 1.2. Characteristics of common frequencies in different RFID cards.

Frequency	Antenna Components	Read Range	Penetration	Usability in Metal Environment
LF	Coil	Proximity	Best	Possible
HF	Coil	Medium	Good	Possible
Microwave	E-field dipole	Long	Poor	Difficult

As the table shows above, low frequency (LF) RFID tags or cards' common operations frequencies are from 125 kHz to 135 kHz. The most common characteristics of LF is that they have very short read ranges because they are passively powered through induction. The reader cost for those tags is the lowest comparing with the other frequencies. LF tags are able to be used in the environments that require high level of endurance such as proximity to metal, liquids, or dirt. One negative characteristics of LF tags is their rate of date reading level. It is relatively lower than the other frequencies [12].

The operation frequency of high frequency (HF) tags is 13.56 MHz. Such frequencies are commonly used in access control, contact-less credit cards, and ID badges. The feature allows HF tags to operate well in those areas is that they often built in a foil inlay or in a credit card form. HF tags' reader cost is more expensive than the LF tags but it is still cheaper than the other frequencies. HF tags have higher rates of data reading than LF while they cannot operate as well as the LF tags in the environments that require endurance [12].

The operation range frequencies of UHF is from 868 MHz to 928 MHz. They have higher read range than LF and HF. This feature allows them to operate efficiently for item tracking and supply chain management applications. The reader cost of such frequencies is cheaper than microwave frequencies but it is more expensive than the others. One negative characteristic about UHF is that they face with electrical interference when they get close or interact with liquids or metals, which makes the users of such frequencies to avoid from using it in the areas such as animal tracking, metal container tracking, or access control systems [12].

The operation range of microwave tags is from 2.45 to 5.8 GHz. Microwave tag technology started to be used in the recent years. Their usage rates are relatively lower than the other frequencies. Semi-passive type of microwave tags is the most common type other than the passive or active ones. Microwave tags are the most expensive tags in the market. A negative feature of microwave tags is that wireless 802.11b/g (Wi-Fi) networks have a possibility of interfering [12].

1.4. Types of Couplings

The type of the coupling in the RFID systems has effects on the read range and the operation frequency of the system. The coupling should be chosen depending on the desired application area of the system. There are three main coupling techniques [11]:

- RFID inductive coupling
- RFID backscatter coupling
- RFID capacitive coupling

The read ranges of those techniques can be seen in Table 1.3.

Table 1.3. Read ranges of different coupling techniques.

Coupling Techniques	Read Range
RFID backscatter coupling	Long
RFID capacitive coupling	Short
RFID inductive coupling	Medium

The decision of using the right type coupling should be made after considering the read range, frequencies needed and the coupling which should be matching to the other components of the system.

1.4.1. Inductive Coupling

The frequencies which use inductive coupling are usually the lower RFID frequencies, under 135 kHz or at 13.56 MHZ. RFID inductive coupling can counted as a near a field effect. When the λ is wavelength of the frequency in use, the range of 0.16λ must be kept between the coils [1, 11].

By using the mutual inductance, RFID inductive technique transfers the energy from the reader to the tag. Reader's antenna coil generates a strong high frequency electromagnetic field for the reader coil to couple to the coil from the tag antenna. This situation becomes possible because of the presence of magnetic field near the reader. The reason that the inductive coupling techniques are used mostly for LF and HF RFID applications is because the wavelength of the frequency which is 13.56 MHz and having 22.12 meter - wavelength that is larger than the distance between tag and reader's antenna. This whole operation system can be seen in Figure 1.2.

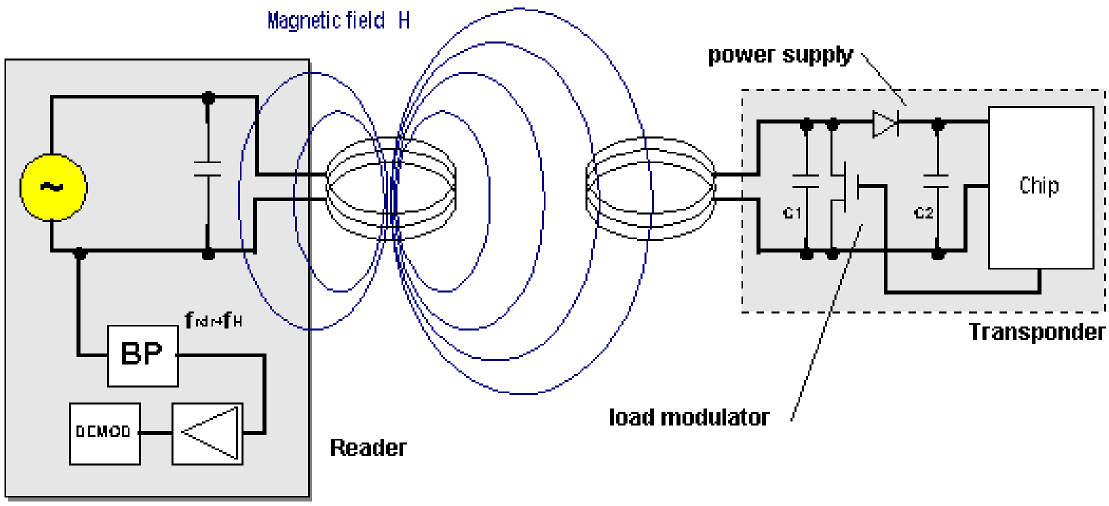

Figure 1.2. Inductive coupling system operation principle.

As it was mentioned before, the passive tags need its power to be supplied from the reader, in order to start operating. Inductively coupled systems are almost always operated passively, so in those techniques, it is also a must for the reader to provide the energy needed for the tag. Therefore, to supply the sufficient energy for the tag, reader's antenna coil generates a strong field and the tags antenna draws the energy [1].

1.4.2. Backscatter Coupling

The objects with having dimensions greater than around half the wavelength of the wave reacts electromagnetic waves. The reaction cross-sections show the efficiency of an object reacting electromagnetic waves [1].

In RFID backscatter coupling, the energy that the tag needs to operate is supplied with the RF power transmitted by the reader. Also in such coupling, a carrier signal is sent to the tag to initiate the communications and supply the energy it needs. The RF voltage that the reader is sending is developed on antenna terminals. That voltage lets the chip to start operating and then the chip sends a backscattered signal to the reader which includes the identification information. This information is sent by varying its front end complex [13]. This technique comes from the radar technology.

1.4.3. Capacitive Coupling

In such couplings, the communication is obtained by capacitive effects between the reader and the tag. Both reader and tag have conductive patches as a component. For the capacitive effect to occur, those patches should be located very close and parallel to each other which would result the system to have short read range. This system is used in the applications which requires small read ranges such as smart cards. Same as the other couplings, the AC signal is sent from the reader to the tag to supply the energy for it and to start the commination. Data is sent to the RFID reader by load modulation. When such items as smart cards are attached into a reader, RFID capacitive coupling operates best [11].

1.5. ISO Communication Standards for RFID Applications

ISO/IEC 18000 standards are the most integrated standards for RFID technologies. There are 6 parts in these standards, each defining different range of frequencies as below:

- Part 1: General standards.
- Part 2: LF.
- Part 3: HF.
- Part 4: Microwave (2.45 GHz).
- Part 5: Microwave (5.8 GHz).
- Part 6: UHF.

For the HF range, ISO/IEC 14443 and ISO/IEC 15693 are the most relevant. They are related with smart card and proximity card interfaces. This standard is set due to the requirements for high security in the communication between devices. IS0 14443, ISO 15693, ISO 18000-3 and 18092 covers the inductive coupled RFID system which functions in the frequency of 13.56 MHz [1, 5, 14].

1.6. EMC Regulations for RFID Applications

Each country has their own policies and regulations for the radiated power. Those regulations are applied in many aspects. One of them is regulations for physical parameters. The allowed strength of field, frequency or bandwidth of RFID applications can be counted as regulations for physical parameters. By considering this fact, in different countries and different areas, the variety of radiating systems will not affect each other.

After manufacturing or design process, each new RFID product or RFID component, must pass the certification test at an officially proved lab before getting into the market. The tests are applied on the products to check if the emission levels are in the emissions limits that are defined by the regulations. In Euro zone the ERC 70-03 determines the emission limits and spectral mask, and the EN 300330 determines the measurement method [6, 15].

NFC and contact-less smart cards requires two interacting devices to be very close to each other. For that reason, they are also known as proximity coupling devices (PCD) or short range devices (SRD) and the operation frequency band of these devices is 13.56 MHz. In the close fields to the carrier frequency, the H-field emission limit for such frequency bands is regulated to be maximum 60 dBµA/m at 7 kHz. The emission limit for the modulation bandwidth of ± 150 kHz is 9 dBµA/m [9]. Table 1.4 shows the regulation limits for different RFID frequencies [11].

Table 1.4. Allowed field strength of common RFID operating frequencies.

Frequency Range	Comment	Allowed field strength / transmission power
<135 kHz	Low frequency and inductive coupling	72 dBµA/m max
13.553 - 13.567 MHz	Inductive coupling, contact-less smart cards (ISO 14443), smart labels (ISO 15693) and item management (ISO18000-3)	60 dBµA/m
865.6 - 867.2 MHz	UHF (RFID only)	2W ERP Europe only
2.446 - 2.454 GHz	SHF (RFID)	0.5 W EIRP outdoor, 4 W EIRP indoor
5.725 - 5.875 GHz	SHF (ISM), backscatter coupling	4 W USA/Canada, 500 mW Europe

2. CRITERIA FOR ANTENNA DESIGN

Under this topic, main principles of HF RFID antennas are examined and determinants of a proper antenna design are described. There are different kind of reader antennas, so it is vital to determine the desired RFID application first. The necessary system requirements can be obtained and implemented to the antenna design, accordingly.

2.1. Special TV Application

In this thesis, the special application has taken as a remote control for TV. It can be in a school, hospital or company as long as there is a public TV with specific applications. The application that will be taken under consideration in this work has the features such as providing authorized users user defined tags to allow them accessing the personal menu and the operating system of TV.

For such application, the reader antenna and reader circuit should be located in the TV set 1 cm deep inside from 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. But for such applications working like an access control system, the RFID system's accuracy has a vital role, so this means for such applications read range is not the priority. The reader antenna's size should be small enough to fit into the TV system.

Furthermore, for such applications that are used in public, the system should be durable enough to endure environmental effects and the cost should be low. Considering those factors that are mentioned, the most effective type of tags are passive tags for such applications.

2.2. Steps of Designing

The very first steps of designing a reader antenna should be determining the construction methods and selecting the material to be used in the antenna, determining the desired application, identifying the requirements and regulations of the RFID reader. After these steps, a simulation tool should be used for the antenna to be modelled, simulated and optimized. In that simulation, the efficiency and the effectiveness of the antenna can be calculated by looking at the return loss rates, complex and real impedance at the desired frequency. At the last stage, if the data about the performance of the antenna obtained from the simulation are satisfying and the antenna is proper for the usage in the special TV application, the prototypes should be built and their performances should be assessed. If all the final values and data are satisfying with the requirements and the regulations, then the design stage of the antenna is finished.

The basic items to be done in the processes of antenna design are shown as below:

- Materials: To be able to keep the cost minimum and making the antenna and TV matching more easy, FR+ substrate with a dielectric permittivity of 4.6 and thickness of 1.5 mm is selected. The material for the top antenna was designed to be copper with a thickness of 35 mm.
- Main IC: NXP PN531 is selected on antenna terminals, which is the most commercially used chip for HF readers.
- Type of the antenna: Rectangular 4-loop antenna is used in design stage.
- Parametric study and optimization: For the loop antenna, diameter, spacing, antenna length, antenna width and the number of turns are considered as key factors. By investigating the simulation results, the most efficient combination of those factors and their optimal sizes have been defined.

2.3. Simulation Tool

Applying numerical methods in the stage of antenna design has a vital role for the whole system. Such methods are applied for various systems. Those methods include Method of Moment (MoM), Finite Element Method (FEM), and Finite Difference Time Domain (FDTD).

All these methods are applied for different designs because they all have their own unique features. The most common analysing tools for reader antennas are electromagnetic modelling and simulation tools. For the planar designs, the best method has defined as method of moments, and for more complicated or more dimensional designs, finite element method or finite difference time domain method are considered to be more effective. For large antenna structures, the MoM is the fastest and the most accurate in measuring the antenna performance. Antenna performance can be analysed directly by using the methods of FEM and FDTD. In the comparison between those two methods, it has seen that the FEM method gives more accurate results than the FDTD method. On the other hand, FDTD methods is the most useful methods for analysing some larger antenna structures, solving the wide band problems in the domain, and mapping the electromagnetic field distribution and radiation. In the area for designing antennas for RFID system, High Frequency Electromagnetic Field Simulation (HFSS) tools are widely used and they have the feature that allows automation on meshing to facilitate the user and develop the precision.

In this work, the developed environment was a complete passive RFID system which had done in Agilent ADS 2009. With such simulation tool, properties of the design which had negative effects on the reader performance could be seen clearly after the analysis [16].

2.4. Basics of Loop Antennas

Antenna circuits have a vital role for the RFID systems. The reason which makes them having a key role is energizing and link between the reader and the tag is obtained via antenna coils [17]. After all, it is substantial to provide a proper antenna circuit for the special TV application.

The RFID reader antenna can contain or use different elements for different frequencies. For lower frequencies, it contains a coil, for the higher frequencies a form of a dipole element can take the coils place. While most of the antennas are meant to have lower frequencies, most of them contain a coil, but when radiative systems are used and the wavelengths are much shorter, by other means, in higher frequencies, form of dipole is more effective [11].

Operating HF band of the RFID reader, 13.56 MHz, and during the reading and writing processes, the reader antenna uses the magnetic field supply for energizing to the tag that needs to be supplied by the power. It has seen from the results of the simulations and the experiments that design of electrically small antennas in 13.56 MHz frequency with a wavelength of 22.12 meter is hard to achieve. The reason behind that is the wavelength is proportional to the antenna dimensions. Considering that factor, designing a perfect matching antenna for most RFID applications is a difficult task. As an alternative to that, a small loop antenna circuit that is operating at the desired frequency is used [17]. For the task of supplying energy to the HF passive tag, the loop antennas are considered as the most proper for generating the magnetic field that is necessary for transferring the energy for the tag. For the features such as ductility, solidity and performance, a copper loop antenna is chosen for the special TV application [2]. Performance of the reader antenna depends on [18]:

- Antenna sizes.
- Number of turns.
- Track diameter and spacing.
- Track material.
- Environmental impacts.

2.4.1. Inductance of Antenna

Figure 2.1 shows the physical dimensions of a rectangular planar antenna with greater than one turn [19].

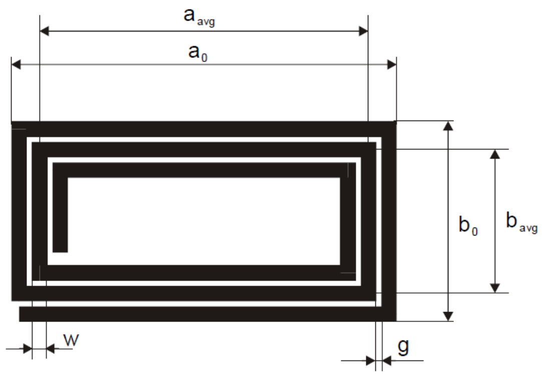

Figure 2.1. Modelling rectangular planar antenna.

There are different formulas that can be used for modelling the inductance given by the following formulas [19]:

$$L_a = \frac{\mu_0}{\pi} \times [x_1 + x_2 - x_3 + x_4] \times {N_a}^{1.8} \tag{2.1}$$

where,

$$d = 2\frac{(t+w)}{\pi} \tag{2.2}$$

$$a_{avg} = a_0 - N_a \times (g + w) \tag{2.3}$$

$$b_{avg} = b_0 - N_a \times (g + w) \tag{2.4}$$

$$x_1 = a_{avg} \times \ln\left[\frac{2 \times a_{avg} \times b_{avg}}{d \times (a_{avg} + \sqrt{{a_{avg}}^2 + {b_{avg}}^2})}\right] \tag{2.5}$$

$$x_2 = a_{avg} \times \ln\left[\frac{2 \times a_{avg} \times b_{avg}}{d \times (b_{avg} + \sqrt{{a_{avg}}^2 + {b_{avg}}^2})}\right] \tag{2.6}$$

$$x_3 = 2 \times [a_{avg} + b_{avg} - \sqrt{{a_{avg}}^2 + {b_{avg}}^2} \tag{2.7}$$

$$x_4 = \frac{[a_{avg} + b_{avg}]}{4} \tag{2.8}$$

where variables;

- a , b : Overall dimensions of the coil
- a_{avg} , b_{avg} : Average dimensions of the coil
- t: Track thickness
- w: Track width
- g: Gap between tracks
- N_a: Number of turns
- d: Equivalent diameter of the track [19]

2.4.2. Antenna Coil's Magnetic Field Strength

Figure 2.2 shows the antenna coil of a square conductor loop and the side of the square loop [3].

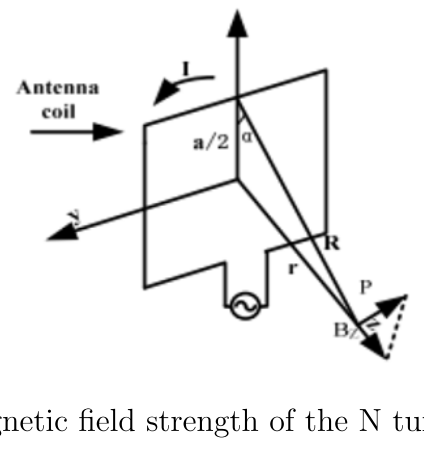

Figure 2.2. Magnetic field strength of the N turns square loop.

The formula that models the magnetic field strength B which is located in the plane of vertical distance r from the centre of the loop is:

$$B_z = \frac{\mu_0 I N a^2}{2\pi\sqrt{(a/2)^2 + r^2}[(a/2)^2) + r^2]}(Wb/m^2) \tag{2.9}$$

for $r^2 \gg a^2$;

$$B_z = \mu_0 I N a^2 / 2\pi r^3 (Wb/m^2) \tag{2.10}$$

Magnetic field constant μ, is the permeability of air given as $4\pi\ 10^{-7}$ H/m. N defines the number of turns in the antenna coil, current going through the antenna coil represented by I, Equation 2.10 indicates that the magnetic field strength decays with the rate of $1/r^3$ [3]. The fundamental limiting factor in the read range of the RFID systems is the near field decaying behaviour of the magnetic field.

2.4.3. Induced Voltage

Faradays law states that voltage around the antenna loop gets induced by the time-varying magnetic field through a plane bounded by a closed path. In a situation that the tag and reader antennas are close enough to each other, in the tag antenna coil, the time-varying magnetic field B that has provided by the reader antenna coil induces a voltage, which can be also defined as electromotive force. The flow current in the coil is caused by the induced voltage in the tag coil V_a. Equation 2.11 shows that the induced voltage in the tag coil is proportional to the number of turns and the surface of the coil, but it is inversely proportional to the square root of the coil tag inductance [20].

$$V_a = 2\pi f N_a Q S B_0 = V_a = 2\pi f N_a (R\sqrt{\frac{C}{L}}) S B_0 \tag{2.11}$$

where,

- f : frequency of the arrival signal
- S : area of the loop in square meters
- B_0: magnetic field strength of the arrival signal
- α: angle of arrival of the signal

2.4.4. The Number of Turns

B field could be increased by increasing the amount of ampere-turns. By doing that, longer read ranges can be obtained. However, there is a negative factor for the situation mentioned, the antenna gets less portable and the reader gets more expensive when the turns in the antenna increases.

The reader antenna circuit increases as square of the number of turns, as a result of the increase in the amount of the turns. A high inductance load results in greater numbers of reacted power as well as a large impedance that differs significantly. By considering the factors that are mentioned, keeping the number of turns as few as possible while obtaining the minimum B field is necessary for the desired read range [2].

In order to obtain small amount of μ inductance, the number of turns should be selected considering the antenna size. Matching the very low inductance values gets increasingly hard and the margin of error gets significantly smaller. In order to obtain a self-resonance frequency $\geq$ 35 MHz, the parasitic capacitance should be kept minimum. For many applications and antenna sizes, the number of turns will be in the range N_a = 1-6 [21].

2.4.5. The Symmetry of Antenna

As Figure 2.3 shows that depending on tuning and EMC behaviour, symmetry in antenna design has a vital role in the antenna system. If the factors of EMC behaviour and tuning are not taken into account, due to the parasitic capacitances from the antenna to the ground, common mode currents would be generated. Such currents would cause emissions would put the system out of the EMC regulation limits [19].

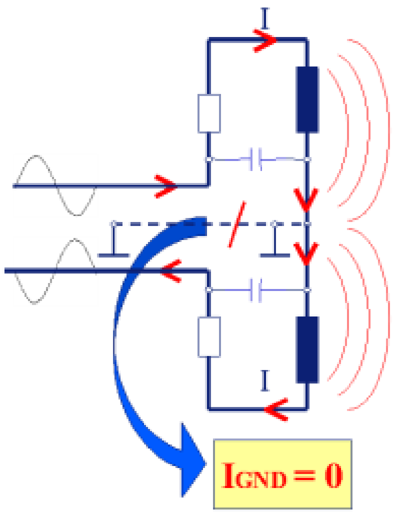

Figure 2.3. Ground current compensation.

An example of symmetric 4 turn antenna design can be seen in Figure 2.4. In that antenna design the centre tap of the antenna is attached to the ground. It is more effective to leave the centre tap floating other than grounding it. By leaving it floating the symmetry of the antenna can be obtained more easily [19].

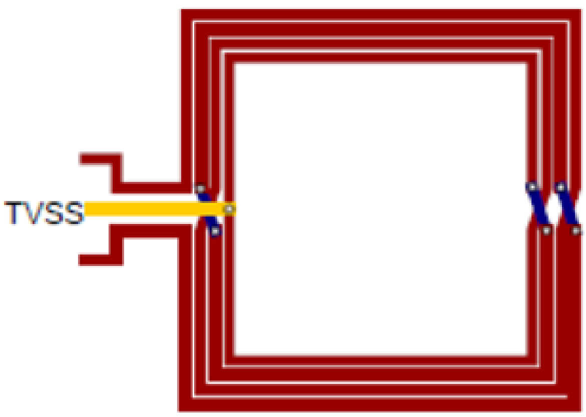

Figure 2.4. 4 turn symmetric antenna design.

2.4.6. Antenna Size

In order to let the current carrying parts add more contribution to the magnetic field, the reader antenna loop should be as large as possible. However, if the loops are designed too large, current carrying parts would start contributing weakly, due to the large span between the current carrying parts and the tag. Furthermore, the total field could be decreased if the total wire length of the loop has a significant part of the wavelength of 22.12 m. The same factor can cause standing waves to inspire multiple resonances. After all, dimensions of the antenna should be determined after simulations and experiments to ensure the sufficient magnetic field [2].

2.5. System Performance

The communication distance between the reader and tag can be defined as read range. The read range is referred to the maximum distance that the reader can read the data coming from the tag. Write range on the other hand, refers to the maximum distance for the reader to write data to the tag [4].

The read/write range depends on [4]:

- Electromagnetic coupling of the reader and tag antennas.
- RF Output power level of reader.
- Carrier frequency bands.
- Power consumption of the device.

2.6. Design Considerations

Before starting on the antenna design, the number of factors should be a number of issues have to be considered [2].

2.6.1. Proximity of Metal

Surrounding environments in which the communication between the reader and the tag obtained can affect the performance of RFID systems significantly. The close materials to the reader and tag antennas such as metals and liquids can affect the performance in a negative way by altering the attributes of the antennas in terms of impedance adaptation and field distribution [7].

The metals that are close to the antenna will affect its performance in a negative way. The electromagnetic waves that are generated by the reader can be cancelled if there is a presence of an eddy current. The eddy current is generated when the metal plate is located close to the antenna [22]. As a result of that situation, drop in the read distance can be examined. It is obtained from the researches done on that topic that the resonant frequency of the loop antenna in the proximity of the metal plate is always shifted upwards while causing a corresponding reduction in the field intensity. When considering the location of the metal plate, it has been observed that the bottom-placement and/or side-placement has better effects than the back-placement plate. The factor that makes the eddy current to be generated is majority of the magnetic flux to be blocked. This reduces the inductance of the antenna significantly. As a result of that, the frequency changes can be observed. To prevent such negative effects, there should be a certain distance between the antenna and the metal [2, 7].

2.6.2. Quality Factor

Quality (Q) factor is also another factor that determines the performance of an antenna. The energy which is stored in the antenna is reacted by the quality factor. Alternating H-field's emitted power varies heavily according to the quality factor of the reader antenna resonance circuit. Parallel and serial resonance circuits can be determined as [9]:

$$Q = \frac{2\pi f_r L}{R_s} = \frac{R_p}{2\pi f_r L} \tag{2.12}$$

Where f_r stands for the resonance frequency while L is the inductance of the antenna. R_s defines the serial resonance circuit and R_p defines parallel resonance circuit. By examining the formula, it can be seen that frequency and values of the equivalent electric components affect the quality factor. When the quality factor gets higher, it decreases the supply energy consumption of the reader for the same emitted H-field strength but while more the quality factor gets high, effective spectral bandwidth of the system also increases. If the spectral bandwidth gets low, it can have a negative impact on the signal shaping, which would affect the data transmission [9]. The bandwidth (B) can be obtained with such calculation as below [19]:

$$B = \frac{f_r}{Q} \tag{2.13}$$

The emitted H-field is sourced by the current in the loop antenna, that current can be reactive or active. Having a higher Q factor, can increase the reactive current, which would make it possible to emit higher H-field amplitude in a long term and modulation bandwidth to be reduced. Beside this factor, frequency regulations on the usage of the modulation bandwidth is also a limiting factor [9, 23]. The bandwidth B-pulse width multiplied by T (maximum timing limit) can be modelled as [19]: B.T $\geq$ 1 Considering the bandwidth which is defined in Equation 2.13, if B multiplied by T can give the results such as: Q $\leq$ fr.T Q $\leq$ (13.56 MHz).(3 μs) Q $\leq$ 40.68. It is shown that maximum allowable quality factor of circuit is limited to 40 in order to follow ISO limitations.

3. READER DESIGN AND ANTENNA MODELLING

In this chapter, by considering the special TV application, HF RFID reader circuit, antenna design and calculation of the parameters are examined. Moreover, simulation, experimental results and optimized results are shown.

3.1. Main Chip

The transmission module for contact-less communication at 13.56 was selected before starting the designing phase. For the application that has chosen, NXP PN531 transmission module that puts together the modulation and demodulation for contact-less communication is used. 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. This module which is the most suitable one for the desired application is also the most common IC for HF NFC applications. PN512 transceiver IC supports the following operating modes [24]:

- Reader/Writer mode supporting ISO/IEC 14443A/MIFARE and FeliCa scheme.
- Card Operation mode supporting ISO/IEC 14443A/MIFARE and FeliCa scheme.
- NFCIP-1 mode.

For NXP contact-less reader to work properly, some requirements have to be achieved. Those requirements are [24]:

- Generating the RF field: Considering the transmitter supply current and general emission limits, magnetic field has to be generated in the maximum level.
- Transmit data: By considering the signal characteristics and timing, the coded and modulated data signal has to be transmitted in a way, to allow every card and NFC devices to receive it.
- Receive data: Within the datasheet limits such as maximum voltage and receiver sensitivity, the response of a card or NFC device has to be transferred to the

receive input of the PN531.

There are some factors that the operating distance of NXP contact-less NFC reader ICs depends on, those factors are [24]:

- 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).

Figure 3.1 shows the circuit of PN531 transmission module for the example application [25].

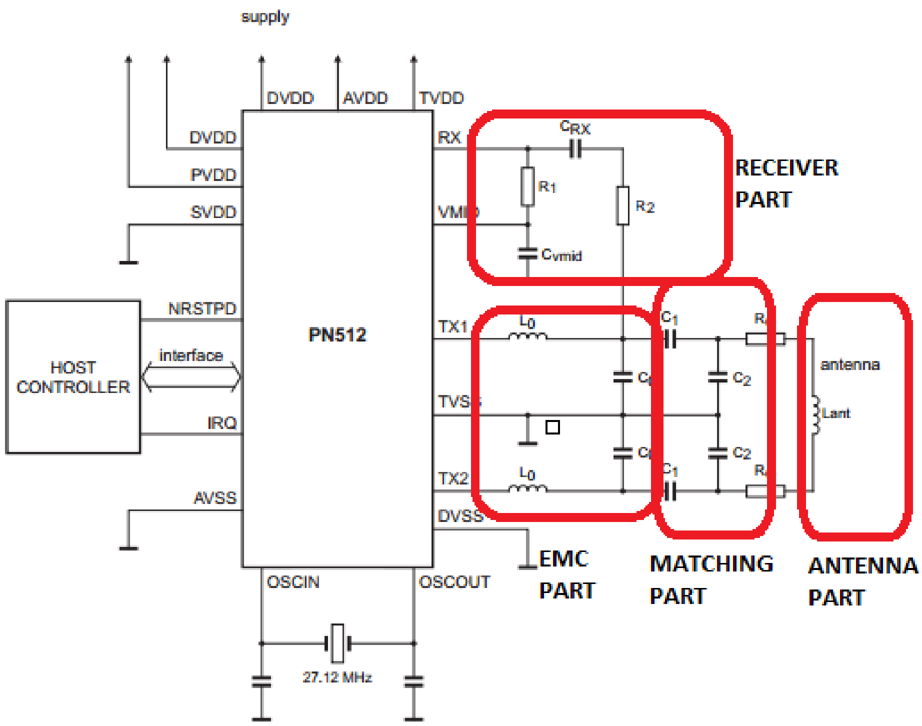

Figure 3.1. Sample application diagram of PN531.

The two branches from different networks which connect the antenna to the driver output is identical. This situation provides to have an output voltage in a magnitude of as twice as the supply voltage. In a result of that the power losses can be reduced in the output driver [23].

The main IC should be tuned to a center frequency of 13.56 MHz with proper antenna and other parts, having a 50 ohm impedance. The Voltage Standing Wave Ratio (VSWR) should be less than 1.2 to achieve the optimum performance [2].

3.2. Antenna Design and Modelling

Main functions of the antenna can be defined as, storing charge as capacitance (the diameter and length of antenna wires), resisting to the changes in current as inductance (size and number of turns of the antenna), and radiates power as resistance (the span between antenna wires and the number of turns). Antenna looks like an R-L-C circuit, by looking from the side as the electrical view. Antenna type should be taken under consideration while doing the configurations of the circuit. A loop antenna, which is shorter than the wavelength, can be defined as series of combinations of an inductor and capacitor with some resistance. The inductance and capacitance are both roughly proportional to the length of the antenna [18, 26].

In the simulation tool, serial and parallel equivalent circuit models of the antenna should be measured as a first step. To obtain the optimum resonance at the frequency of 13.56 MHz, all affecting factors and components should be calculated.

In the antenna design phase, the first step should be obtaining the series and parallel equivalent circuit models. 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. This type of antenna circuit is the most common and the most useful one for proximity reader antenna, because of its characteristics such as simple circuit topology and low cost [17]. The series equivalent model of the antenna is shown in Figure 3.2 [19].

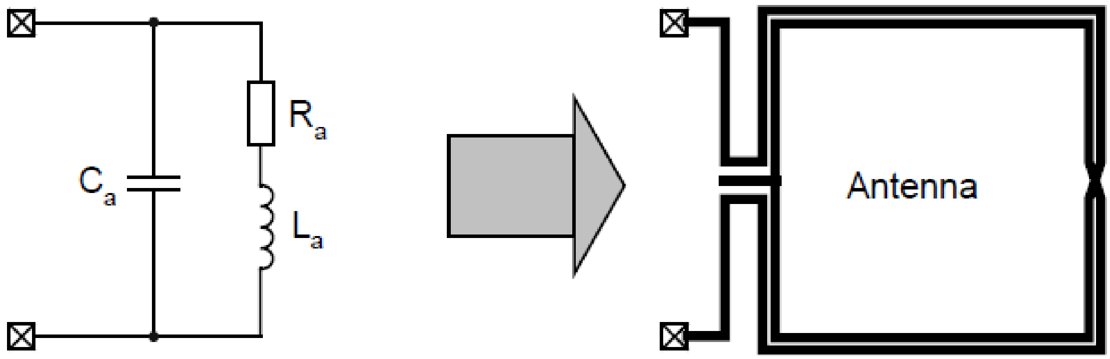

Figure 3.2. Series equivalent model for antenna.

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. Although parallel resonant circuits have the lowest level of resonant current, it can still provide a strong circulating current that is proportional to Q of the circuit. For the desired application, use of double loop antenna coil which is including two parallel antenna circuits is also possible [17]. It can be used for the tag antenna [20]. Figure 3.3 shows the parallel equivalent model of antenna [19].

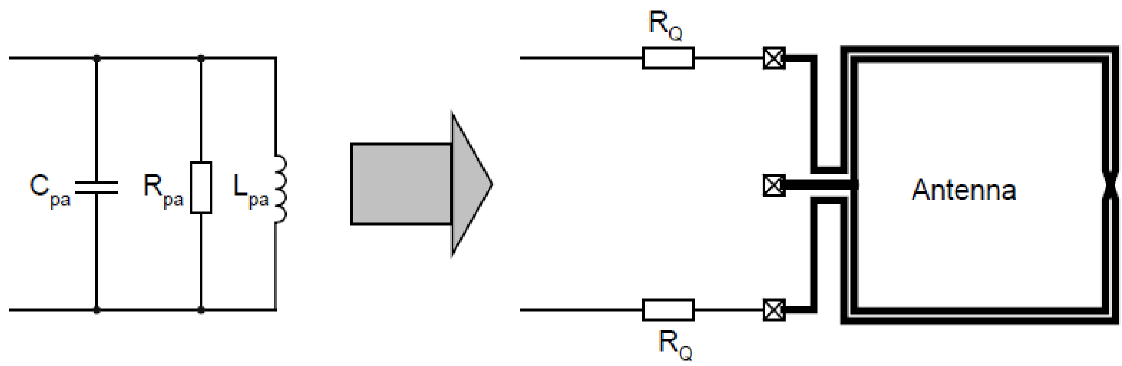

Figure 3.3. Parallel equivalent model for antenna.

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. The reader antenna windings and the path to the antenna can be defined with DC resistance of few ohms. Insufficient magnetic field can be obtained due to a high resistance path which would block current flow [21].

When the bandwidth increases, it would make Q factor to get lower. It 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. After all, it has examined that small reactance antennas will provide higher levels of performances at the desired frequency [26].

With the restrictions that are mentioned and the condition of fitting the reader into the TV unit, ADS simulator can be used by doing parametric analysis for the antenna sizes and number of turns. For the low cost applications, the most commonly used dielectric material is FR4 which is also used in this application. Table 3.1 shows the physical dimensions of the antenna.

Table 3.1. Physical dimensions of the reader antenna.

a_0 (Overall dimensions of the coil) [mm]	b_0 (Overall dimensions of the coil) [mm]	t(Track thickness) [μm]	w (Track width) [mm]	g (Gap between tracks) [mm]	N_a (Number of turns)
61	34	35	0.38	0.25	6

Table 3.2 shows the properties of the substrate material and Figure 3.4 shows the layout of the antenna. The antenna which is modelled by using ADS Momentum analysis and its input impedance simulation results can be seen in Figure3.5.

Table 3.2. Properties of the dielectric material.

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

Figure 3.4. Reader antenna model.

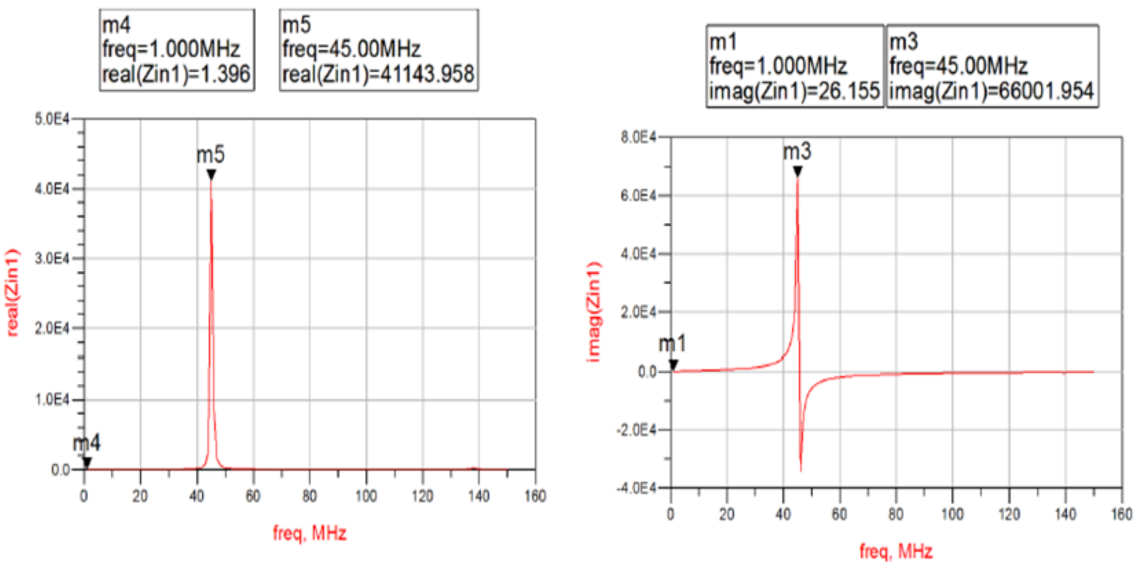

Figure 3.5. ADS input parameter simulation results.

The measurements of the loop antenna by the values of series inductance (L_a) and series resistance (R_s) has shown that they are well below the self-resonance frequency of the antenna, but they are sufficient enough for good measurement accuracy. By using the following formulas, L_a and R_s is measured at 1 MHz frequency by the following formulas:

$$L_a = \frac{imag(Zin)}{2\pi f} = 4.15\mu H \tag{3.1}$$

$$R_s = real(Zin) = 1.38\Omega \tag{3.2}$$

In the location that 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 are: f_{res}= 46.2 MHz The series equivalent resistance R_a of the antenna is measured taking into account of parallel and series resistances of the antenna. Those calculations can be seen in Figure 3.6.

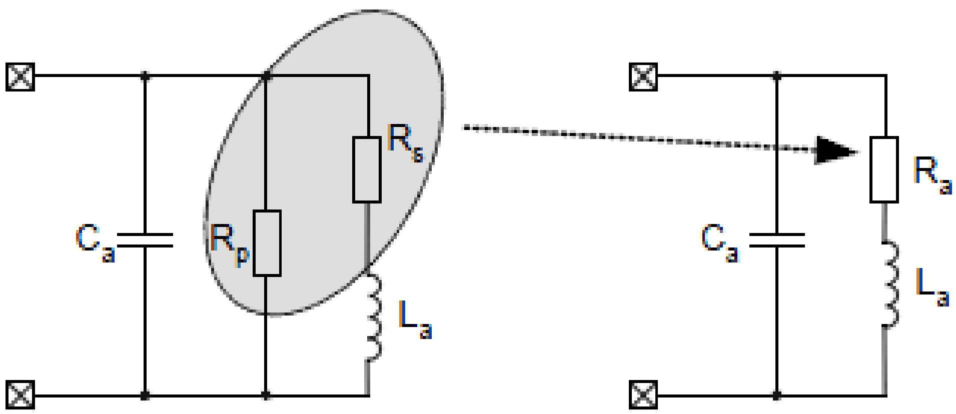

Figure 3.6. Antenna series equivalent resistance calculation.

The parallel resistance at the self-resonance frequency is calculated as R_p= 41.2k Ω. This result on the parallel resistance is caused by the skin-effect. For the desired application, the antenna was designed to operate at the carrier frequency (f_0) 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 3.3 [23];

$$R_p(13.56MHz) = \sqrt{\frac{f_{res}}{f_0}} \times R_p = 76.05k\Omega \tag{3.3}$$

After all, calculations of antenna's series equivalent resistance and the parallel equivalent resistance are given by 3.4 and 3.5 respectively.

$$R_a = R_s + \frac{(2\pi f_0 L_a)^2}{R_p(13.56MHz)} = 3.03\Omega \tag{3.4}$$

$$R_{pa} = \frac{(2\pi f_0 L_a)^2}{R_a} = 11.06k\Omega \tag{3.5}$$

Calculation of the capacitance of the antenna (Ca)is given by Equation 3.6:

$$C_a = \frac{1}{(2\pi f_{res})^2 L_a} = 2.9pF \tag{3.6}$$

3.2.1. 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 that high Q factor would result a limited bandwidth and long-time constants which causes defects in the signal during the test setup. To be able to decrease the quality factor and in order to satisfy the regulations, an external damping resistor (R_Q) has used, which is used to decrease quality factor to 35 [23,24]. R_Q can be seen in the Figure 3.3

Quality factor of antenna can be calculated by,

$$Q_a = \frac{\omega_{res} L_a}{R_a} = 116.93 \tag{3.7}$$

The value of R_Q resistor can be calculated as,

$$R_Q = 0.5(\frac{\omega_{res} L_a}{35} - R_a) = 4.38\Omega \tag{3.8}$$

3.3. Design of the EMC Filter Part

One of the functions that EMC filter circuit 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 [24].

In Figure 3.1 LC pass EMC filter has been shown. 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,

$$C_0 = \frac{1}{(2\pi f_{r0})^2 L_0} = 221.2pF \tag{3.9}$$

3.4. Matching Part Design

Coupling of two resonant loop antennas and HF system of such antennas' properties are determining factors for the near field communication. These properties dynamically vary during the operation. Such properties can also affect power transfer and communication performance significantly. Varying coupling factor can result increasing the impedance mismatch which can affect these properties in return [27].

The antenna has typical sizes which includes low impedance and resonance frequency of higher than 13.56 MHz. In order to prevent the negative consequences that can be experienced, antenna matching and tuning are required [18]. Matching brings benefits such as reacting less power on the connection between the IC bumps and the label antenna pads [26].

Figure 3.7 shows the elements are alternatively connected in series and shunt.

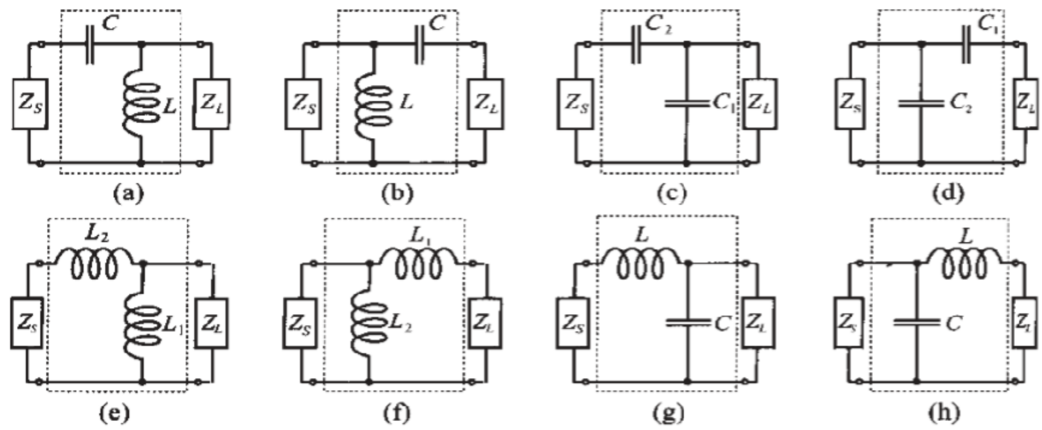

Figure 3.7. Eight possible configurations of the two-component matching networks.

To achieve the optimal system performance for the desired application, to transform the load impedance (Z_{load} to the desired input impedance (Z_{in}), two component network is used. The elements are alternatively connected in series and shunt configuration, which provides eight different possible arrangements for the capacitors and inductors [2].

For the reasons that are mentioned before, the antenna should be matched to 50 Ohm and has to be tuned to radiate with a quality factor of 35. By configuring at 50 ohm driver impedance R_{match}, the load at the frequency of 13.56 MHz, would match. For building a resonator and matching the inductive load, the capacitances are used [23, 27]. It can be seen in Figure 3.8 that a serial capacitor C_1 and a parallel capacitor C_2 are used as a matching network to achieve the optimum performance for the desired application [19].

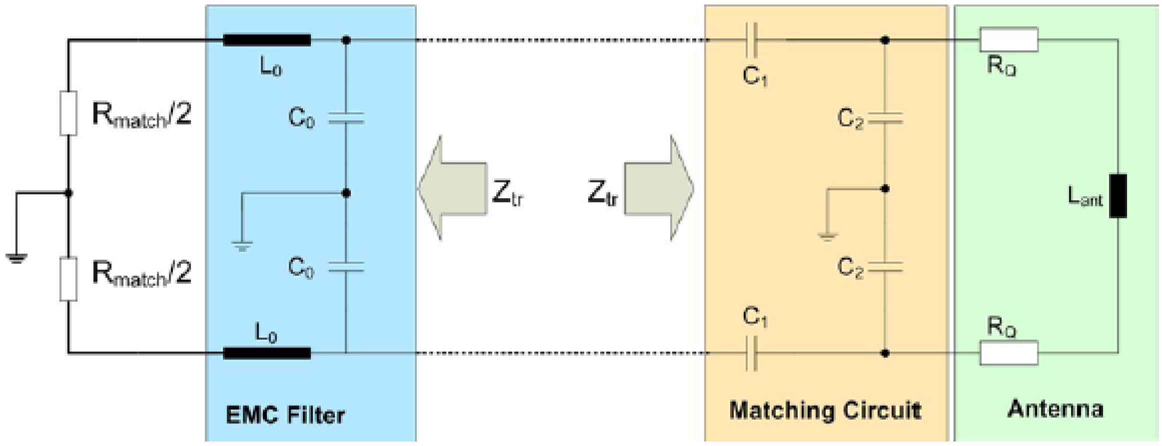

Figure 3.8. Definition of transformation impedance (Z_{tr}).

One of the functions of both EMC filter and matching circuit is to transform the antenna impedance to the required TX matching resistance $Z_{match(13.56MHz)}$. The matching elements can be calculated by [24];

$$Z_{tr} = R_{tr} + jX_{tr} \tag{3.10}$$

where,

$$R_{tr} = \frac{R_{match}}{(1-\omega^2.L_0.C_0)^2 + (\omega.C_0.\frac{R_{match}}{2})^2} = 216.7\Omega \tag{3.11}$$

$$X_{tr} = 2.\omega.\frac{(1-\omega^2.L_0.C_0)^2.L_0 - (\frac{R_{match}}{4})^2 C_0}{(1-\omega^2.L_0.C_0)^2 + (\omega.C_0.\frac{R_{match}}{2})^2} = -57.83\Omega \tag{3.12}$$

Series and parallel capacitances can be calculated as the following equations:

$$C_1 = \frac{1}{\omega(\sqrt{\frac{R_{tr}.R_{pa}}{4}} + \frac{X_{tr}}{4})} = 16.02pF \tag{3.13}$$

$$C_2 = \frac{1}{\omega^2.\frac{L_a}{2}} - \frac{1}{\omega(\sqrt{\frac{R_{tr}.R_{pa}}{4}})} = 45.2pF \tag{3.14}$$

3.5. Design of the Receiver Part

Voltage in the RX pin is regulated by the voltage driver. Resistors R_1 and R_2 in the receiving part as shown in Figure 3.1 function as voltage divider. The level of voltage should stay under the limit of 3 V_{pp}, but to achieve the optimum R/W performance it should be maximized under the limitations. Low capacitance probe measures the voltage level at the RX pin. After all, those measurements are vital in the housing/positioning, otherwise it can cause defections in the antenna and affects RF signalling negatively [24].

Results obtained from the simulation and experiments defines the receiver's components. From the results, it has also obtained that the maximum write distance is where voltage at RX pin is 2.8V with components;

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

3.6. Considerations for Layout

In order to meet the governmental restrictions, the harmonics, which are generated by the RF systems having high numbers of outputs, should be suppressed to stay in the limits of the restrictions. During the design phase, the antenna circuitry might resonate at some frequencies above 100 MHz, or function at a certain frequency above 13.56 MHz. This issue occurs due to the limited Q factor and some parasitic effects of the passive components. It is an issue that should be checked in the designing phase.

EMC low pass filter can be counted as the most critical element of the antenna circuit. In order to prevent defections or some negative effects, component area of this filter is minimized, and a sufficient ground connection of this filter is directly connected to the TVSS pin as described in Section 2.4.5.

3.7. Simulation Results

Figure 3.9 shows ADS simulation results with the antenna and all of the calculated components in the system.

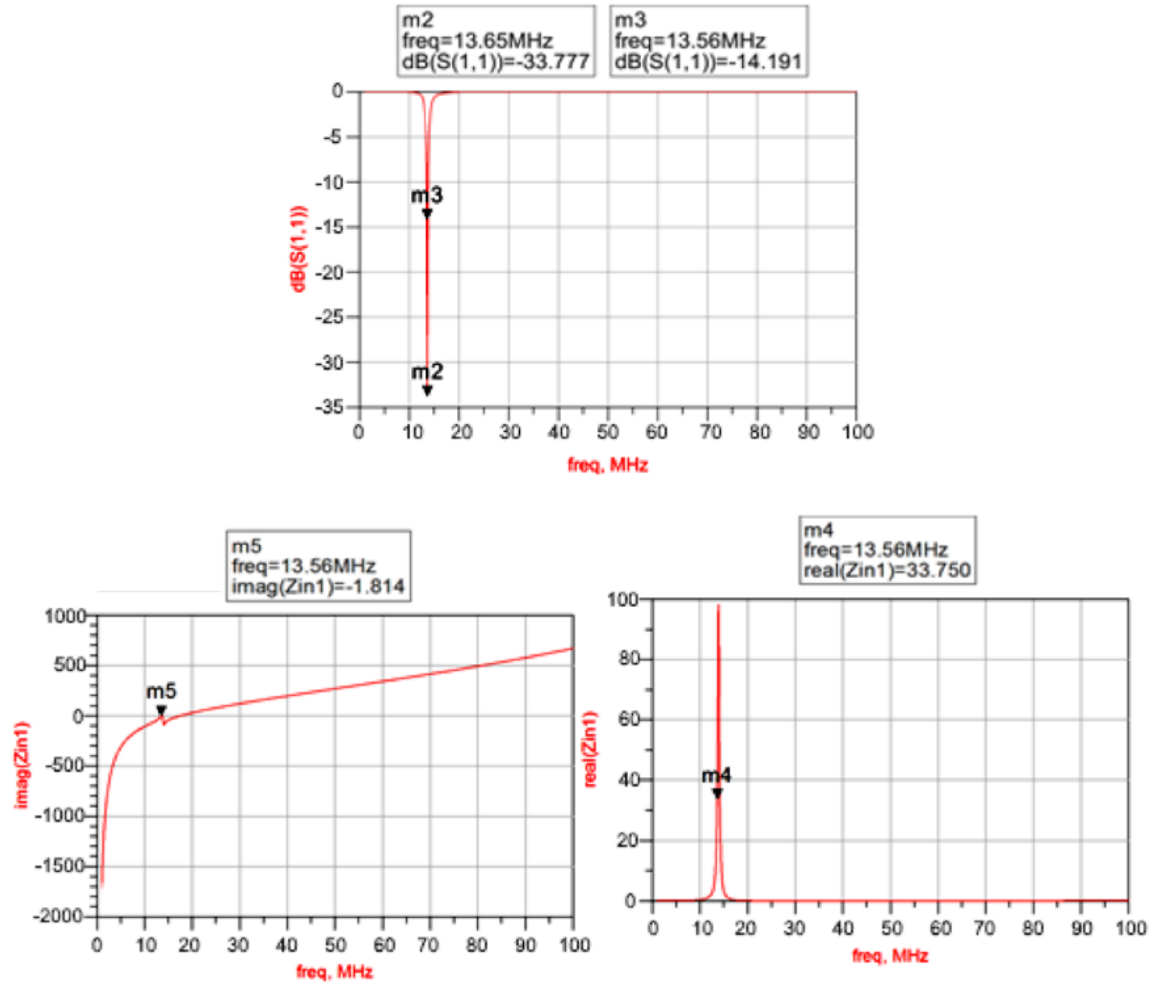

Figure 3.9. ADS simulation results of the design with all of calculated components.

According to the ADS simulation results, at the frequency of 13.56 MHz the value of S_{11}= -14.2 dB. The results also show that, by using the calculated component values, desired carrier frequency (f_0=13.56 MHz) is not achieved. With the calculated values which are 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.

3.7.1. Optimization and Tuning

In the Smith Chart, C_1 , as a main element can be used to tune the antenna along a circle of constant real part impedance. When the serial capacitor increases it causes the reactive impedance (into the upper, inductive half plane) to experience an increase also. C_2 takes part as a reactive and resistive component. For that reason, for matching the antenna input impedance and a real part close to 50 Ohms, the adjustable parallel capacitor is usually used [24]. The calculations and the results can be seen in Figure 3.10.

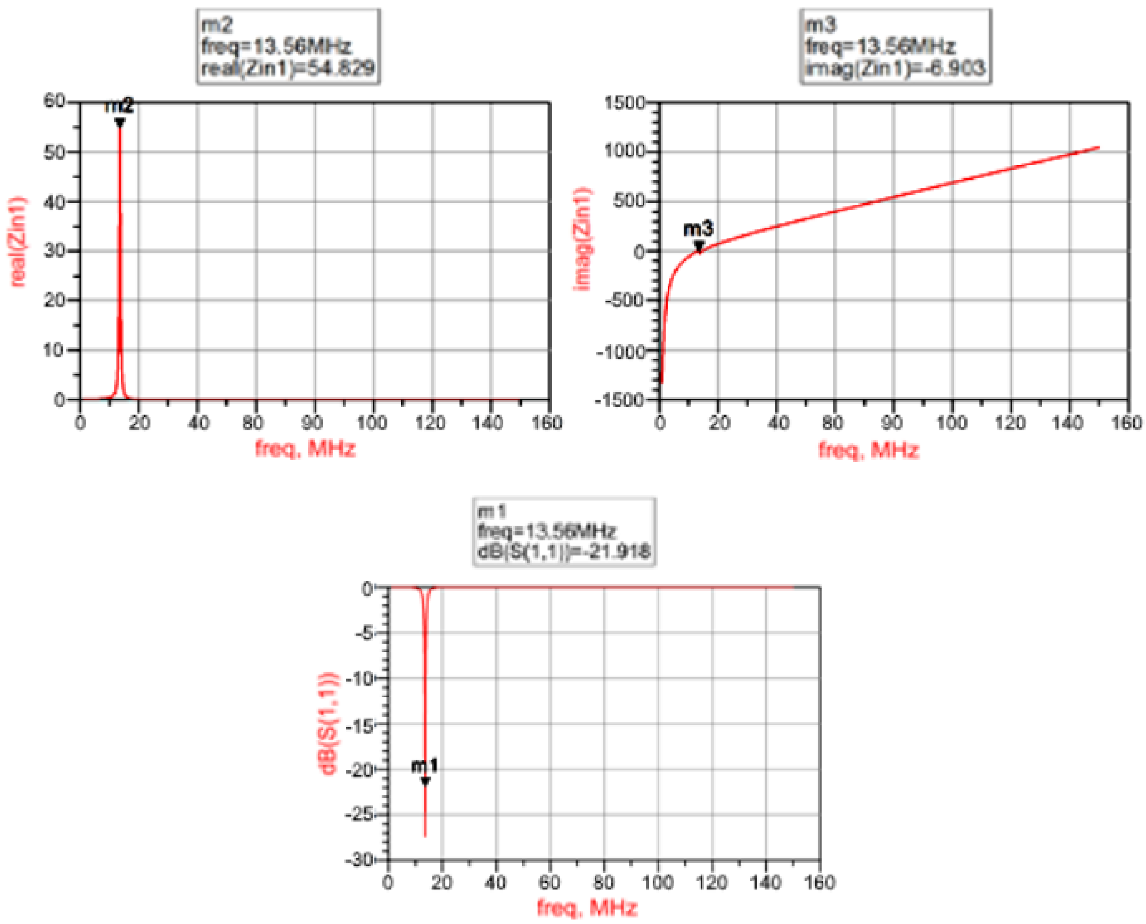

Figure 3.10. Simulation results using optimized values of matching components.

Tuning simulations in ADS are used to calculate the values of matching components C_1 and C_2. It is seen from the ADS simulation results that the best results are obtained where $C_1 = 46$ pF and $C_2 = 16$ pF.

It is seen from the results that optimum resonance performance is obtained at a frequency of 13.56 MHz. The optimum conditions were set to send the power with the highest magnitude by the antenna when the input impedance is matched to 50 Ω and the value of the reactance is 0Ω at the resonance frequency. Input impedance is 54.83 Ω with a reactance value of -6.9 Ω. Return loss result at 13.56 MHz is obtained as -21.92 dB from the results.

3.8. Measurements and Experimental Results

Rodhe&Schwarz ZVB4 vector network analyser was used for measuring the antenna parameters. Figure 3.11 shows the measurement results while the impedance of the antenna was kept between 1 MHz and 5 MHz.

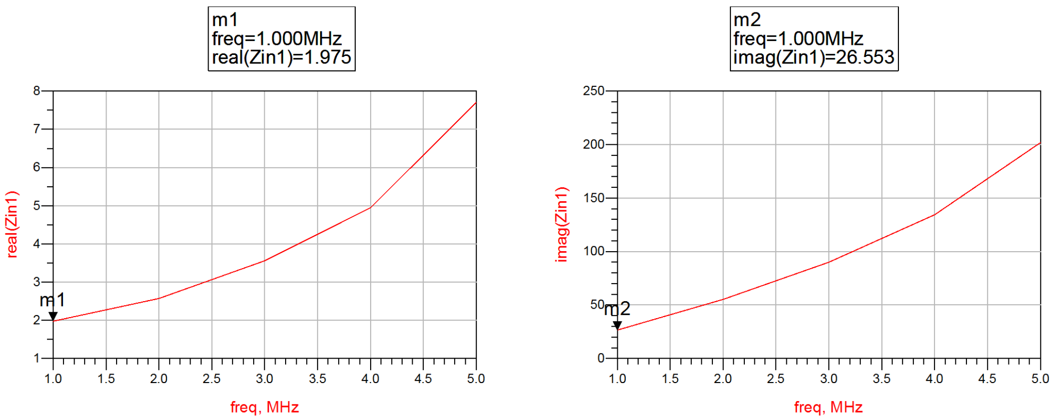

Figure 3.11. Antenna input impedance measurements (1-5 MHz).

Equation 2.1 and Equation 3.4 shows the calculation of the antenna inductanceL_a and series resistance R_s; respectively $R_s = 1.98$ ohm and $L_a = 4.23\mu$H. From the equations, it is observed that self-resonance frequency (f_{res}) of the antenna is calculated as 54 MHz and parallel resistance of antenna at self resonance frequency is calculated (R_p) as 8.5 kΩ. R_Q is calculated from Equation 3.8 as 3.1 Ω and R_Q is selected 3.3 Ω.

As defined in Section 3.3, L_0 is chosen 560 nH and C_0 is chosen 220 pF.

Using Equation 3.2, Equation 3.3, Equation 3.4, Equation 3.5, Equation 3.6, and Equation 3.7 with measured antenna series and parallel equivalent parameters; C_1 = 15.95 pF (selected as 18 pF). C_2 = 45.68 pF (selected as 47 pF). Antenna and reader circuit is built with the parameters which are defined. Table 3.3 shows the values of all elements in the design. The built prototype can be seen in Figure 3.12.

Table 3.3. Bill of Materials of the design using calculated components.

Component	Value	Component	Value
L_0	560 nH	R_1	1 kΩ
C_0	220 pF	R_2	2.7 kΩ
C_1	18 pF	C_{vmid}	100 nF
C_2	47 pF	C_{RX}	100 nF
R_Q	3.3 Ω		

Figure 3.12. Built protoype.

For measurement of the return loss, real and imaginary impedance of the design, A SMA connector is attached to TX1 and TX2 inputs of PN531 transmission module. Figure 3.13 shows the measurement setup, and the results of the measurements can be seen in Figure 3.14.

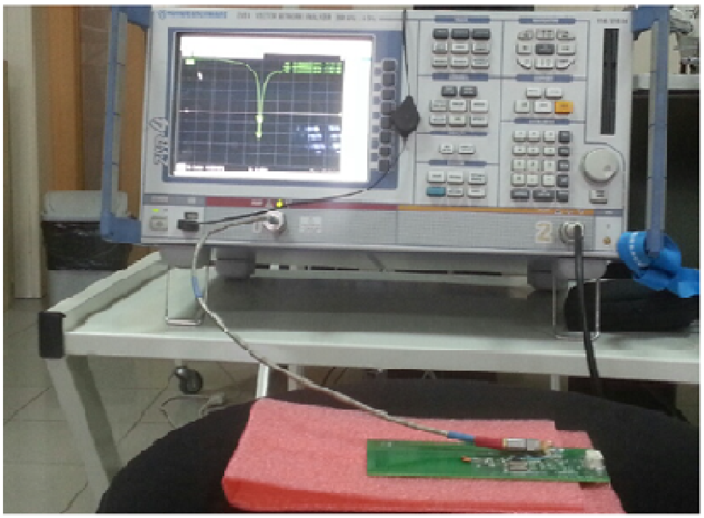

Figure 3.13. Measurement setup.

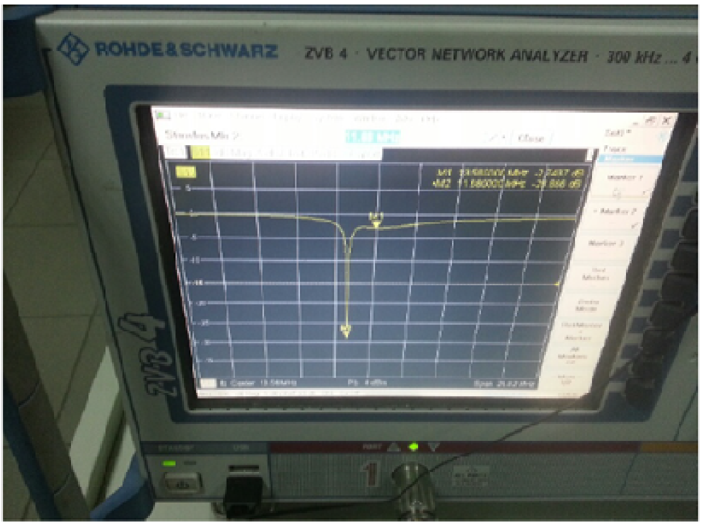

Figure 3.14. Experimental return loss measurements of the design.

By looking at the measured results, operation frequency is lowered to 11.68 MHz and it is seen that an optimization process is required in order to achieve desired final values.

3.9. Optimized Results

Tuning process applied on C_1 and C_2 values to achieve the intended return loss. The best return loss is achieved as where, $C_1 = 15$ pF and $C_2 = 33.8$ pF. Figures 3.15 and 3.16 shows the measurements results using the optimized values of C_1 and C_2.

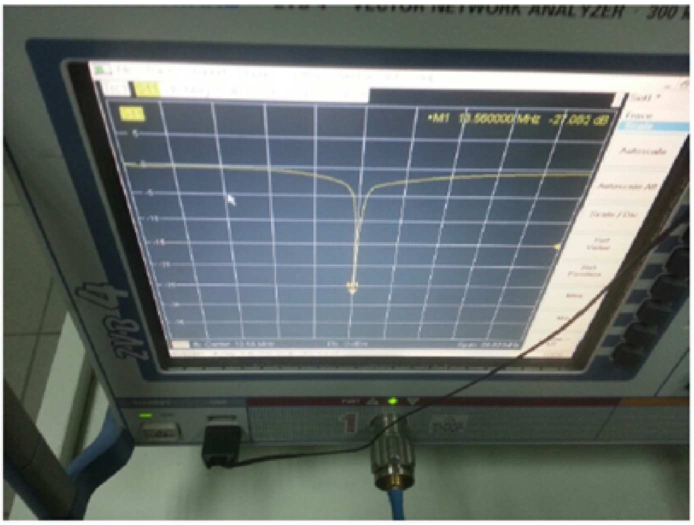

Figure 3.15. Experimental return loss measurements with optimized design.

Figure 3.16. Smith Chart measurements with optimized design.

The measurement results show that input impedance is obtained as 52.36 Ω while the reactance level is 3.8 Ω. At the frequency level of 13.56 MHz, return loss value is obtained as -27 dB. At the frequency of 13.56 MHz, resonance performance and return loss value that is proper for the design application are achieved.

3.10. Measurements for Read Range

Figure 3.17 shows the measurement setup for measuring the read range.

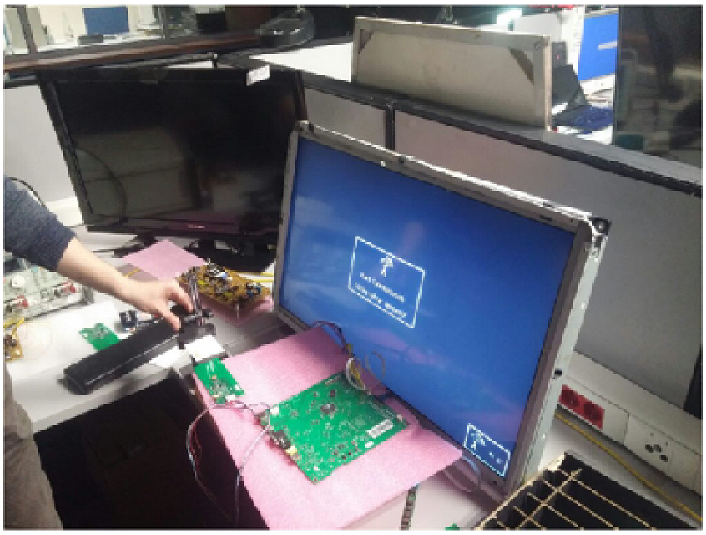

Figure 3.17. Measurement setup for range measurement.

As Figure 3.18 shows that optimum reading is obtained from distance of 4.6 cm with the elements of values in Table 3.4. For measuring the read distance, the TV set

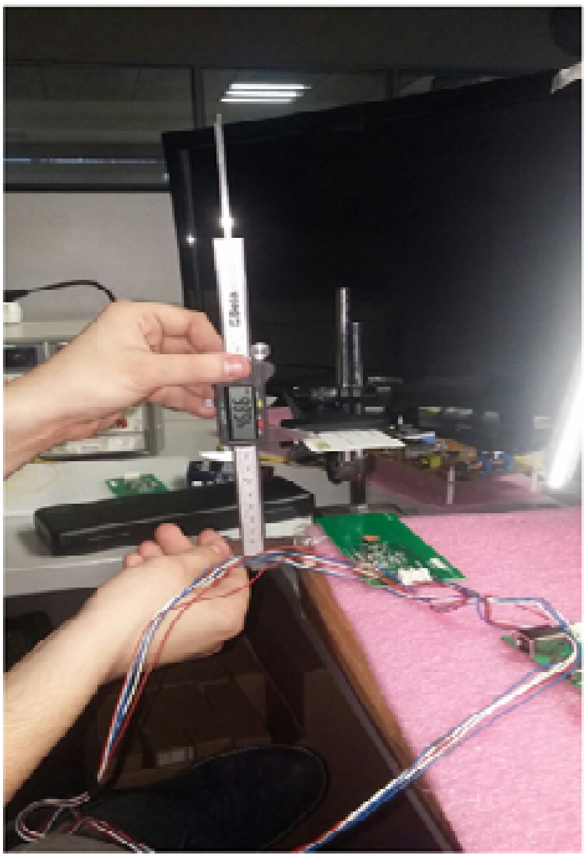

Figure 3.18. Maximum read range measurements of the optimized reader design.

has used with a special software installed and its applications which does not allow the usage of any menus in TV without the reader circuit reads 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 user to use menus on TV. If desired communication is not obtained, a notification saying "RFID CARD ISN'T READ" shows up on the screen and system does not allow user to use menus until the reader can read the signal coming from the tag successfully.

Table 3.4. Bill of Materials of the optimized design.

Component	Value	Component	Value
L_0	560 nH	R_1	1 kΩ
C_0	220 pF	R_2	2.7 kΩ
C_1	15 pF	C_{vmid}	100 nF
C_2	33.8 pF	C_{RX}	100 nF
R_Q	3.3 Ω		

3.11. Smart Card Effect

When passive smart cards are located closed to the antenna of the reader, as a result of the capacitive effect, reader antenna performance experiences a decrease. Therefore, the loop antenna's resonant frequency also decreases and the field intensity is reduced at operation frequency of 13.56 MHz. For this application, smart card is located in a fixed position with the distance of 3 cm from the reader antenna and to obtain the resonance frequency of 13.56 MHz. Matching elements are detuned as below.

At the frequency level of 13.56 MHz, the return loss value is seen as -17 dB. The maximum read range is achieved as 3.6 cm, which is a smaller value than the previous measurements in Section 3.9. The reason for reduced read range is that the measurements for the last calculations were done by using detuned values of components. For calculating the system accuracy, an experiment made for 100 times, passive card is in x, y, and z coordinates from a distance of 3 cm and no misreading is experienced.

Best results are experiences with those values; $C_1 = 18$ pF, $C_2 = 53.8$ pF. Figure 3.19 shows the measurement setup based on measuring the card effect and Figure 3.20 shows the return loss values of the system with detuned values of matching elements.

Figure 3.19. Measurement setup for measuring smart card effect.

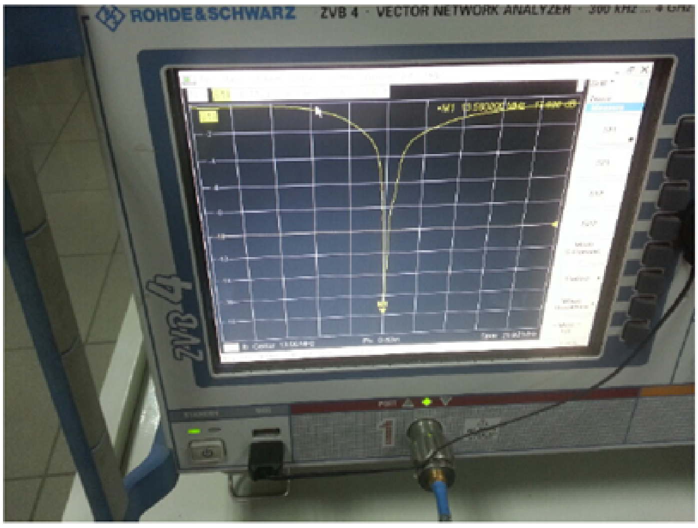

Figure 3.20. Return loss measurements using the detuned values of matching components.

4. MEASUREMENTS IN DIFFERENT ANTENNA'S GEOMETRY

In our work, we have tested and measured 4 different types of antennas as 6 loop square, 4 loop square, rectangular and circular. Each antenna has different size and geometry that their return loss, real and imaginary impedance parameters has been measere with Spectrum Analyser (Rodhe&Schwarz). For the simulation, measured data is transferred to the ADS software. ADS software is a proper tool to build a matching circuit. In order to do the simulation with different values, there is no need to change any of the components, we can see the results of the simulations also with different component values. So comparing theoretical and practical results would be easier.

4.1. The Antenna Geometry and Sizes

The antennas', which have been used in this project, size and geometry features are presented as below.

4.1.1. 4 Loop Square Antenna

Figure 4.1 shows 4 loop square antenna view and the main features can be seen as below;

- Dimensions: 8x8 cm
- Area: 64 cm2
- Number of turns: 4
- Length of the coil: 243.36 cm.

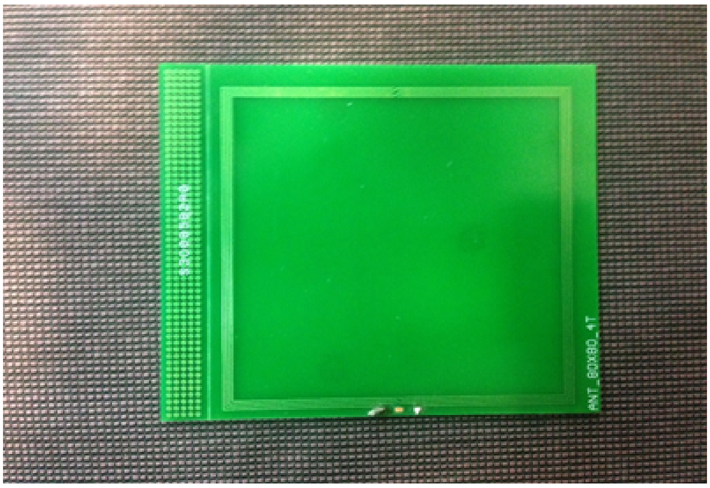

Figure 4.1. 4 loop sqaure antenna view.

4.1.2. 6 Loop Square Antenna

Figure 4.2 shows 6 loop square antenna view and the main features can be seen as below;

- Dimensions: 8x8 cm
- Area: 64 cm2
- Number of turns: 6
- Length of the coil: 346.56 cm.

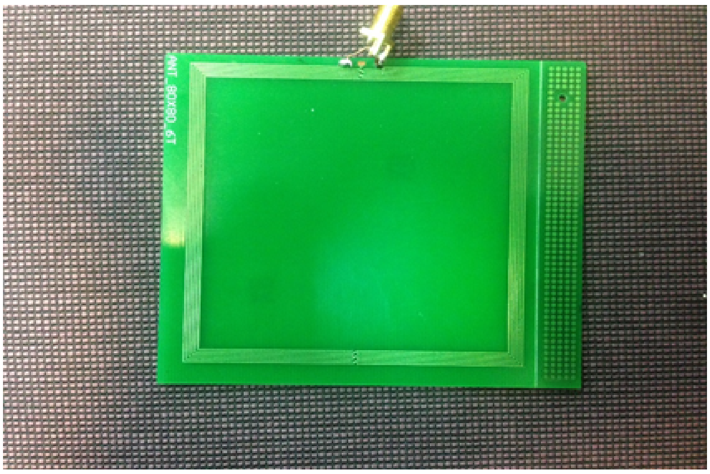

Figure 4.2. 6 loop sqaure antenna view.

4.1.3. Circular Antenna

Figure 4.3 shows circular antenna view and the main features can be seen as below;

- Dimensions: rout=3 cm rin=2.8 cm
- Area: 18.85 cm2
- Number of turns: 4
- Length of the coil: 72.848 cm

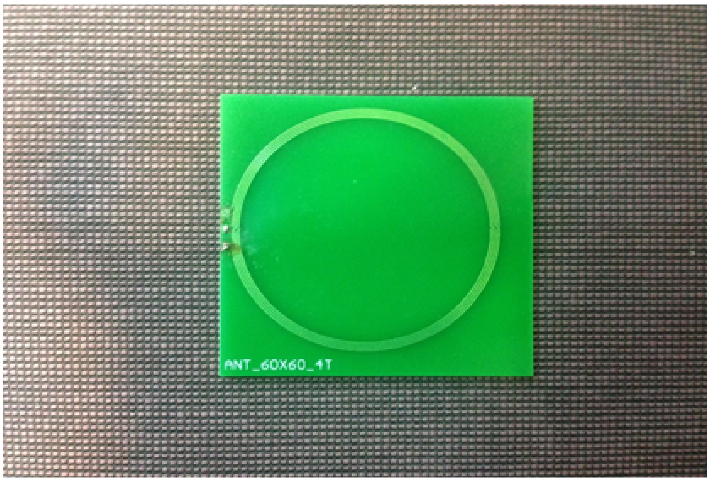

Figure 4.3. Circular antenna view.

4.1.4. Rectangular Antenna

Figure 4.4 shows circular antenna view and the main features can be seen as below;

- Dimensions: 6.2x3x5 cm
- Area: 21.7 cm2
- Number of turns: 4
- Length of the coil: 136.68 cm

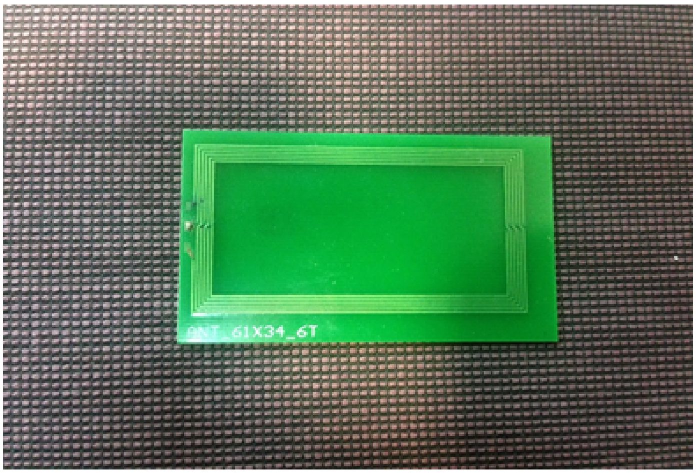

Figure 4.4. Rectangular antenna view.

4.2. Measurements & Tuning

The basic model of the system, which has been generated in ADS, is shown in Figure 4.5. On the right side of the schematic, the antenna components exist. The schematic contains the necessary data for the simulation and it is possible to change these values, which allows us to make simulations with various data.

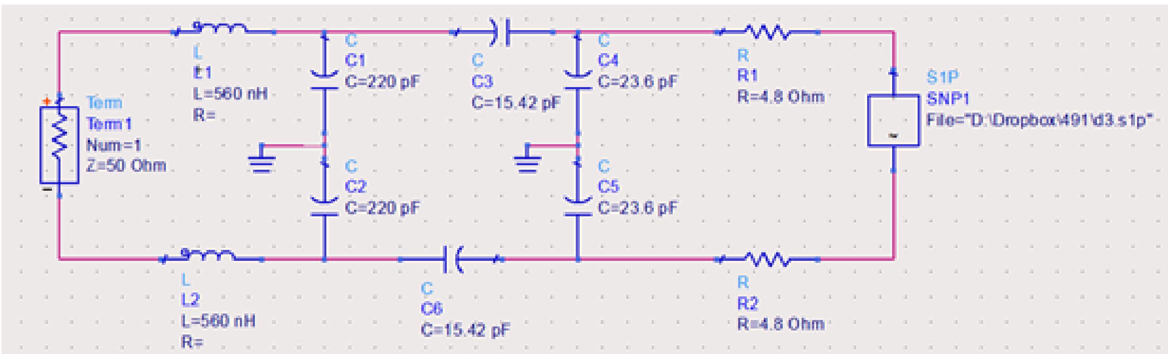

Figure 4.5. Main schematic of reader design.

For this project, inductance (L_1) and the capacitance (C_1) values which exist on the left side of the model are taken constant; those values are L_1 = 560 nH and C_1 = 220 pF. To make the simulation simplier, 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 4.6.

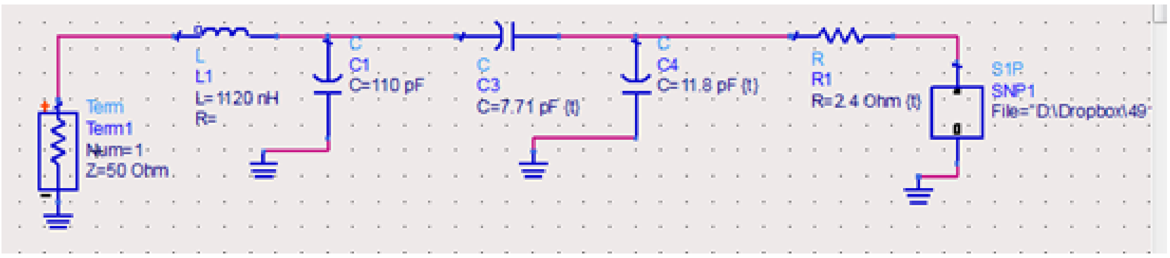

Figure 4.6. Simplified schematic of reader design.

Determining the optimum values of matching circuit capacitance is the most vital factor for this schematic. By using the ADS software, these capacitor values 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. By using the formulas and the ADS software simulation, those calculations were done. Figure 4.7 shows the modelling of those simulations.

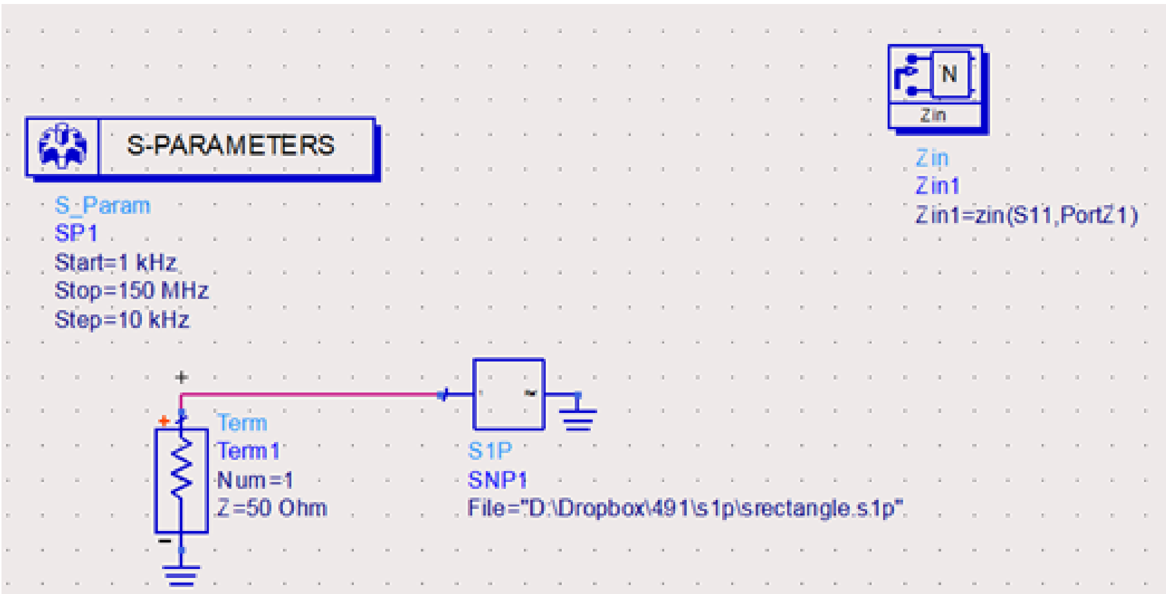

Figure 4.7. Antenna impedance simulations via ADS software.

(R_s), (R_a), (R_p), (L_a), and Q values' calculations has been made by using formulas and the ADS software simulation. Impedenses and resonant frequencies have been observed for all antenna types as seen in the following sections.

4.2.1. Rectangular Antenna

The calculations for rectangular antenna was resulted as below;

L_a = 4.33 uF, R_s = 0.82 Ω, R_a = 2.72 Ω, R_p = 70.71 kΩ, f_{res} = 23.46 MHz, Q = 134.7.

Impedences and resonant frequency are measured as shown in Figure 4.8

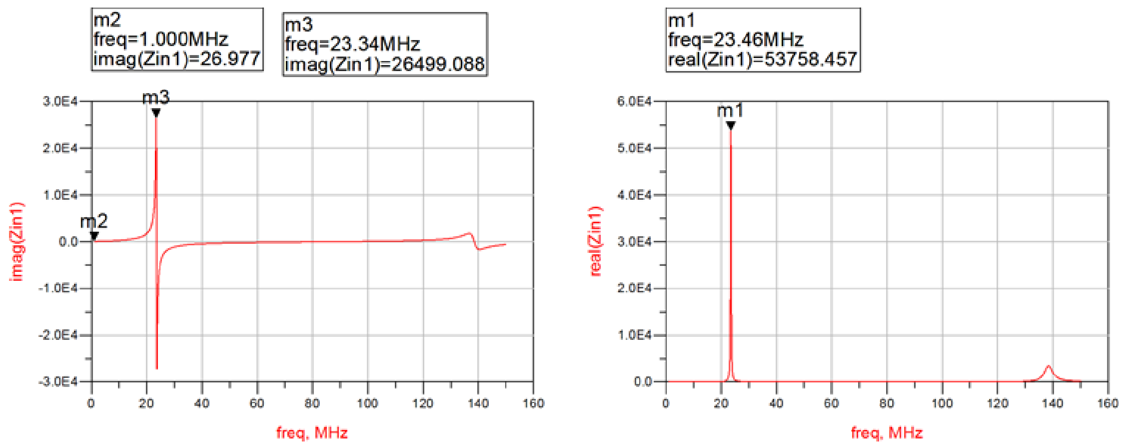

Figure 4.8. Impedance measurements of the rectangular antenna.

The antenna for the desired application, considering the ADS measurements and assumptions must operate at the frequency level of 13.56 MHz. However, that frequency level was not obtained. So there is a need for detuning the matching circuit.

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

Tuning is made with below values in matching circuit; C_1 = 15.8 pF, C_2 = 27.4 pF, R_pa = 10.99 kΩ, R_Q = 4.75 kΩ, Q = 30 is obtained at 13.56 MHz.

Figure 4.9 shows the measurements of matched circuit of rectangular antenna.

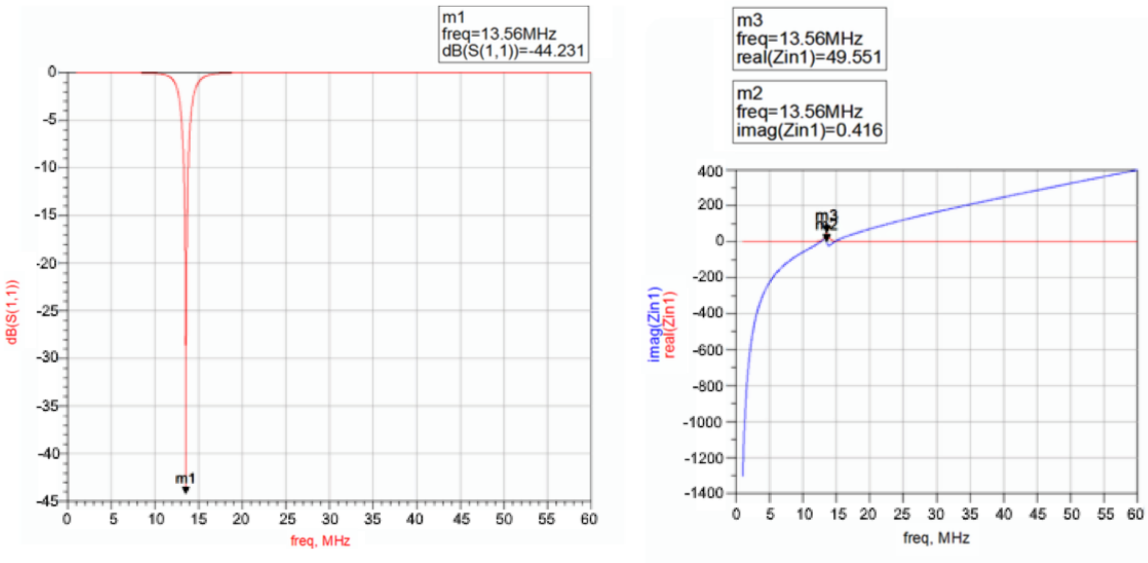

Figure 4.9. Measurements of matched circuit of rectangular antenna.

After matching, rectangular antenna has a gain of -44.231 dB, resistance 49.55 Ω, Reactance 0.416 Ω

4.2.2. 4 Loop Square Antenna

Impedences and resonant frequency are measured as shown in Figure 4.10

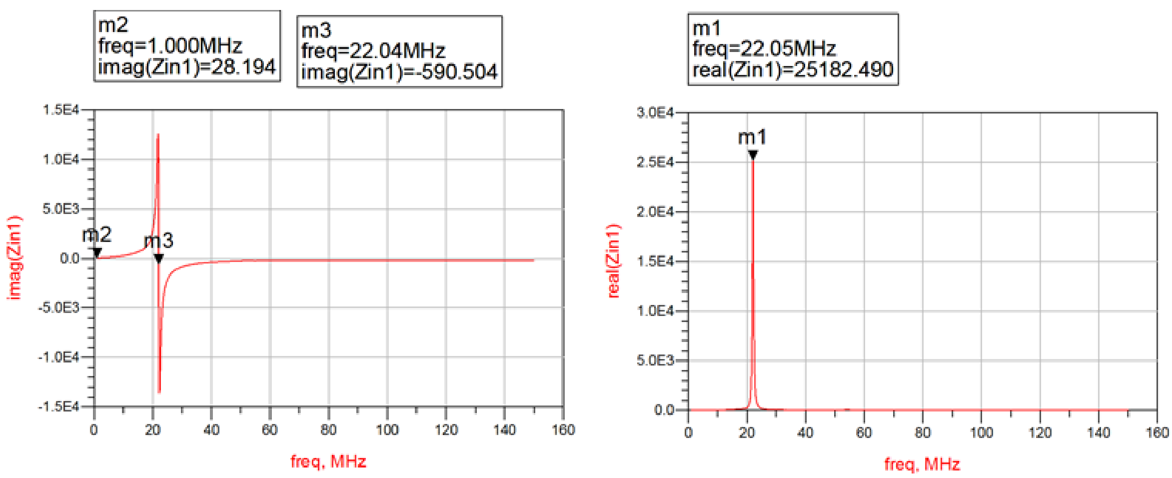

Figure 4.10. Impedance measurements of 4 loop square antenna.

The calculations for 4 loop square antenna was resulted as below;

L_a = 4.53 uF, R_s = 0.49 Ω, R_a = 5.13 Ω, R_p = 32.11 kΩ, f_{res} = 22.05 MHz, Q = 75.2.

There is a need for detuning the matching circuit.

Tuning is made with below values in matching circuit;

C_1 = 15.5 pF, C_2 = 23.3 pF, R_pa = 11.45 kΩ, R_Q = 3.85 kΩ, Q = 30 is obtained at 13.56 MHz.

After tuning, Figure 4.11 shows the measurements of matched circuit of rectangular antenna.

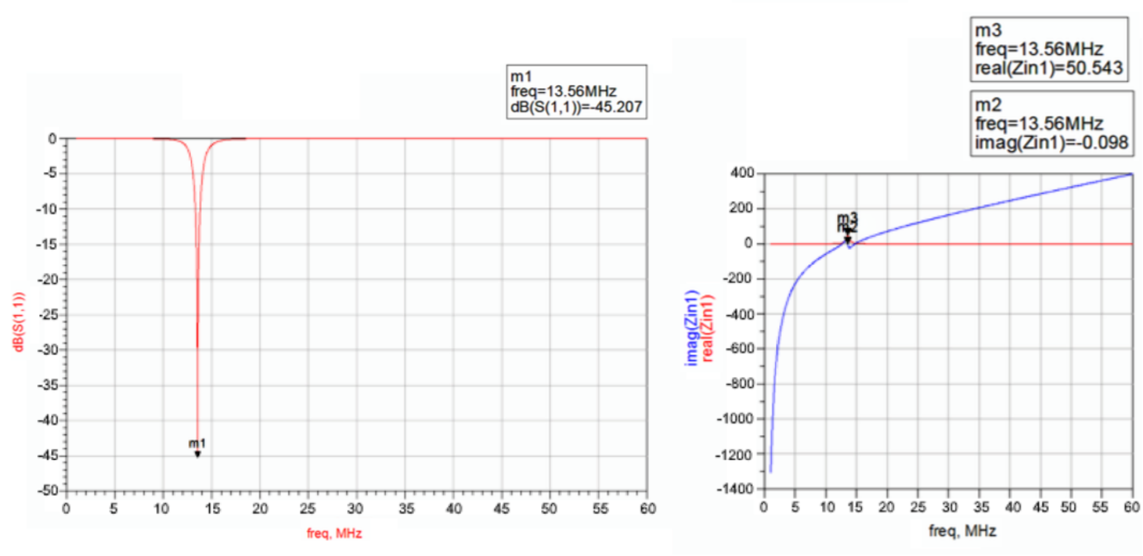

Figure 4.11. Measurements of matched circuit of 4 loop square antenna.

After matching, 4 loop square antenna has a gain of -45.207 dB, resistance 50.54 Ω, Reactance -0.098 Ω

4.2.3. 6 Loop Square Antenna

It is not possible to match this antenna since it has a resonant frequency of 13.21 MHz that is lower than the operating frequency of 13.56 MHz. Main reasons for the issue are the high inductance and capacitance values of the antenna.

Impedences and resonant frequency are measured as shown in Figure 4.12

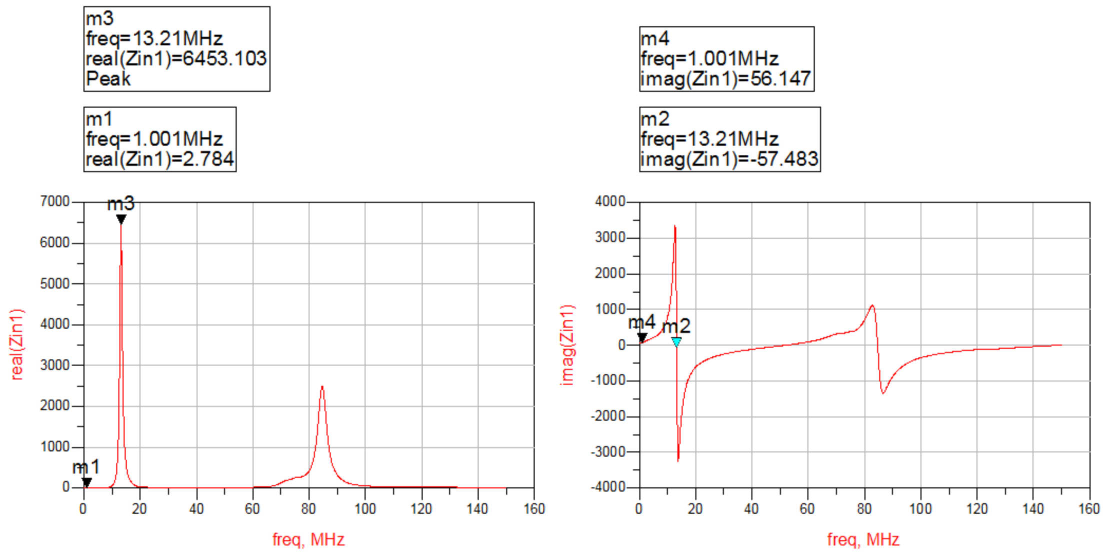

Figure 4.12. Impedance measurements of 6 loop square antenna.

4.2.4. Circular Antenna

The calculations for circular antenna was resulted as below;

L_a = 2.6 uF, R_s = 0 Ω, R_a = 0.67 Ω, R_p = 73.03 kΩ, f_{res} = 35.37 MHz, Q = 330.6.

Impedences and resonant frequency are measured as shown in Figure 4.13

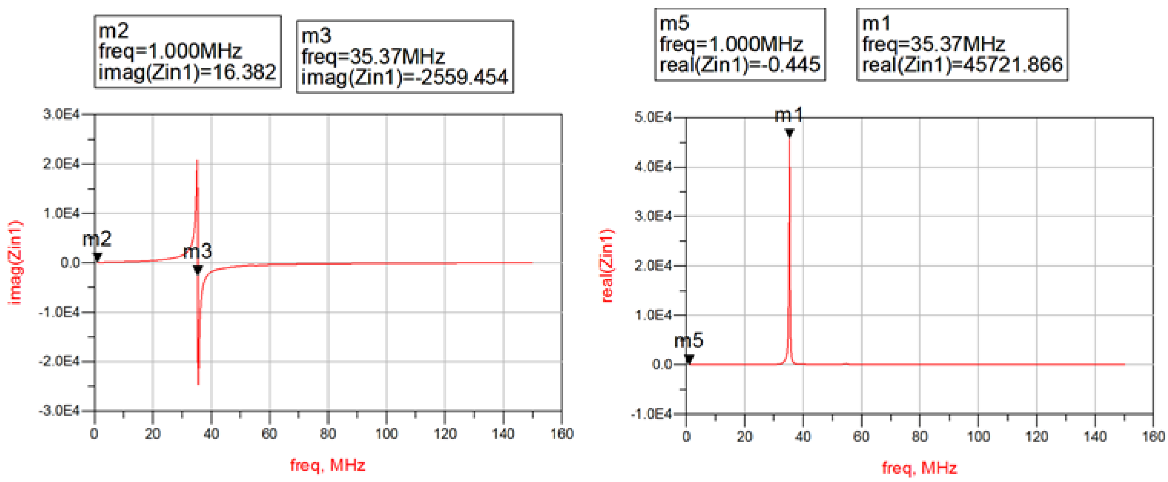

Figure 4.13. Impedance measurements of the circular antenna.

There is a need for detuning the matching circuit.

Tuning is made with below values in matching circuit;

C_1 = 20.5 pF, C_2 = 70.8 pF, R_pa = 6.65 kΩ, R_Q = 3.35 kΩ, Q = 30 is obtained at 13.56 MHz.

Figure 4.14 shows the measurements of matched circuit of circular antenna.

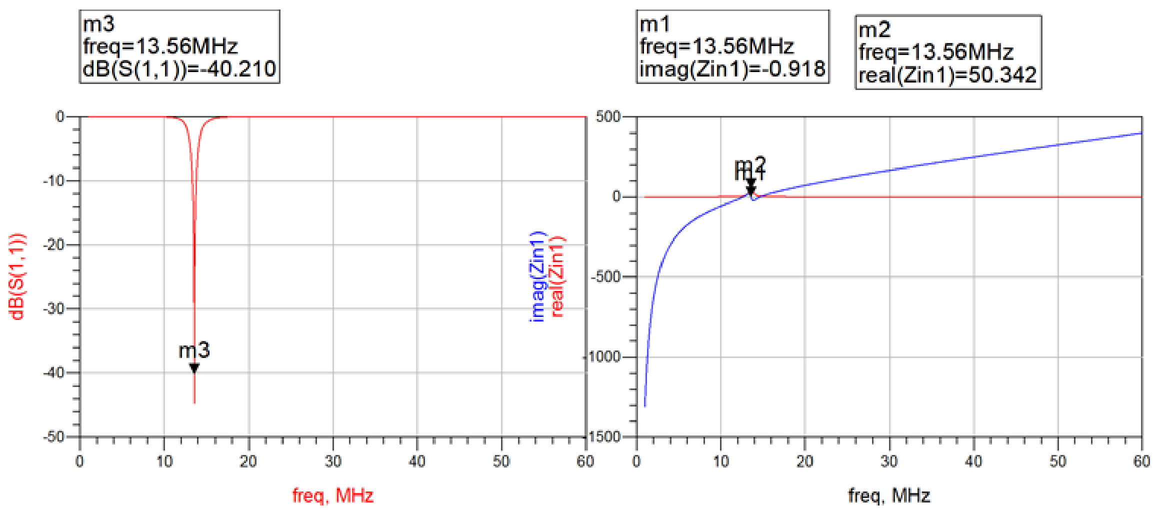

Figure 4.14. Measurements of matched circuit of circular antenna.

Circular antenna has a gain of -40.210 dB, resistance 50.342 Ω, Reactance –0.918 Ω.

4.3. Proximity of Metal Effects

It was defined on the previous chapters that proximity of metals affects the return loss of antenna. In this section, the value of the return loss caused by metal effect was aimed to be obtained with the measurements.

Test circuits were; a tag with rectangular antenna and a 4 loop square antenna. In order to build better matching circuit, a network analyser was necessary for measuring the tag return loss and the operating frequency.

4.3.1. Measurements with Rectangular Antenna

Figure 4.15 and Figure 4.16 shows experimental setup and spectum analyzer measeurements respectively.

Figure 4.15. Experimental setup of reader with rectangular antenna.

Figure 4.16. Spectrum Analyser measurement of reader with rectangular antenna.

The antenna, considering the ADS measurements and assumptions must operate at the frequency level of 13.56 MHz. However, that frequency level was not obtained. The antenna operates at 11.87 MHz and the return loss is -17 dB.

When there are no external effects such as liquid or metal, the operation frequency is obtained as 11.87 MHz. After locating a metal with 2 cm distance from the reader antenna as shown in Figure 4.17, the operating frequency increases to 12.2 MHz and return loss increases to -17.91 dB.

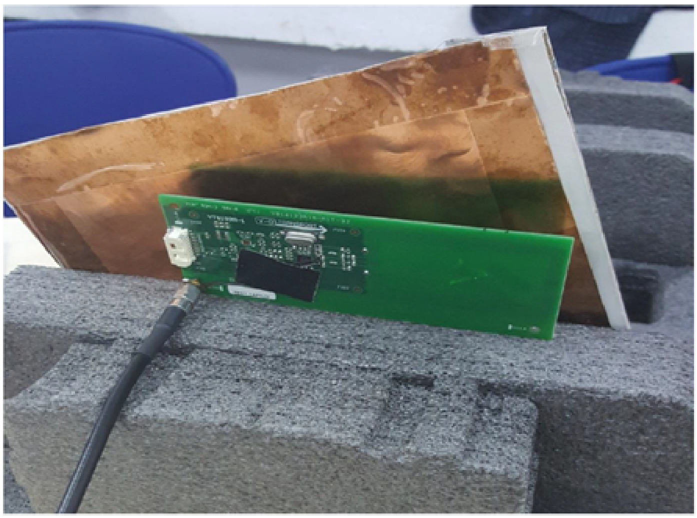

Figure 4.17. Setup of metal located with distance of 2 cm from reader antenna.

Figure 4.18 shows that spectrum analyzer's output of shifted operating frequency with the effect of metal (2cm distance).

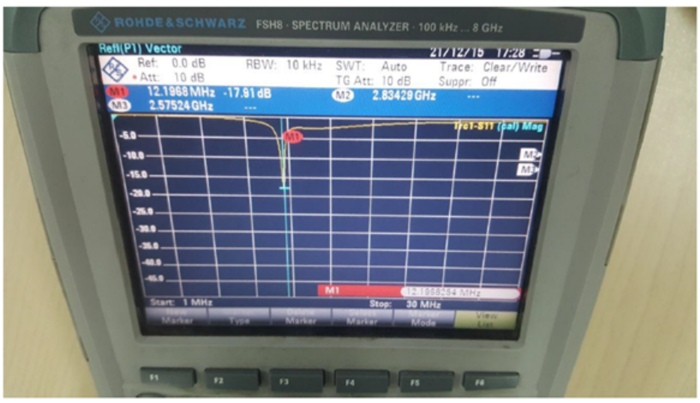

Figure 4.18. Shifted operating frequency with the effect of metal (2cm distance).

When the location of the metal shifted 1 cm towards the reader antenna, the operating frequency shifts to 13.34 MHz and the return loss increases to -22.9 dB. When the metal is located with a distance of 1mm from the reader antenna, the operating frequency shifts to 15.23 MHz and the return loss decreases to -15.19 dB. The results show that the proximity of a metal affects the operation frequency and the return loss. When the metal comes closer it increases operating frequency and initially increases return loss then decreases it.

4.3.2. Measurements with 4 Loop Square Antenna

4 loop square antenna for the desired application, considering the ADS measurements and assumptions, must operate at the frequency level of 13.56 MHz. However, that frequency level was not obtained. The antenna operates at 11.5 MHz and the return loss is -19.32 dB. The factor which causes the operation frequency to be shifted, is the same as the previous antenna. There can be external and internal effects to change this operating frequency. The same method can be used to get the frequency level of 13.56 MHz. The difference between the ADS and real measurement is 2.06 MHz. so if we try to get 15.6 MHz on the ADS software then we can have approximately 13.56 MHz operating frequency for spectrum analyser measurements. Another aim of the project is to see proximity of metal effect on the system. Like previous measurement, the experiments and calculations were made with the distances of 2cm, 1cm and 1mm from the reader antenna. When the metal placed with a distance of 2cm from the reader antenna, the operating frequency shifts to 11.73 MHz and the return loss decreases to -20.69 dB. When the metal placed with a distance of 1cm from the reader antenna, the operating frequency shifts to 12.24 MHz and the return loss decreases to -25.00 dB. When the metal placed with a distance of 1mm from the reader antenna, the operating frequency shifts to 14.45 MHz and the return loss decreases to -23.14 dB. Each of the results from the measurements show that the proximity of metal, affects the operation frequency significantly. The proximity of metal also affects the return loss, but the results of the affect is not linearly proportional between the distance from metal from the reader antenna and return loss values. It has seen that when the metal gets closer to the antenna, it increases both operating frequency and absolute value of

return loss, but if the metal is too close such distances like 1mm, absolute value of gain loss begin to decrease.

4.4. Experimental Results

For the desired application, eventhough lots of surface mounted device (SMD) capacitors from 1 pF to 100 pF were needed in the design phase the resonance frequency of 13.56 MHz was unable to achieved in any of the designs. To obtain the desired frequency for rectangular and square antennas, capacitor values of matching circuit has changed and tested to see experimental results.

4.4.1. Experimental Results in Rectangular Antenna

Table 4.1 shows the resonance frequency changes with the matching circuit capacitor values for the rectangular antenna.

Table 4.1. ADS and Measured resonant frequency values with respect to capacitor values in rectangular antenna.

Example	C3 (pF)	C4 (pF)	ADS Result Frequency (MHz)	Measured Frequency (MHz)
1	46	30	15,27	14,33
2	20	12,6	15,91	14,61
3	22	15	15,37	14,3
4	30	15	14,68	13,52
5	22	22	14,49	13,4
6	22	18	14,97	13,89
7	27	18	14,56	13,42

The first obtained rectangular antenna resonant frequency was 11.87 MHz. Figure 4.19 shows that C_3 and C_6, C_4 and C_5 values were 15.42 pF and 23.6 pF respectively.

These capacitor values were changed according to the calculations.

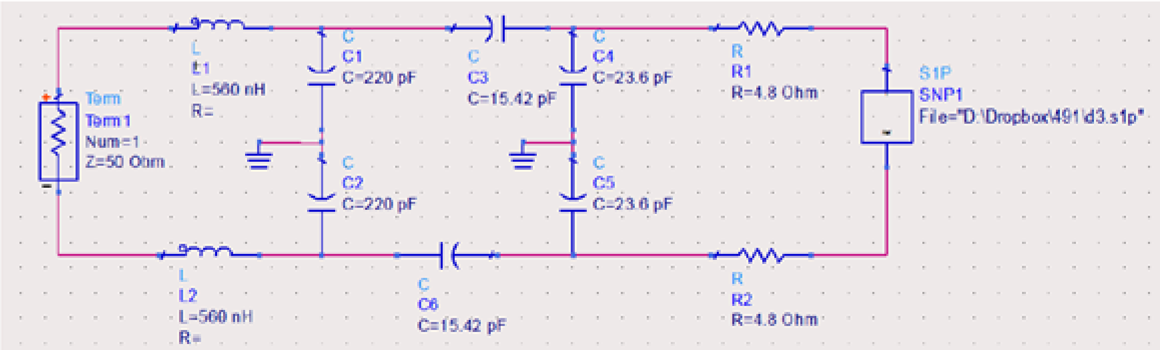

Figure 4.19. Schematics of reader design with rectangular antenna.

Figure 4.20 shows the results of the calculations to obtain the operation frequency.

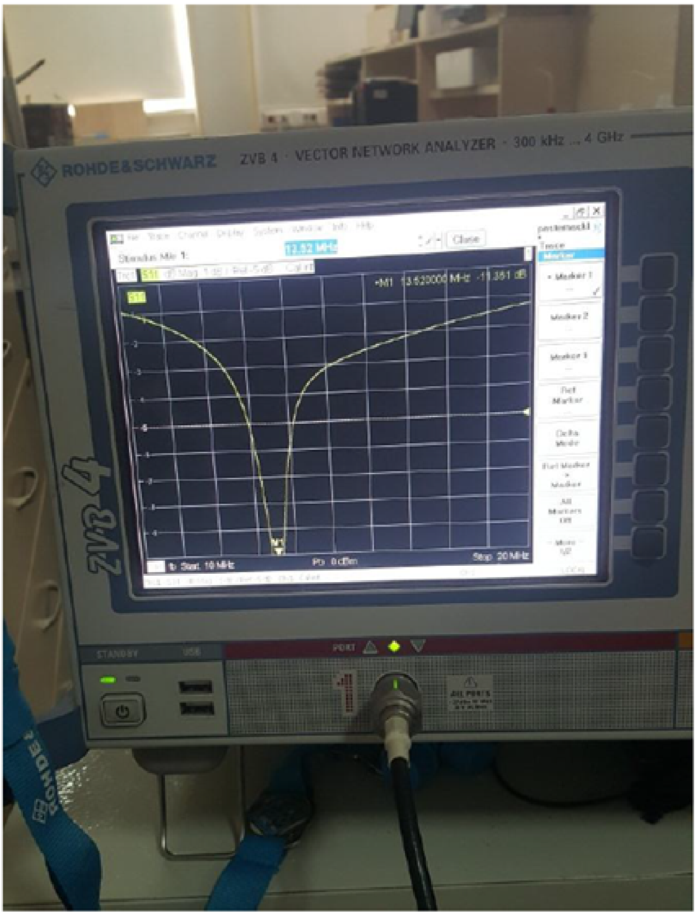

Figure 4.20. 13.52 MHz operating frequency.

The optimum result was obtained with the values of $C_3 = 30$pF and $C_4 = 15$pF. The resonant frequency has obtained as 13,52 MHz which is close enough to the ideal frequency for the desired application.

As the Figure 4.19 shows, $C_3 = C_6$ and $C_4 = C_5$. By examining the Table 4.1, it can be observed that the resonant frequency decreases significantly if one of these capacitor groups at the specified frequencies are increased. If the capacitor values are decreased, then an increase in the resonant frequency would be observed. In conclusion, from the issues that are mentioned before, it is a fact that matching circuit capacitor values and resonant frequency are inversely proportional.

4.4.2. Experimental Results in Square Antenna

Figure 4.21 shows the basic modelling of the reader antenna.

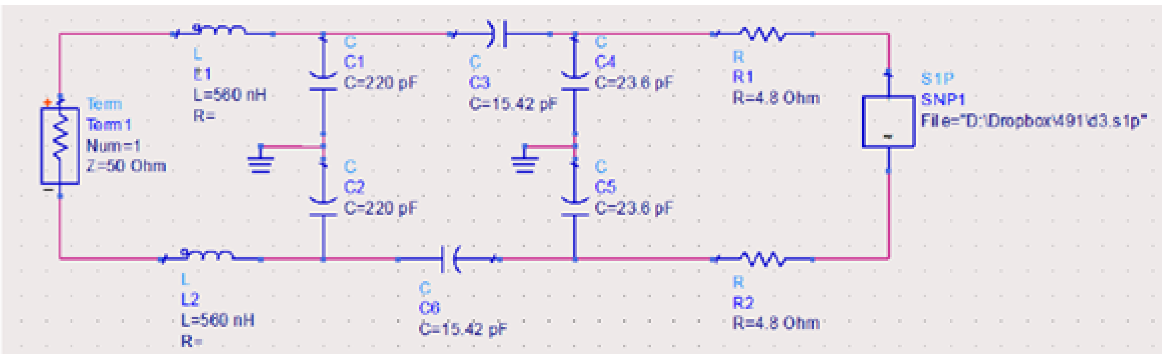

Figure 4.21. Schematics of reader design with square antenna.

The first obtained 4 loop antenna resonant frequency was 11.5 MHz. In the laboratory, by changing the capacitor values in the matching circuit, it was aimed to get the frequency level of 13,56 MHz by using network analyser.

In order to get the optimum results for the 4 loop square antenna, the simulation and calculations began with the same capacitor values. Table 4.2 shows the results of these calculations.

Table 4.2. ADS and Measured resonant frequency values with respect to capacitor values in square antenna.

Example	C3 (pF)	C4 (pF)	ADS Result Frequency (MHz)	Measured Frequency (MHz)
1	23	13	14,92	13,21
2	22	11	15,29	13,5
3	23	15	14,66	13
4	18	13	15,42	13,63

By looking at the Table 4.2 it is seen that the relations are the same as the rectangular antenna. An increase in any of the capacitor values, causes a decrease in the operating frequency. Optimum resonant frequency of 13.50 MHz has obtained for 4 loop square antenna with the capacitor values of, $C_3 = C_6 = 22$ pF and $C_4 = C_5 = 11$ pF.

5. CONCLUSION

First, There are few articles observing RFID systems' performance with comparison different size and geometry antennas by setting forth the best antenna geometry with metal and smart card effects. By examining the results, different size and geometry of antennas has different resonant frequencies and return losses and optimum return loss and input impedance have been achieved in all types of antennas.Considering read range and gain performance of the antennas, 4 loop square antenna gives us the best antenna geometry and size for intended RFID design.

On the other hand, proximity of metals has a vital effect on operating frequency. It shifts operating frequency to higher values when gets closer to the reader. Additionally, metal has also an effect for return loss, but is not linearly proportional. Metal increases both operating frequency and absolute value of return loss, but when it is too close like 1 mm, absolute value of gain loss begin to decrease.

Lastly, Passive smart cards place in proximity to the antenna of the reader, reader antenna performance is effected due to the capacitive effect. Resonant frequency of the loop antenna is shifted downwards and circuit is needed to be detuned.

REFERENCES

1. Finkenzeller, K., *RFID handbook: fundamentals and applications in contactless smart cards, radio frequency identification and near-field communication*, John Wiley & Sons, 2010.

2. Liu, W. and M. M. Wong, "3D RFID Simulation and Design-Factory Automation", *Factory Automation*, IntechOpen, 2010.

3. Zhang, H. and X. Lv, "Antenna Circuit Design and Simulation for the Reader of 125 KHz RFID", *2012 International Conference on Computer Science and Service System*, pp. 507–510, IEEE, 2012.

4. Microchip, *MicroID 13.56 MHz RFID System Design Guide*, 2004, `http://ww1.microchip.com/downloads/en/DeviceDoc/21299E.pdf`, accessed in March 2019.

5. ISO, I., "IEC 14443: Identification cards—Contactless integrated circuit cards—Proximity cards", *International Organization for Standardization, Geneva*, 2000.

6. ETSI, *Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment in the frequency range 9 kHz to 25 MHz and inductive loop systems in the frequency range 9 kHz to 30 MHz*, 2001, `http://www.etsi.org/deliver/etsen/300300300399/30033002/01.01.0130/en30033002v010101v.pdf`, accessed in March 2019.

7. Qing, X. and Z. N. Chen, "Proximity effects of metallic environments on high frequency RFID reader antenna: Study and applications", *IEEE transactions on Antennas and Propagation*, Vol. 55, No. 11, pp. 3105–3111, 2007.

8. Agilent, *Using a Network and Impedance Analyzer to Evaluate 13.56 MHz RFID Tags and Readers/Writers Application Note*, 2012, `http://cp.literature.`

agilent.com/litweb/pdf/5991-1475EN.pdf, accessed in March 2019.

9. Gossar, M., M. Stark, M. Gebhart, W. Pribyl and P. Soser, "Investigations to achieve very high data rates for proximity coupling devices at 13.56 MHz and NFC applications", *2011 Third International Workshop on Near Field Communication*, pp. 71–76, IEEE, 2011.

10. Harle, R., *Topical Issues: RFID*, 2014, http://www.cl.cam.ac.uk/teaching/1112/TopIssues/Files/TIL3RFID.pdf, accessed in March 2019.

11. Poole, I., *RFID Radio Frequency Identification Technology Tutorial*, 2014, http://www.radio-electronics.com/info/wireless/radio-frequency-identification-rfid/technology-tutorial-basics.php, accessed in March 2019.

12. Weis, S. A., "RFID (radio frequency identification): Principles and applications", *System*, Vol. 2, No. 3, pp. 1–23, 2007.

13. Rao, K. S., P. V. Nikitin and S. F. Lam, "Antenna design for UHF RFID tags: A review and a practical application", *IEEE Transactions on antennas and propagation*, Vol. 53, No. 12, pp. 3870–3876, 2005.

14. ISO, I., "IEC 15693: Identification cards—Contactless integrated circuit cards—Proximity cards", *International Organization for Standardization, Geneva*, 2003.

15. CEPT, E., "ERC recommendation 70-03, Relating to the use of Short Range Devices (SRD)", *Electronic Communications Committee*, 2017.

16. Mayordomo, I., R. Berenguer, A. García-Alonso, I. Fernández and Í. Gutiérrez, "Design and implementation of a long-range rfid reader for passive transponders", *IEEE Transactions on Microwave Theory and Techniques*, Vol. 57, No. 5, pp. 1283–1290, 2009.

17. Microchip, *Antenna Circuit Design for RFID Applications*, 2003, http://ww1.microchip.com/downloads/en/appnotes/00710c.pdf, accessed in March 2019.

18. Schroder, J. and S. Chang, *RFID and NFC antenna design, Part II*, 2014, http://www.cartes-asia.com/content/download/128139/1408624/↓le/Schroeder-RFIDandNFCantennadesignCartesAsia.pdf, accessed in March 2019.

19. NXP, *Antenna design guide for MFRC52x, PN51x and PN53xs*, 2011, https://my.eng.utah.edu/~mlewis/ref/NFC/AN1445.pdf, accessed in March 2019.

20. Lee, Y., "Antenna coil design", *Application manual of Microchips Technology*, 1999.

21. Atmel, *Atmel Tag Tuning/RFID, Application Note*, 2012, http://www.atmel.com/Images/DOC2055.PDF, accessed in March 2019.

22. Wang, H.-j., G. Wang and Y. Shu, "Design of RFID reader using multi-antenna with difference spatial location", *2007 International Conference on Wireless Communications, Networking and Mobile Computing*, pp. 2070–2073, IEEE, 2007.

23. Gebhart, M., S. Birnstingl, J. Bruckbauer and E. Merlin, "Properties of a test bench to verify Standard Compliance of Proximity Transponders", *2008 6th International Symposium on Communication Systems, Networks and Digital Signal Processing*, pp. 306–310, IEEE, 2008.

24. NXP, *RF Amplifier for NXP Contactless NFC Reader ICs*, 2015, https://manualzz.com/doc/9384171/an142522-rf-amplifier-for-nxp-contactless-nfc-reader-ic-s, accessed in March 2019.

25. NXP, *Near Field Communication PN531- uC Based Transmission Module*, 2011, http://www.nxp.com/documents/data-sheet/100020.pdf, accessed in March 2019.

26. NXP, *AN 1629 UHF RFID Label Antenna Design*, 2008, `http://www.nxp.com/documents/applicationnote/AN162910.pdf`, accessed in March 2019.

27. Schober, A., M. Ciacci and M. Gebhart, "An NFC air interface coupling model for contactless system performance estimation", *Proceedings of the 12th International Conference on Telecommunications*, pp. 243–250, IEEE, 2013.