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RFID SYSTEM DESIGN

Ayşe Zeynep SAYLAN

Master Thesis

Advisor

Yrd. Doç.Dr. Serkan TOPALOĞLU

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Bu tez çalışması, Maltepe Üniversitesi Fen Bilimleri Enstitüsü Yönetim Kurulu'nun 05/10/2010 tarih ve 2010/12 sayılı kararıyla oluşturulan jüri tarafından Elektronik Mühendisliği ***Yüksek Lisansı Tezi*** olarak kabul edilmiştir.

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ABSTRACT

RFID systems have become very popular in recent years due to their wide area of usage. RFID systems are used in supply chain, security related areas, logistics, and so on. By using RFID system, human based errors can be eliminated so the costs can be reduced. The RFID systems are composed of four main components; namely the reader, the antenna, the tag and the computer.

In this master thesis, a linear polarized UHF RFID antenna and a multiplexer are designed and fabricated to reduce RFID equipment costs. Wide reading range can be achieved using a multiplexer instead of multiple RFID reader. The designed antenna is cheaper than the antennas in the industry while presenting similar operational parameters.

The designed UHF RFID antenna is simulated from 850 MHz to 880 MHz. Return loss of the antenna is lower than -10dB in the range of 855 MHz to 875 MHz. The fabricated antenna has an input impedance of $54.2 + j18.3\Omega$, a return loss of -18.57 dB, a relatively high gain of 5.4 dBi and a read range of 8 meters at 2 Watt reader power. The fabrication cost of a single antenna is around 15 $ which is fairly cheap. The operation parameters are similar to the antennas in the industry, since conventional materials and components are used. Cost reduction can be achieved by using the presented antenna.

A multiplexer is designed and fabricated to multiplex the RFID reader port to two ports and extend the read range of the RFID reader. The main contribution in this design is the usage of pin diodes which are very cheap and easy to find. This in return reduces the fabrication costs. The designed circuit has only a few components, thus a relatively low complexity. It is easy to replace any component in case of a failure. The multiplexer is controlled by a PIC which allows the user to determine the read times of each RFID reader antenna. This innovative design allows a cheap solution to wide area applications of RFID where multiple antenna usage is necessary to read every tag in the reading zone.

ÖZET

RFID sistemler geniş kullanım alanları sayesinde son yıllarda tedarik zincirinde, güvenliğin gerektiği alanlarda, lojistikte ve daha bir çok alanda yaygin olarak kullanılmaya başlandı. RFID sistemler ile insana bağlı hatalar azaltılıp maliyetler düşürülürken, etkin stok kontolü ile müşteri memnuniyeti arttırılabilir. RFID sistemler 4 ana bileşenden oluşur. Bunlar; okuyucu, anten, etiket ve server yada bilgisayardır. Bu yüksek lisans projesinde, lineer polarize UHF RFID anten ve çoğullayıcı tasarlanıp, ürettirilmiştir. Daha geniş bir okuma alanına RFID okuyucu sayısını arttırmak yerine, maliyeti daha az olan çoğullayıcı kullanılması önerilmiştir. Tasarlanıp ve ürettirilen anten piyasaki antenler ile benzer özellilker göstermesine rağmen çok daha ucuzdur.

Dizayn edilen RFID anten 850 MHz – 870 MHz aralığında simule edilmiş ve 855 MHz – 865 MHz aralığında -10 dB'den daha az geri dönüş kaybına sahip olduğu görülmüştür. Üretilen anten $54.2 + j18.3\Omega$ giriş empedansına, -18.57dB geri dönüş kaybına, piyasada bulunan antenlere göre nispeten yüksek kazanca, 5.4 dBi, ve 2 W okuyucu gücü ile 8 metre okuma mesafesine sahiptir. Tek bir antenin üretim maliyeti yaklaşık 15$ civarındadır, oldukça ucuzdur. Piyasadaki antenlere benzer özelliklere sahip bu anten kullanılarak, maliyetler azaltılabilir.

RFID okuyucu portlarını çoğullamak ve RFID okuyucunun okuma mesafesini arttırmak amacı ile 1 portu 2 porta çoğullayan bir çoğullayıcı dizayn edilmiş ve ürettirilmiştir. Piyasada bulunması kolay ve ucuz pin diyotlar kullanılması ve dizayn edilen devrenin az devre elemanına sahip olması, karmaşıklığı azaltmış, maliyetleri düşürmüştür. Çoğullayıcı PİC ile kontol edilerek RFID antenlerin okuma süreleri kullanıcının kontrolüne bırakılmıştır. Bu yaratıcı dizayn, özellikle geniş okuma alanının gerekli olduğu RFID uygulamaları için ucuz ve kolay bir çözüm sunmuştur.

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ABBREVIATIONS

ABBREVIATION	MEANING
dB	Decibel
dBm	Decibel, referenced to one milliwatt
EPC	Electronic Product Code
FDA	Food and Drug Administrative
HF	High Frequency
ID	Identification
IFF	Friend and Foe
LF	Low Frequency
MHz	Megahertz
MUX	Multiplexer
PCB	Printed Circuit Board
RF	Radio Frequency
RL	Return Loss
RFID	Radio Frequency Identification
UID	Unique Identification
ULF	Ultra Low Frequency
UHF	Ultra-High Frequency
VSWR	Voltage Standing Wave Ratio

LIST OF SYMBOLS

Γ	Reflection coefficient
μ_0	Free space permeability
ε_0	Free space permittivity
ε	Dielectric constant
ℓ'	Ground plane length
λ	Wavelength
Ω	Ohm, unit of impedance
Δx	Distance from the edge of the patch to the feed point
$\tan\delta$	Loss tangent
c	Speed of light
$D\ \ \theta,\phi$	Directivity of the antenna
$E\ \ \theta,\phi$	Radiated electric field in the far field
$H\ \ \theta,\phi$	Radiated magnetic field in the far field
f	Frequency
$G\ \ \theta,\phi$	Gain of the antenna
G_R	Gain of the receiver antenna
G_T	Gain of the transmitter antenna
h	Thickness
I_A	Current at antenna’s input terminals
P_S	Power delivered by the source

P_A	Total power transferred to the antenna
P_S	Source power
q	Mismatch or reflection efficiency of the antenna
q_R	Receiver impedance mismatch factor
q_T	Transmitter impedance mismatch factor
R_r	Radiation resistance
R_D	Loss resistance
$U\ \theta,\phi$	Antenna's radiation intensity
U_a	Antenna's average radiation intensity
V_A	Voltage at antenna's input terminals
Z_A	Input impedance of the antenna

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1 INTRODUCTION

RFID, radio frequency identification system, is a wireless communication technology which is used to identify tagged items using radio frequencies. [18] Different frequency bands are used in different regions for RFID applications; 865-868 MHz in Europe, 902-928 MHz in America, and 950-956 MHz in Japan and some Asian countries.

The RFID system is composed of four main components. These are RFID reader, reader antenna, tag and a computer. Tags can be classified into three groups as active, passive and semi-passive with respect to their power supplies. The communication between the RFID reader and the tag is established through the antennas. For high efficiency the tag and the reader antenna have to be in correct orientation and sufficient power has to be transferred to the tag by the antenna. The most common type of antennas used as RFID reader antennas are microstrip antennas which were proposed in late 1960s. [5] A lot of microstrip patch antenna have designed and presented for RFID applications.

Qing, Chen and Chung, in reference [3], designed and presented a broadband circularly polarized patch antenna for UHF RFID applications in 2009. They used air as the substrate. The designed antenna was simulated over a wide frequency range. -15 dB return loss has been achieved over the wide frequency range of 760-963 MHz. 8.3 dBic gain was measured over the band of 815-970 MHz. Beamwidth was estimated as 75^o. The maximum reading range of the designed antenna is 7.5 m. In the same, year a group of engineer from Sabanci University were designed a linearly polarized microstrip patch antenna using FR4 as the substrate. -22 dB return loss has been achieved at 867 MHz. Directivity was measured as 7.5 dBi with 80.78^o estimated beamwidth. [2] Javier Dacvna and Rafael Pous were presented a patch antenna for RFID applications in 2009 as well. Polytetrafluroethylena-based substrate was used as the dielectric. -15 dB return loss has been achieved at 915 MHz and 7.13 m read range was calculated. [1] Microstrip patch antenna array has been designed by Abbak and Tekin for RFID applications for extending the range. A dielectric material with relative electric permittivity of 4.55 and thickness of 1.5 mm was used as the substrate. -22 dB return loss has been achieved at 867 MHz. 90^o of beamwidth has been measured with 5.5 dB directivity. [4]

This master thesis presents a linear polarized UHF RFID reader antenna at 866MHz. The designed antenna is very cheap and easy to fabricate due to its simple shape while presenting high gain, high directivity, low return loss, high read range similar to the antennas presented in literature and commercial.

A multiplexer circuit is presented by Ozgur Bostan for RFID applications designed using an integrated circuit to multiplex one port to two ports. Supply and control voltages were used. The device is powered by the supply voltage and the port selection is done by the control voltage. [6] In this master thesis a multiplexer circuit is designed using pin diodes for UHF RFID applications. The antenna read times are controlled by the user through a PIC circuit. The only available multiplexer circuit for RFID applications is expensive and it is hard to fix in case of a component failure. In this master thesis, by using pin diodes, a cheap and easy to fabricate, and easy to fix multiplexer circuit has been designed.

2 RFID

2.1 The Importance of RFID

In recent years, RFID technology is rapidly improving due to its wide area of usage. RFID systems can be used for labeling items in supply chain, security related areas, logistics and so on. The benefits of RFID are explained thoroughly in Chapter 1.3. [9] In order to regulate this improvement, Electronic Product Code (EPC) standards have been developed by supply chain operators and retailers. [18]

2.2 History of RFID

RFID history began at 1864 with James Clerk Maxwell who published the Maxwell equations that proved the existence of electromagnetic waves. Using Maxwell's equations, microwaves could be achieved. [9] In 1867, Heinrich Hertz, transmitted and received electromagnetic waves by demonstrating an apparatus which produces and detects electromagnetic waves in the UHF region. [8]

In 1896, Guglielne Marconi, transmitted the radiotelegraphy through Atlantic. [13]

The first radar systems were considered in the beginning of 20th century. Their working principle is similar to the RFID's which is based on transmitting and receiving radio waves. [16]

Radar systems were especially used for the identification of Friend and Foe (IFF) during the II. World War. The first RFID applications were demonstrated in conjunction with radar technology. [12] During the 2nd World War, IFF systems were designed to recognize the enemy airplanes, which contained a RF transponder (tag) and an integrator (reader). [14]

In 1970s Electromagnetic Surveillance (EAS) systems were used for anti theft as the initial applications of passive RFID systems. These systems could determine the presence or the absence of the tag. [8]

In 1970s, researchers and manufacturers started to work actively on RFID in research laboratories. In 1975, Alfred Kelly Steven Deep and Robert Freyman published "Short-range Radio Telemetry for Electronic Identification using Modulated Backscatter". Passive tags were effectively improved with this study. In the same years, the companies like Raytheon's Raytag, Richard Klensch, General Electric and Philips started researches on RFID technology. [13]

Intended applications of RFID, which mostly used in Europe, were for animal tracking, vehicle tracking and factory automation. [17]

Tag technology developments continued in size reduction. In conjunction with the usage of CMOS logic circuits, tag technology started to develop rapidly. [7, 8]

Nowadays, CMOS circuits are still being used in tags and EEPROM is being used for the nonvolatile memory and the tag size is determined by the tag antenna size. [8]

In 1990s, more than 3 millions of RFID tags were installed on cars and started to use in electronic toll collections in America. In 1991, first highway tolling system opened in Oklahoma, thus, the cars could pay in high speeds. In late 1990s, this system was started to use in Europe. [13]

In 1990s, microwave Schottky diodes were fabricated. By using these Schottky diodes in CMOS integrated circuits, RFID tags, composed of only one integrated circuit, were developed. [12]

In the same year, Auto ID center was established by Massachusetts Institute of Technology to keep the RFID manufacturers, researchers and users together and to determine the related standards. [9]

RFID took place in the supply chain when Wall-Mart began to use RFID system in April 2004 with a pilot project included eight suppliers. In January 2005, Wall-Mart asked their 100 suppliers to provide the goods with RFID tags attached. Wall-Mart eliminated theft, reduced labor costs and the time of inventorying by using RFID system. [14]

In the 21st century, tags composed of at least one antenna and CMOS integrated circuit were produced and the size of the tags was determined by the antenna size. EEPROM has been used as nonvolatile memory. [8]

Nowadays, RFID is used in inventory management applications, transportation and logistics, manufacturing, location ascertainment, livestock identification, access control systems, sport contests, container positioning and shipyards. [11] RFIDs are more beneficial in some sectors like healthcare, luxury good industries, textile, automotive and library material tracking. [13] The history of RFID is summarized in the Table 2-1.

Table 2-1The History of RFID

The History of RFID	
1860-1900	Initial investigations like Maxwell Equations (existence of electromagnetic waves), Hertz (transmitted and received electromagnetic waves in UHF region) and Marconi (transmitted radiotelegraphy through Atlantic).
1940-1950	Radar, IFF systems. RFID invented in 1948.
1950-1960	Laboratory experiments.
1960-1970	First RFID applications (anti theft systems).
1980-1990	Commercial applications of RFID (highways), AUTO ID center established.
1990-2000	RFID started to use in everyday life.
2000-	RFID applications widespread rapidly.

2.2.1 AUTO ID Technology

Automatic Identification Technology, including barcodes, contact memories and RFID grew rapidly in recent years. [9]

Barcodes are the most common and the most familiar computer-readable tags. They use laser to scan the barcode, which introduces some limitations. It requires a direct “line of sight”, meaning the item has to be in the right location and nothing blocking the beam between the laser and the barcode. [9]

The other well known computer–readable tags are magnetic strips on credit cards which also must line up correctly. [9] Different Auto ID technologies have different advantages and disadvantages listed in the Table 2-2 below.

Table 2-2 AUTO ID Technology [9]

	Bar codes	***Contact Memory***	***Passive RFID***	***Active RFID***
Modification of Data	Un-modifiable	Modifiable	Modifiable	Modifiable
Security of Data	Minimal Security	Highly Secure	Ranges from minimal to highly secure	Highly Secure
Amount of Data	Linear bar codes can hold 8-30 characters; other 2-D bar codes hold up to 7200 numbers	Up to 8 MB	Up to 64 KB	Up to 8 MB
Costs	Low (pennies of fraction of a penny per item)	High (more than $1 per item)	Medium (less than 25 cents per item)	Very high ($10-$100 per tag)
Standards	Stable and agreed	Proprietary; no standard	Evolving to an agreed standard	Proprietary and evolving open standards
Life Span	Short unless laser-etched into metal	Long	Indefinite	3-5 year due to battery life
Reading Distance	Line of sight (3-5 feet)`	Contact required	No contact or line of sight required; distance up to 50 feet	No contact or line of sight; distance up to 100 meters and beyond
Potential Interference	Optical barriers such as dirt or objects placed between tag and reader	Contact blockage	Environments or fields that affect transmission of radio frequency	Limited barriers since the broadcast signal from the tag is strong

2.3 Differences Between EPC and UPC

The Electronic Product Code, EPC, code was developed in 2003 by MIT's AUTO ID center for different RFID systems to share information. [9] EPC system is universal for all the systems using the EPC, since the EPC code is unique. [8] EPC is working with the same principle as Universal Product Code, UPC, which is used in barcodes. EPC is used to label the products uniquely in the supply chain. [9] UPC can be programmed with the information required only once. Information contains the manufacturer and product codes. [8]

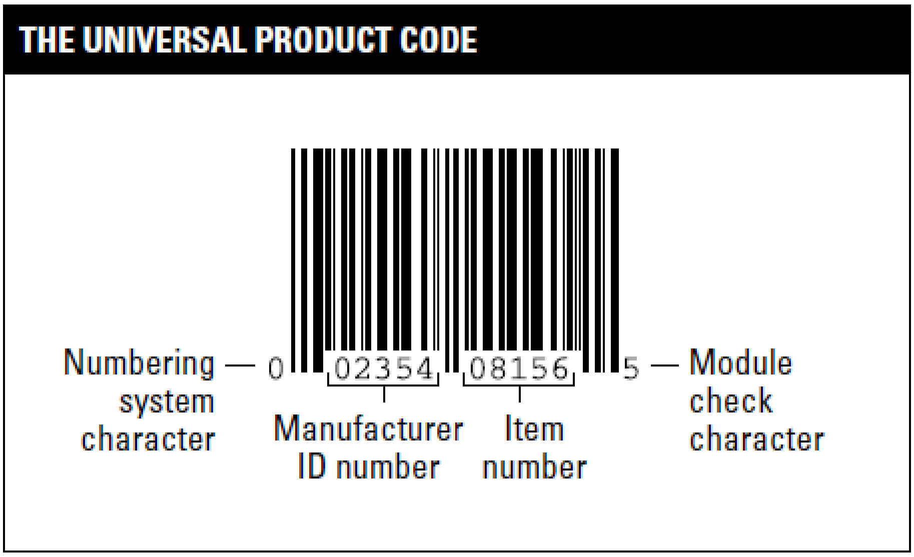


Figure 2-1UPC Code [9]

100000 manufacturer identifiers, 100000 product types for each manufacturer can be provided by UPC code.

EPC number varies due to the data carrying of a tag. The length of the EPC number changes between 32 to 256 bits long. By using a 96 bits EPC number, more than 263 million manufacturers, more than 16 million types of objects and almost 69 million goods for each manufacturer can be tagged. [10] EPC code is composed of a header, an EPC manager number, an object class and a serial number. The header identifies the type of the EPC code. It can represent a military unique identification, UID, or a food and drug administrative code, FDA. [9]

The EPC manager number represents the corresponding company. The object class number is used for a stock-keeping unit (SKU). Finally, the serial number represents a unique tag and known as the most important part of the EPC code. [9] EPC code example can be seen in Figure 2-2.

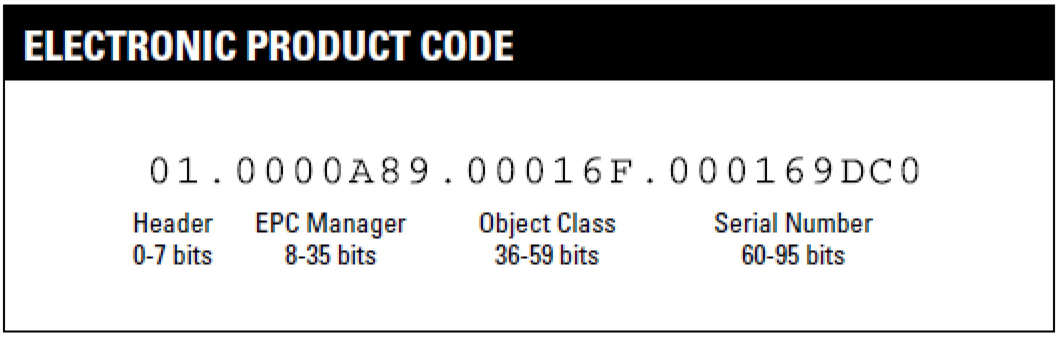


Figure 2-2EPC code [9]

UPC code can accommodate 100000 different numbers while the EPC can label millions of trillions different items. [9]

The ongoing industries such as Marks and Spencer, Metro, Wall-Mart, Alien Technology, Impinge Corporation, Skytel helped to improve the protocols for RFID systems under the control of AUTO ID center. Protocols which are using today are listed in the below table. [18] Although today’s standardized protocol is EPC generation 2.0, some companies are still using carrier protocols.

Table 2-3RFID Interface Protocols [9]

Protocol	***Corresponding Frequency***	***Capabilities***	***Pros***	***Cons***
Generation 1.0 Class 0	UHF	Read-only preprogrammed tag, means the end user can't write a new number to the tag.	Fast data communication protocol	Preprogrammed tags increase administrative and logistics cost of affixing the correct tag to the correct item and also minimize tag's flexibility
Generation 1.0 Class 1	UHF anf HF	Write once, read many (WROM)	Keep data in sequential order; manage data easier.	Can be written to only once.
ISO standard	LF. HF and UHF	Read Only Tag Identifier with read, write and lockable user memory to store object identifier and information.	Keep data in sequential order; manage data easier.	Does not account for the data structure but only how the tag and reader communicate.
Generation 2.0 Class 1	HF and UHF	Write once, read many (WROM)	Keep data in sequential order. More globally accepted protocol.	Can be written to only once.

2.4 Advantages and Disadvantages of RFID

In RFID systems, electronic product codes (EPC) are used for labeling items. They are written in computer-readable tag and can be extracted through an antenna. [8]

Every item has a unique ninety-six bits EPC code, which allows one to define billions of items. This also allows one to learn how long the item is waiting in the backroom, and production details like date, country, time spent for carrying. By using the RFID system, one can control the inventory better while reducing the loss and carrying costs. [8, 9]

The EPC codes can be tracked automatically without needing human involvement. From the perspective of logistics, this is a very important feature since RFID allows one to read hundreds of items at the same time including the details of an item. Using RFID in a logistics system reduces costs, damages, returns and speeds up the throughput which are directly related with humans. [8, 9]

Since an RFID antenna can read the tags while they are in its reading zone (3-7 meters), many items can be counted and the information can be updated simultaneously. An RFID reader can read all the items in the shopping basket while the basket moving through the exit. This feature is very useful also in airports for luggage. By using the RFID in these areas, the costs can be reduced together with the working time. [8, 9, 23]

RFID is a real time system and reads/extracts the data simultaneously, which reduces costs, waste, errors and increases the customer satisfaction. [9]

Security can also be increased by using RFID. The most important field that can be mentioned about importance of RFID is pharmaceutical industry. Production date, manufacturer and cost information can be achieved from the RFID tags. [9, 25, 26]

Although there are all these benefits, a few problems are still needed to be solved. The cost of a single tag slows down the widespread of RFID usage, especially in fast-moving consumer goods. The read tags ratio over the total number of tags is still not satisfying which is affected from the reader, the tag position, and also from the data collision. [25, 26]

2.5 Basic Components of RFID System

RFID system consists of three basic components, which are an antenna, a transponder and a reader. A computer or a controller can be used as a bridge between enterprise applications and RFID hardware. [18, 19]

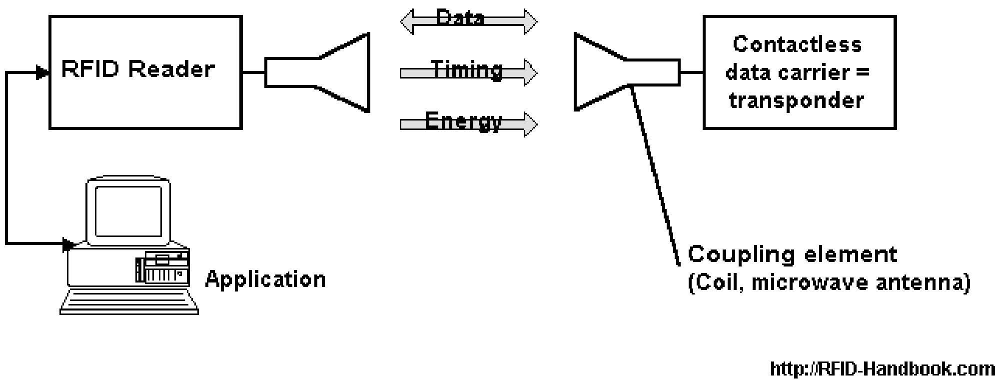


Figure 2-3The Basic Building Blocks of an RFID system [31]

2.5.1 Antenna

There are two antennas suited in RFID system. One placed in the reader, which is called reader antenna, and is responsible for the wireless communication between the reader and tag. Different types of antennas can be used as reader antenna. The most popular and effective one is a patch antenna. The design of a patch antenna is simple in structure and can be fabricated easily at a very low cost. The antenna gain and directivity is satisfying as well. [9, 23, 28]

The other antenna which is suited on the tag is called the tag antenna and it is responsible to take the energy from the RFID reader and send its information via backscattering. [9, 23]

Both antennas should be in compact size and should have directivity with high gain. [9, 23]

2.5.2 Transponder

Transponder, which is also known as a tag, is the component which carries the information. They are composed of a microchip for memory and an antenna for receiving the transmitted signals. Power is needed to activate the tag which is in sleep mode. This power can be obtained from the reader antenna or from the tag itself. [9]

Transponders can be divided into three types regarding to their power supplies. They are active tags, semi-active tags and passive tags. [9]

Active tags: Active tags have their own internal power supplies which also determine the reading range and the lifetime of the tag. This internal power is used to activate the integrated circuits as well as the transmission between the reader and the tag. [22]

Semi-passive tags: In semi-passive tags, the integrated circuits are fed from the internal power supply which also determines the lifetime. For the transmission, the required energy is supplied from the signal propagated from the reader. The semi-passive tags reflect or backscatter this energy to send the information. [9, 24, 27]

Read range is related with the reader or the tag sensitivity. [9]

Passive tags : Passive tags have no internal power supply. The required power is extracted from the radio frequency. [22] In such kind of tags RF energy is used not only to activate the integrated circuit but also to establish the communication between the tag and the reader. The passive tags use the energy transmitted by the reader and backscatter the same energy after inserting the information. [21]

The range limitation is related with the efficiency and the power consumption of the tag. [9]

2.5.3 Reader

The reader creates and transmits electromagnetic signal. Reader antenna broadcasts this signal to the reading zone then listen the response from the tag and the reader converts the received signal into digital information. [20, 27, 29]

2.5.4 Computer or controller

A computer or a controller is a conduit component between the hardware and the user interface. It collects the information extracted from the tag and distributes the related information to the user. Since the usage of the RFID systems widespread rapidly, they can be used for different applications in the many fields. A middleware can be used to arrange the information and distribute them to the related user. [8, 9]

2.6 Working Principle of an RFID System

As stated in the previous Chapter 2.3, the tags can be classified into three types due to their power supply needs. All tags works with similar principles. In this chapter, the working principle of an RFID system with a passive tag will be presented.

The tag is composed of a chip which is programmed with information that uniquely identifies the tag. When the reader antenna sends the RF field, tag antenna, suited in its reading zone, absorbs this energy. The chip inside the tag converts this RF energy into usable electrical power to retrieve or store the data and modulate the backscatter signal. [8, 9, 29, 30]

In most applications of RFID reader, the same reader antenna is used for transmitting and receiving the signal. After the signal transmitted to the tag, the same antenna listen the backscatter signal from the tag. When the reader receives the backscattered signal, it decodes and sends the information to the computer which distributes the useful information to the user interface. [8, 9, 29, 30]

2.7 The Importance of the Operating Frequency

RFID systems can be designed in different frequency ranges. These transmission frequencies can be classified into four groups. They are low frequency (LF, around 125KHz), high frequency (HF, 13.56MHz), ultra-high frequency (UHF, 860MHz – 960MHz) and microwave frequency (2.45GHz). Frequency bands can be found in the Table 2-4. [25, 29]

Since the frequency affects the wavelength and the read range accordingly, it is important to select the operating frequency carefully. As the frequency increases, wavelength decreases and so the read range increases. [8, 9, 29]

Read range is small at LF, HF and microwave frequencies. (< 60 cm at LF and HF, <1 m microwave) Environment sensitivity is high at microwave frequencies. UHF is effective for all supply chain applications due to its long reading range capability $(\approx 8m)$ and low cost. [32, 21] UHF frequency is selected in the scope of this master thesis.

Table 2-4 Fundamentals of Frequencies [29, 30]

	LF (low frequency)	***HF (high frequency)***	***UHF (ultra high frequency)***	***Microwave***
Frequency	<135 kHz	13.56 MHz	860-960 MHz	2.45 GHz
Read range	<0.5 m	<1 m	<4 m	differentiates to the medium
General Information	Large antenna size, high cost. Penetrate is maximum around metals and liquids.	Cheaper than LF tags. Can be used in small range, multi tag applications.	Cheaper that LF and HF tags. Can be used in long range, multi tag applications. Penetration is worse than LF and HF around metals and liquids.	Faster reading capacity than UHF. Effective around metals and liquids.
Power source of the Tag	Passive	Passive	Active and Passive	Active and Passive
Applications	Access control Animal tracking Pay quick cashless systems (gas stations) Guard patrol routes Maintenance Asset identification	Smart Cards for cashless payment systems Casino chips Hospitality industry High level security Library and video store rentals Evidence management Document management	Pallet and case level tracking Healthcare patient tracking Asset tracking Fleet maintenance Security for laptops, etc. Manufacturing Environmental controls Field service	Container and rail car tracking Toll collection Pallet level tracking Environment controls Truck tracking and monitoring
Reading capability of multiple tags	Very Slow	Slow	Fast	Very Fast
Passive tag size	Too Big	Big	Small	Very Small

3 RFID ANTENNA

3.1 Overview of Antennas

Antennas are used as transducers between the electromagnetic waves moving in the free space and the guided electromagnetic signals in transmission line. As such, antennas have a critical role in RFID systems. The communication between the reader and the tag is established between tag and reader antennas. With the wide usage of RFID systems in daily life, the costs of the devices become more important. Since the cost of the total system is directly proportional to the cost of a single antenna, designers started to work low cost antennas as much as the operational reasons. [33, 35, 48] As a result, designers have been trying to meet the demands of consumers while following the theory, simulations and experimental results.

As stated in the introduction section a lot of different microstrip antenna have been presented in recent years. References [1], [2], [3], and [4] present microstrip antennas for UHF frequency bands in Europe for RFID applications. In reference [1], the antenna has been designed by using FR 4 with a thickness of 1.5 mm. The antenna had over 7 meters read range at 2 W power. Another microstrip antenna has been designed by using FR 4 with dielectric constant of 4.55 in Reference [2]. The dimensions of the patch selected as 10x12cm. The measured input impedance, return loss and directivity at 867 MHz measured as 42.2Ω, -22 dB and 7.5 dBi respectively. For 840-960 MHz frequency band, a circularly polarized RFID antenna is presented in Reference [3] with 15 dB return loss, 8.3 dBi gain, 3 dB of axial ratio and 7 meters read range for 4W power. A microstrip patch antenna array has been designed to improve the characteristics of the antenna presented with Reference [4] operating at 867 MHz. Arlon AD450 with a dielectric constant of 4.5 was use as the substrate while the patch dimensions were 34x45cm. The measured directivity was 9.5 dBi, return loss was -22 dB and HPBW, half power beam width, was 90^{o}. Phased antenna array was composed of four identical microstrip patch antennas and three Wilkinson power dividers.

An important criterion of RFID antenna is the gain. The aim is to design a linearly polarized antenna with approximately 5 dBi gain and achieve more than 7 meters read range.

In the scope of this master thesis, a cheap, high gain and linearly polarized microstrip patch antenna is designed and fabricated for RFID applications.

This chapter provides a detailed explanation of RFID antenna design and its operational parameters which permit the analysis of a complete antenna, including input impedance, efficiency, radiation pattern, directivity and gain.

3.2 Microstrip Patch Antenna

A microstrip device is a layered structure consists of a patch on top of a grounded dielectric substrate. [33, 35, 36]

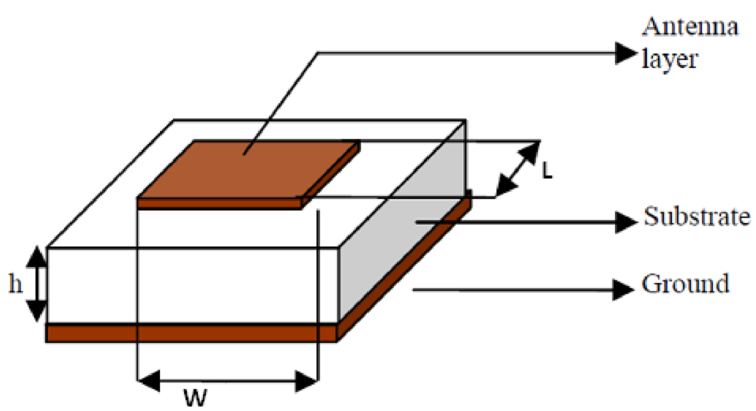


Figure 3-1 Basic Microstrip Patch Antenna [23]

Microstrip antennas have an important role in the applications where size, weight, cost, performance, ease of installation and aerodynamic profile are constraints, and low profile antennas may be required like high performance aircrafts, spacecrafts, satellites, missile applications and commercial applications. [9, 35] Microstrip antennas are preferable when produced in large quantities due to their low manufacturing costs. They are produced using printed circuit fabrication techniques. In most applications, metallization layer, which is very thin (h<< λ_0 where λ_0 is the free space wavelength) is used for radiation and placed on the ground plane. [9, 35, 36] Microstrip antennas are very versatile in terms of resonant frequency, polarization, pattern and impedance if the suitable patch shape and mode are selected. On the other hand they have poor scan performance, low efficiency, low power, spurious feed radiation and very narrow frequency bandwidth. In some applications, such as RFID systems, narrow bandwidths are desirable. [35, 44, 52]

There are different types of microstrip patch antennas like rectangular, dipole, elliptical, square, circular, triangular, etc. Rectangular patch microstrip antenna, which is fed from a microstrip transmission line, is the most commonly used one. [40]

The length L of the rectangular patch is usually $\lambda_0/3 < L < \lambda_0/2$. The patch and the ground plane are separated by a dielectric sheet (referred as the substrate) as shown in Figure 2.1. [36]

The dielectric constant of the substrate is usually in the range of $1 \le \varepsilon_r \le 12$. [36] The thick substrate whose dielectric constant is in the lower end of the range, provide better efficiency, larger bandwidth but large in antenna size. The thin substrates which have high dielectric constants, are less efficient, have small bandwidths but are small in antenna sizes. [35, 36, 40, 49]

The designed microstrip antenna should have more than 4 dBi gain and narrow bandwidth.

3.3 Antenna Structure and Design Methodology

The goal of the design is to achieve desired performance characteristics at the operating frequency, 866MHz. In this master thesis a rectangular patch antenna is designed.

Microstrip antennas can be fabricated using printed circuit technologies and they have very low profile. Microstrip antennas are conformable, potentially at low cost, easy to fabricate into linear or planar arrays, and easy to integrate with microwave integrated circuits. [35, 40, 52]

As shown in Figure 2.1, the basic configuration of a microstrip patch antenna is a metallic patch printed on a thin, grounded dielectric substrate. Originally, the element is fed either with a coplanar microstrip line or a coaxial line through the bottom of the substrate. [47]

When a particular patch shape and dielectric are selected, they become very versatile in terms of polarization, resonant frequency, radiation pattern and impedance. [43, 36, 47]

3.3.1 Substrate Selection

The first design step is to choose a suitable dielectric substrate of appropriate thickness, h, and loss tangent, $\tan\delta$.

A thicker substrate increases the radiated power, dielectric loss, surface wave loss, and reduces conductor loss and also improves impedance bandwidth. A lower dielectric constant for the substrate increases the fringing field and radiated power. To design a smaller patch size, dielectric constant should be preferred to be below 2.5. A high loss tangent increases dielectric loss and therefore reduces antenna efficiency. [33, 34, 35]

The bandwidth and efficiency of a patch are increased by increasing the substrate thickness and lowering the dielectric constant. [35]

Under these circumstances, Duroid 5880 has been chosen as the substrate which has a loss tangent of 0.005 and a dielectric constant of 2.2. [50]

3.3.2 Antenna Width and Length Calculation

Patch width affects the input resistance and the bandwidth rather than the resonant frequency and the radiation pattern. It has been suggested that; $1 < L/W < 2$. [36]

The patch length has an important effect on resonant frequency. Equation 3.1 can be used to calculate the patch length, L. [46]

$$L = \frac{c}{2f\sqrt{\varepsilon_r}} \qquad \text{Eq. 3.1}$$

where;

c ; speed of the light in vacuum $(3\times10^8 m/s)$

f ; resonant frequency of the designed antenna

ε_r ; dielectric constant of the substrate

The center frequency is highly affected by the length, compared to the other design parameters. [46]

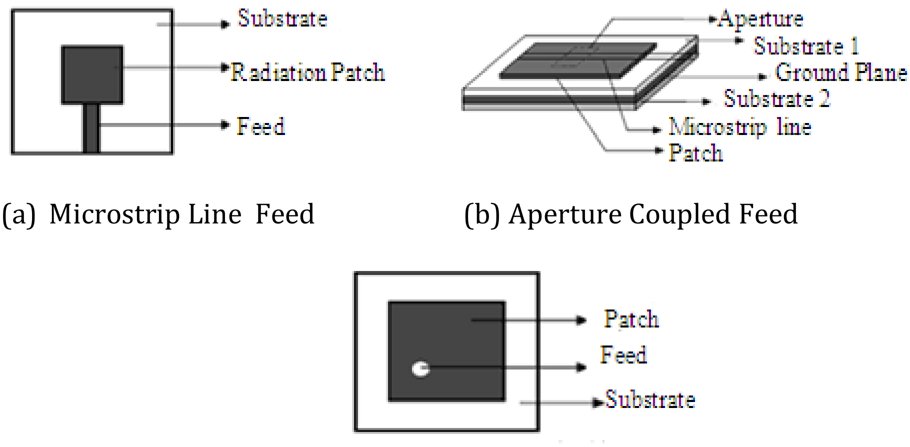
3.3.3 Feeding Technique Selection

Different feeding techniques can be used to feed the antenna. The feeding techniques have an effect on the efficient transfer of power between the feed structure and radiating patch, that is, impedance matching between the two. Impedance matching is associated with discontinuities leading to spurious radiation and surface wave loss. The undesired radiation may increase side lobe level and the cross-polar amplitude of the radiation pattern. [47] Three types of well known feed techniques will be summarized.

The first well known technique is microstrip line feed, as shown in Figure 3.2a, permitting the patch and feed to be printed on a single metallization layer. [35] They are easy to fabricate but they have high line radiations for thick substrates which leads to distortions in the radiation pattern. [35]

The second technique is aperture-coupled feed, shown in Figure 3.2b, which is becoming more popular. It is composed of two antenna substrates which can be different from each other. A radiating patch is etched to the upper side of the first substrate and a microstrip feed line is etched to the bottom side of the second substrate. There is a ground plane between the substrates. Although they can be designed for frequencies from 800 MHZ to 94 GHZ, they have a narrow bandwidth. [33, 35, 36, 47]

The last well known technique is a coaxial line feed, shown in Figure 3.2c, which is selected in the design of the presented antenna. The inner conductor of the coax is attached to the radiation patch while the outer conductor is connected to the ground plane. It is easy to fabricate and match. However, it has a narrow bandwidth. [33, 35, 36, 47]



(a) Microstrip Line Feed (b) Aperture Coupled Feed

(c) Coaxial Probe Feed

Figure 3-2Feeding Techniques [52]

3.3.4 Feed Point Location of the Antenna

The feed point location needs to be determined, which have an effect on the input impedance, after the substrate, the patch length and the width. [36] When the feed point location is selected properly, input impedance, Z_A will be equal to the feed line impedance. The input impedance of a patch antenna due to the feed location can be calculated with Equation 3.2 when Δy is constant. [36]

$$Z_A = 90.\frac{\varepsilon_r^{\,2}}{\varepsilon_r - 1}.\left(\frac{L}{W}\right)^2 \cos^2\left(\frac{\pi.\Delta x}{L}\right) \qquad \text{Eq. 3.2}$$

where;

Δx ; distance from the edge of the patch to the feed point

Z_A ; input impedance of the patch

Δy ; distance from the bottom of the patch to the feed point

3.3.5 Polarization

The polarization of a transmitting antenna in a given direction is defined in the antenna’s far field where the electric and magnetic fields behave like plane waves. Polarization of an antenna is the orientation of its electric field in the antenna’s far field region. [37, 38, 39] Electric and magnetic far field components of a plane wave are illustrated in Figure 3-3.

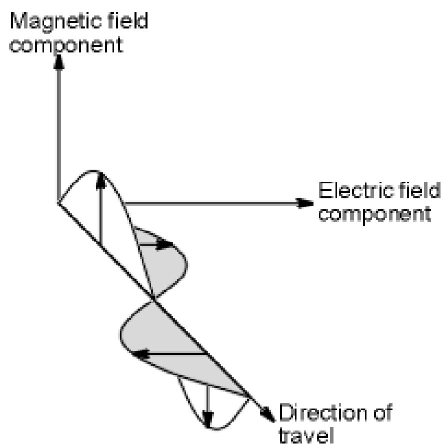


Figure 3-3 Electric and Magnetic Field Components of a Wave [37]

UHF RFID reader antennas can be classified in two groups according to their polarization types which are linearly and circularly polarized. [38]

In linear polarization, the electric field vectors move back and forth along a line. Linear polarized antennas are the most effective types, where the antenna completely matched with the tag’s antenna in polarization. This can be verified when the tag orientation is known and fixed. Best read rates can be obtained by matching the RFID antenna and the tag antenna in the same polarization. [43, 44]

In circular polarization, the electric field vectors remain constant in magnitude but rotate around a circular orientation. Circular polarized antennas are used when the tag antenna orientation is unknown. If the tag antenna is linear, 3 dB is lost, when compared to matched polarized linear antenna. [43, 44] Figure 3-4 shows the linear and circular polarizations.

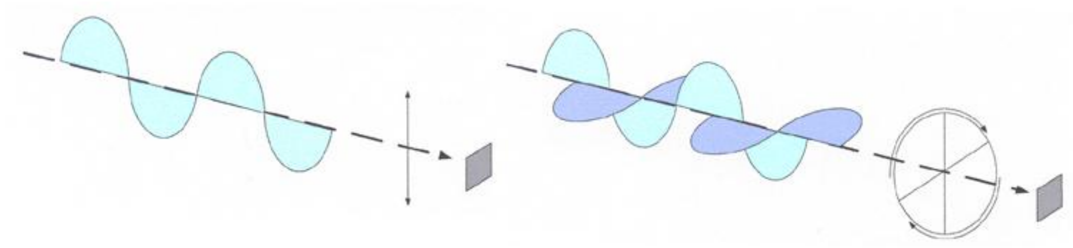


Figure 3-4 Linear and Circular Polarization [45]

In this master thesis, a linear polarized microstrip patch antenna is designed due to its high read range capability, which is approximately 7 meters.

3.4 Final Design of the Antenna

In this master thesis, a linear polarized microstrip patch RFID antenna with a coaxial feed design is presented. For simplicity, a rectangular shaped antenna is selected.

The patch length, L, and the patch width, W, are calculated by using Eq. 3.2 and $1 < L/W < 2$ ratio. The final design is obtained by tuning the values. The ground plane length (ℓ') is calculated by using Eq. 3.3 [36], presented below, to create an infinite ground plane effect. After the calculated results are tuned, the ground plane of the antenna is selected as $150\ \text{mm} \times 200\ \text{mm}$.

$$\ell' = \sqrt{\varepsilon_r} \times \ell \qquad \text{Eq. 3.3}$$

Duroid 5880 is used as the substrate as stated in the previous section. The dielectric constant ε_r of RT/duroid 5880 is 2.2, which is constant for this material, over a wide frequency range. The tangent loss (tan δ) is 0.005 low that extends the usefulness of RT/duroid 5880. Duroid material can easily cut, sheared and machined to shape. [50]

The designed microstrip patch antenna resonates with a center frequency of 866MHz. The simulation is desirable between 860-870 MHz which covers the UHF range of RFID in Europe which is 865MHz to 868MHz.

The target port impedance is 50 Ohm for this antenna since the reader port impedance is 50 Ohm which should be matched to the designed antenna. Designed antenna dimensions and characteristics are summarized in Table 3.1.

Table 3-1 Antenna Dimensions

Substrate	Rogers Duroid 5880
ε_r	2.2
$\tan\delta$	0.005
W	114.25 mm
L	113 mm
Ground plane dimensions	$150\text{mm}\times 200\text{mm}$
Feeding technique	Coaxial feed
Polarization type	Linear
Input impedance	50 Ω

3.5 Simulation of the Designed Microstrip Patch Antenna

The microstrip antenna design, was simulated using AWR (Applied Wave Research) based on the method of moments. Designed antenna is simulated in FEKO to execute the radiation pattern, the gain and the directivity.

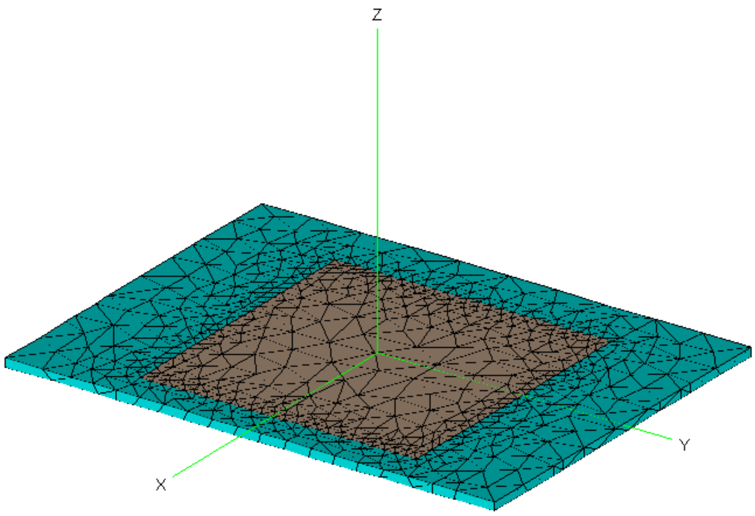


Figure 3-5 Microstrip Patch Antenna seen on FEKO

3.5.1 Antenna Input Impedance

The input impedance of the antenna, Z_A, is the impedance presented by the antenna at its terminals. It can be calculated from the ratio of the voltage, V_A and the current I_A at its input terminals. [33, 35, 36]

$$Z_A = \frac{V_A}{I_A} = R_A + jX_A \qquad \text{Eq. 3.4}$$

Where;

R_A; antenna resistance
X_A; antenna reactance
Z_A; antenna impedance

Antenna resistance is the sum of radiation resistance R_r and loss resistance R_D. [33, 35, 36]

$$R_A = R_R + R_D \qquad \text{Eq. 3.5}$$

An antenna equivalent circuit can be refined in Figure 3.6.

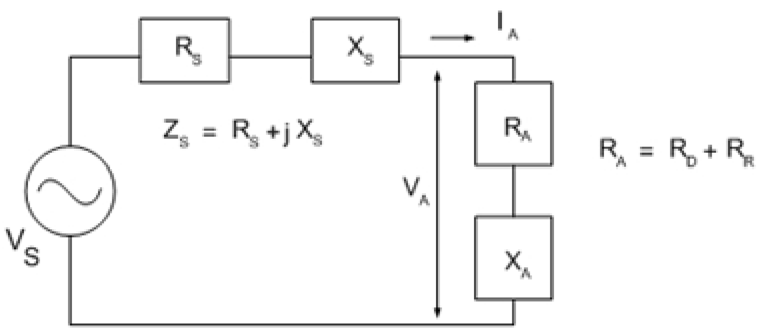


Figure 3-6 Antenna and Its Equivalent Circuit

Z_S is the internal impedance of the antenna.

The power absorbed by the antenna terminal P_A and power radiated from the antenna P_R can be expressed as shown below. [33, 35, 36]

$$P_A = \frac{1}{2}|I_A|^2 R_A = \frac{|V_S|^2}{2} \frac{R_A}{(R_S + R_R + R_D)^2 + (X_S + X_A)^2} \quad \text{Eq. 3.6}$$

$$P_R = \frac{1}{2}|I_A|^2 R_R = \frac{|V_S|^2}{2} \frac{R_R}{(R_S + R_R + R_D)^2 + (X_S + X_A)^2} \quad \text{Eq. 3.7}$$

The maximum power is transferred when $R_A = R_S$ and $X_A = -X_S$. When this condition is met, it is called that the source is conjugate matched to the antenna. The power delivered by the source is expressed with P_S and calculated using equations 3.8 and 3.9. [33, 35, 36]

$$P_S = P_A\big|_{[Z_A = Z_S^*]} \quad \text{Eq. 3.8}$$

$$P_S = \frac{|V_S|^2}{8R_s} \quad \text{Eq. 3.9}$$

When this condition is not satisfied, the total power transferred to the antenna can be found from Eq. 3.10 in terms of P_S . [33, 35, 36]

$$P_A = qP_S \quad \text{Eq. 3.10}$$

Where $q \leq 1$ is the mismatch or reflection efficiency of the antenna. [33, 35, 36]

From equations 3.7 and 3.9, q can be defined with Eq. 3.11.

$$q = \frac{4R_A R_S}{|Z_A + Z_S|^2} \quad \text{Eq. 3.11}$$

When Z_S is purely real and $X_S = 0$, q can be expressed with Eq. 3.12. [33, 35, 36]

$$q = 1 - |\Gamma|^2 \quad \text{Eq. 3.12}$$

Reflection coefficient , Γ, is defined with Eq. 3.13. [33, 35, 36]

$$\Gamma = \frac{Z_A - Z_S}{Z_A + Z_S} \quad \text{Eq. 3.13}$$

The reader antenna should be designed with an input impedance of around 50 ohms to transfer maximum power. [52] So, the maximum power transfer condition is met and reflection coefficient equals to 1.

Designed antenna is simulated from 850 MHz to 880 MHz and its input impedance is $48.79+j0.14\,\Omega$ at the operation frequency which is 866 MHz. Input impedance of the designed antenna is shown with Smith Chart in Figure 3.8.

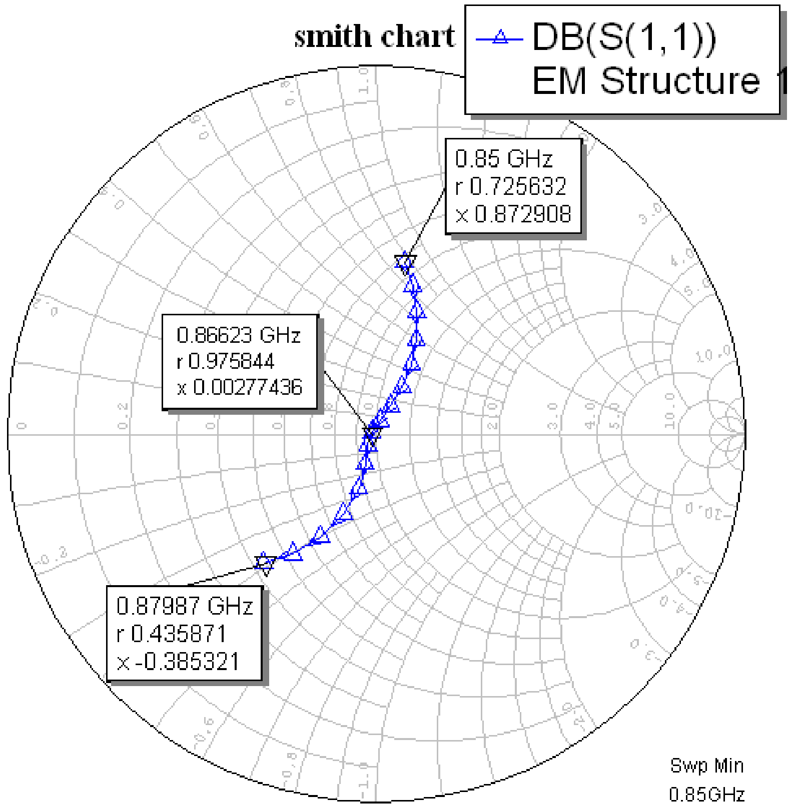


Figure 3-7Input Impedance

VSWR, voltage standing wave ratio, represents the mismatch of the line. It can be calculated from the reflection coefficient. [42] VSWR equals to 1 when the antenna is matched to the transmission line. [33]

$$\Gamma = \frac{VSWR - 1}{VSWR + 1} \quad \text{Eq. 3.14}$$

When the load is mismatched, some of the power can be delivered to the antenna from the generator (RFID reader). This "loss" is called return loss (RL) and can be expressed as Eq. 3.15. [42]

$$RL = -20 \log \left| \Gamma \right| dB \quad \text{Eq. 3.15}$$

If the antenna is matched, Γ is 0 and RL equals to ∞ dB. [42]

Return loss and VSWR simulation results are presented over the frequency range of 850-880 MHz in Figure 3.8. The return loss is given by S11(dB).

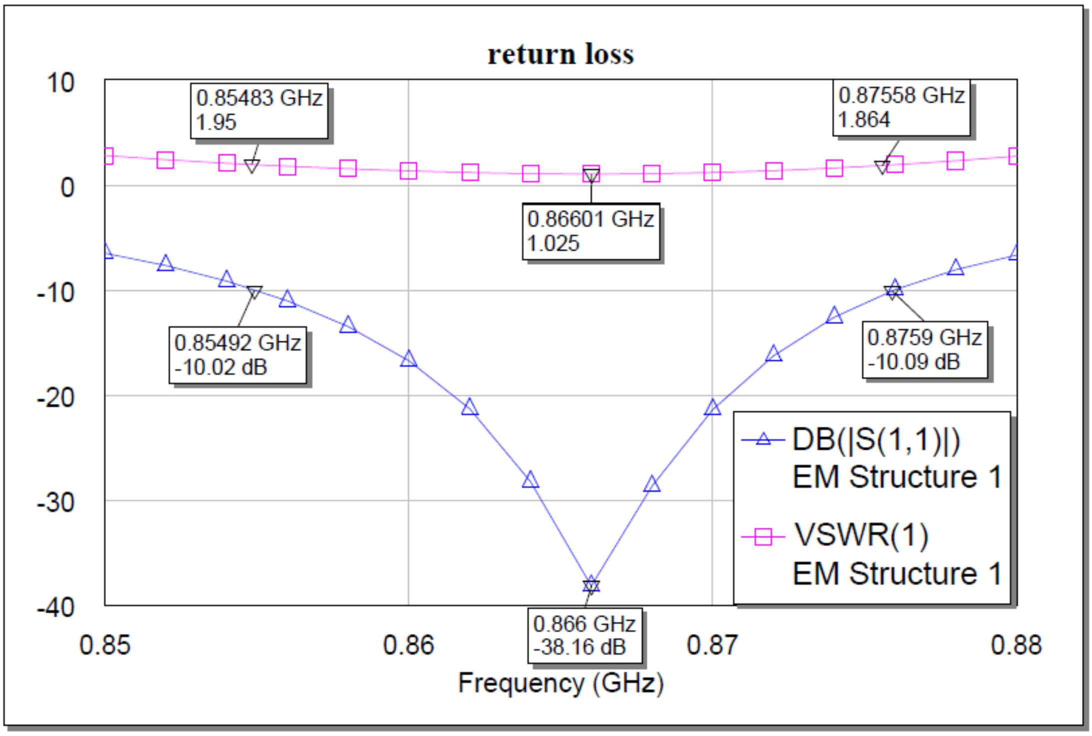


Figure 3-8 Return Loss and VSWR Simulation Results

Simulation results show that the antenna is almost matched to the RFID reader at 866 MHz.

The above plots show that the maximum power transfer occurs at 866 MHz when the return loss is minimum (-38.11 dB).The matching network provides a narrowband match between 855 to 876 MHz, where the return loss is less than -10dB which is acceptable value of RL for microstrip patch antennas.

3.5.2 Radiation Pattern

Radiation pattern gives the graphical representation of the radiation properties of the antenna in the far field region. [33, 35, 36]

Transmitting antenna resides in free-space and near the origin of an assumed coordinate system. $FF_\theta(\theta,\phi)$ and $FF_\phi(\theta,\phi)$ represents the function of the strength of the field along θ and ϕ which depends direction of radiation. Both of them are complex numbers (phasors). $\hat{r}$ is the direction of propagation. [48]

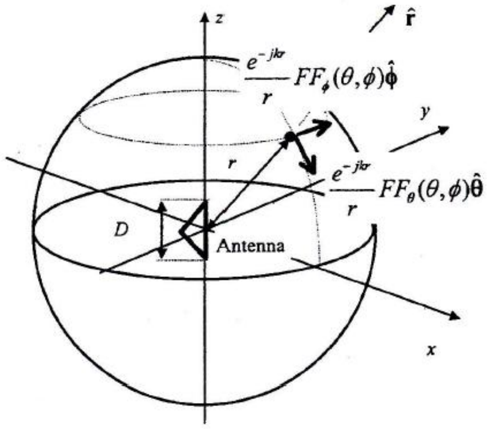


Figure 3-9 Electric and Magnetic Fields of the Antenna [48]

Radiated electric field in the far field can be expressed by Eq. 3.16. [48]

$$\vec{E}\ r\ = e^{0}\,\frac{e^{-jkr}}{r}\left[FF_\theta(\theta,\phi)\hat{\theta}+FF_\phi(\theta,\phi)\hat{\phi}\right] \quad \text{Eq. 3.16}$$

where;

$$k=\frac{\omega}{c}=\frac{2\pi}{\lambda} \quad \text{Eq. 3.17}$$

$$\omega=2\pi f \quad \text{Eq. 3.18}$$

f ; operation frequency

c ; speed of light in free space

μ_0 ; free space permeability

ε_0; free space permittivity

λ; free space wavelength

The electric field hasn't got a component in its direction of propagation.

Magnetic field radiated by the antenna can be expressed as Eq. 3.19. [48]

$$\vec{H}(r) = \frac{1}{\eta} e^{0} \frac{e^{-jkr}}{r} \left[FF_{\theta}(\theta,\phi)\hat{\phi} - FF_{\phi}(\theta,\phi)\hat{\theta} \right] \qquad \text{Eq. 3.19}$$

$\eta = \sqrt{\mu_0 / \varepsilon_0} \approx 120\pi \approx 377\Omega$ free space impedance.

Antenna magnetic far field has no radial component. The electric and magnetic far fields are perpendicular to the local direction of the propagation like plane waves and perpendicular to one another. [48]

The aim of the radiation pattern is to compare antenna performance in different directions. [33, 34] The radiation pattern of the simulated antenna is presented in the following sections.

3.5.3 Antenna Directivity

The directivity of an antenna is the ratio of the radiation intensity in a certain direction to the average radiation intensity. [33, 35, 36] It is expressed as $D(\theta,\phi)$ with Eq. 3.20.

$$D(\theta,\phi) = \frac{U(\theta,\phi)}{U_a} \qquad \text{Eq. 3.20}$$

where;

$U(\theta,\phi)$; antenna's radiation intensity

U_a ; antenna's average radiation intensity

Antenna's average radiation intensity can be expressed as the Eq. 3.21. [33, 35, 36]

$$U_a = \frac{P_r}{4\pi} = \frac{1}{4\pi} \oiint_S U(\theta,\phi)\, d\Omega \qquad \text{Eq. 3.21}$$

where $d\Omega = \sin\theta d\theta d\phi$.

Usually, the directivity is expressed in decibels as $D_{dB}(\theta,\phi) = 10\log D(\theta,\phi)$. [33, 35, 36]

Antenna patterns are simulated using a commercial software called FEKO. Simulated directivity pattern can be seen in Figure 3.10.

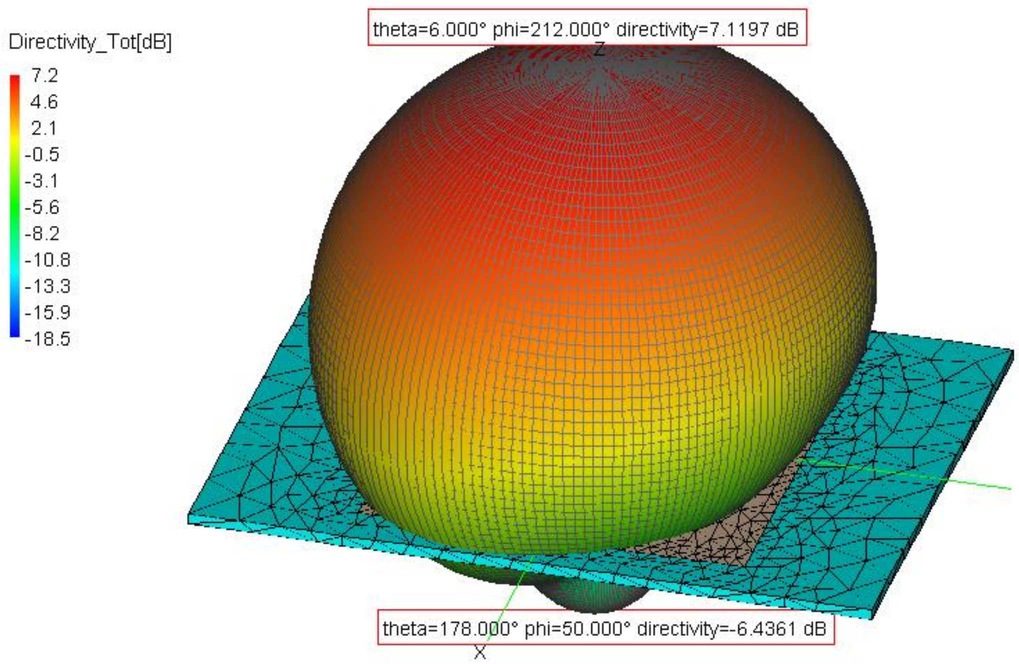


Figure 3-10 3D- Directivity Results of Simulation

As seen above, the max directivity is 7.2 dB for the designed antenna.

3.5.4 Half Power Beam Width

The HPBW of the main beam of the antenna (in a given plane) measures the angle surrounding the direction of maximum radiation across which the antenna's radiation intensity is larger than one half. Defining $\tilde{\theta}_{HPBW}^{right}$ and $\tilde{\theta}_{HPBW}^{left}$ as the angles starting from the direction of the main beam maximum in the clockwise and counterclockwise directions. [33, 35, 36, 48]

Simulated results of HPBW can be seen in Figure 3.11.

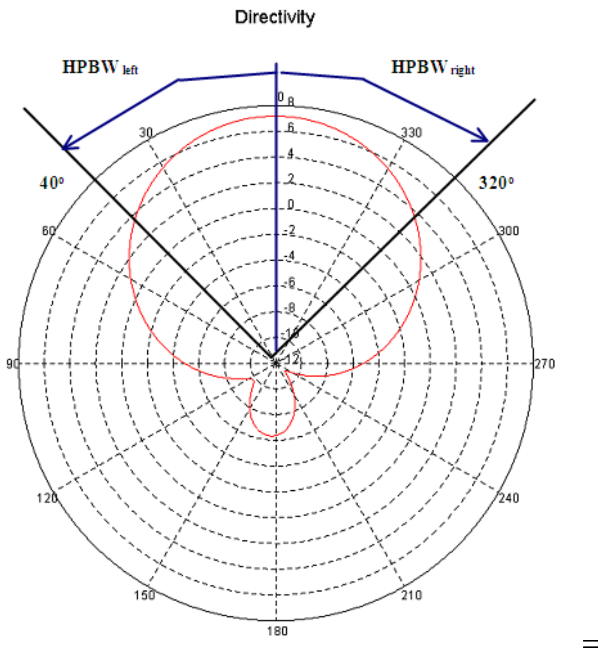


Figure 3-11 Half Power Beam Width

3.5.5 Antenna Gain

Using equations 2.17 and 2.18, directivity, $D(\theta,\phi)$ can be rewritten as Eq. 3.22. [36]

$$D(\theta,\phi) = \frac{4\pi U(\theta,\phi)}{P_r} \qquad \text{Eq. 3.22}$$

The gain of the antenna can be calculated form Eq. 3.23. [36]

$$G(\theta,\phi) = \frac{4\pi U(\theta,\phi)}{P_A} \qquad \text{Eq. 3.23}$$

The relation between the directivity and gain can be given by Eq. 3.24. [36]

$$G(\theta,\phi) = eD(\theta,\phi) \qquad \text{Eq. 3.24}$$

The maximum gain can be expressed by Eq. 3.25. [36]

$$\begin{aligned} G &= G(\theta,\phi)|_{\max} \\ &= \frac{4\pi U(\theta,\phi)|_{\max}}{P_A} \\ &= \frac{4\pi U_{\max}}{P_A} \end{aligned} \qquad \text{Eq. 3.25}$$

Similar to directivity, gain is also expressed in dB mostly as $G_{dB}(\theta,\phi) = 10\log G(\theta,\phi)$. [36] The gain of the designed antenna can be seen in Figure 3.12.

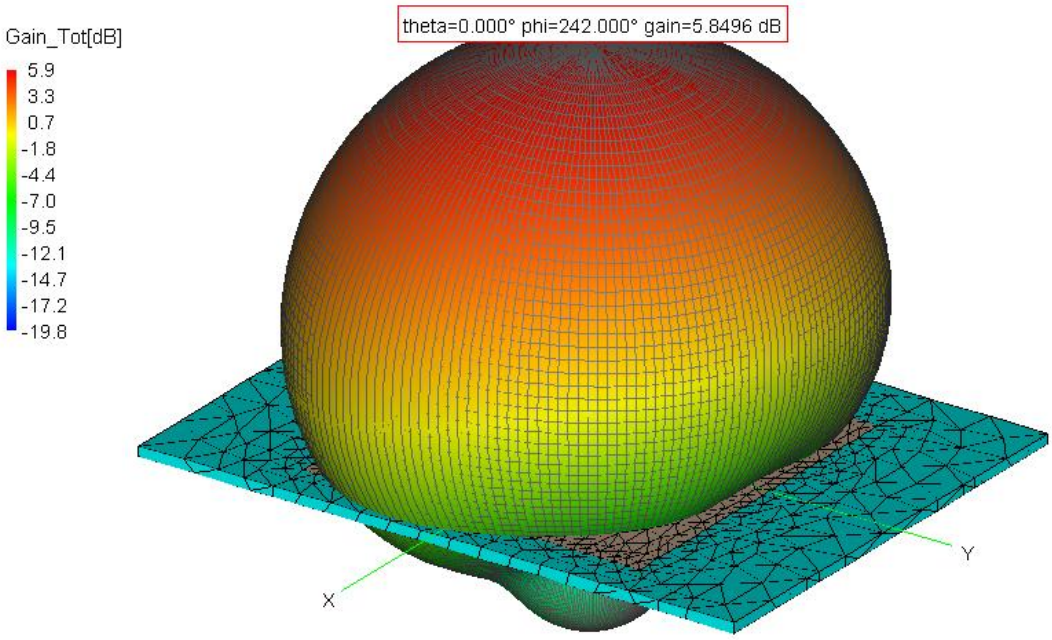


Figure 3-12Gain Simulation Results

The max gain of the simulated antenna is 5.9 dB as seen in the radiation pattern.

3.5.6 Antenna Efficiency

The ratio of the transmitting power from the antenna to the power absorbed by the antenna is called efficiency and can be calculated by using the Eq. 3.26. [36]

$$e = \frac{P_r}{P_A} \qquad \text{Eq. 3.26}$$

where $e \leq 1$

The difference between P_A and P_r equals to the dissipated power in the antenna and can be expressed with Eq. 3.27. [36]

$$P_D = P_A - P_r$$
$$= (1 - e)P_A \qquad \text{Eq. 3.27}$$

In summary, radiated power from the antenna, P_r, equals to the antenna efficiency times the power accepted by the antenna terminals (P_A). [36] From Eq. 3.22 ($G(\theta,\phi) = eD(\theta,\phi)$), efficiency, e, of the simulated antenna can be calculated as 81 %.

Designed microstrip patch antenna characteristics is summarized in the below Table-3-2.

Table 3-2Microstrip Patch Antenna Simulation Characteristics

Antenna Input impedance	48.79+j0.14 Ω
Return Loss	-38.11 dB
VSWR	1.025
Antenna Gain	5.9 dBi
Antenna Directivity	7.9 dBi
Antenna Efficiency	81%
Half Power Beam Width	80^o

3.5.7 Communication Between the antennas of the reader and the tag

Up to now, all the equations given in the previous chapters are valid for transmitting antennas. With similar approach the formulas can be extended for a receiving antenna. This section is focused on the relation between a transmitter and a receiver antenna. In RFID systems, the transmitting antenna is the antenna on the reader and the receiver antenna is the antenna on the tag which are separated by a distance R. Assume that the receiver antenna is located in direction θ,ϕ , as measured in the transmitting antenna's coordinate system. Transmitting and receiving antennas can be seen in Figure 3-14.

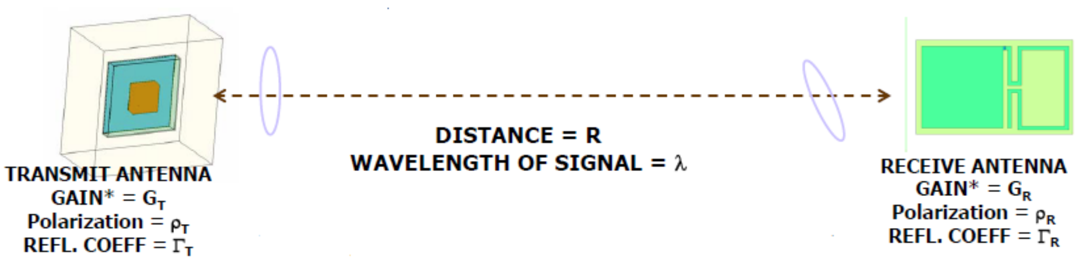


Figure 3-13 Communication Between Antennas [45]

The power deposited into Z_L is expressed with the equation 3.28, called the Fiiris equation. [36, 48]

$$P_L(dBm) = P_S(dBm) + G_R \;\; \theta_r,\phi_r \;\; (dB) + G_T \;\; \theta_t,\phi_t \;\; (dB) - \\ 20\,\text{logr(km)-20logf(MHz)+}q_T(dB) + q_R(dB) + \\ 20\log\left|\hat{p}_r(\theta_r,\phi_r).\,\hat{p}_t(\theta_t,\phi_t)\right| - 32.44 \qquad \text{Eq. 3.28}$$

P_S ; source power

q_R ; receiver impedance mismatch factor

q_T ; transmitter impedance mismatch factor

G_R ; gain of the receiver antenna

G_T ; gain of the transmitter antenna

P(dBm); power level in dB reference to one milliWatt (1mW=0dBm, 10mW=10dBm, 100mW=20dBm..etc.) [48]

3.6 Measured Results of the Microstrip Patch Antenna

Validation of the above simulations was done by fabricating prototype of the designed antenna in a private company and its performance characteristics were experimentally measured in ITU laboratories. The prototype validation procedure and measured results are presented in this chapter. Fabricated antenna can be seen in Figure 3.15.

Figure 3-14 Fabricated Antenna

The measured return loss, VSWR and the input impedance can be seen on the Figures 3.16, 2.17 and 2.18 respectively.

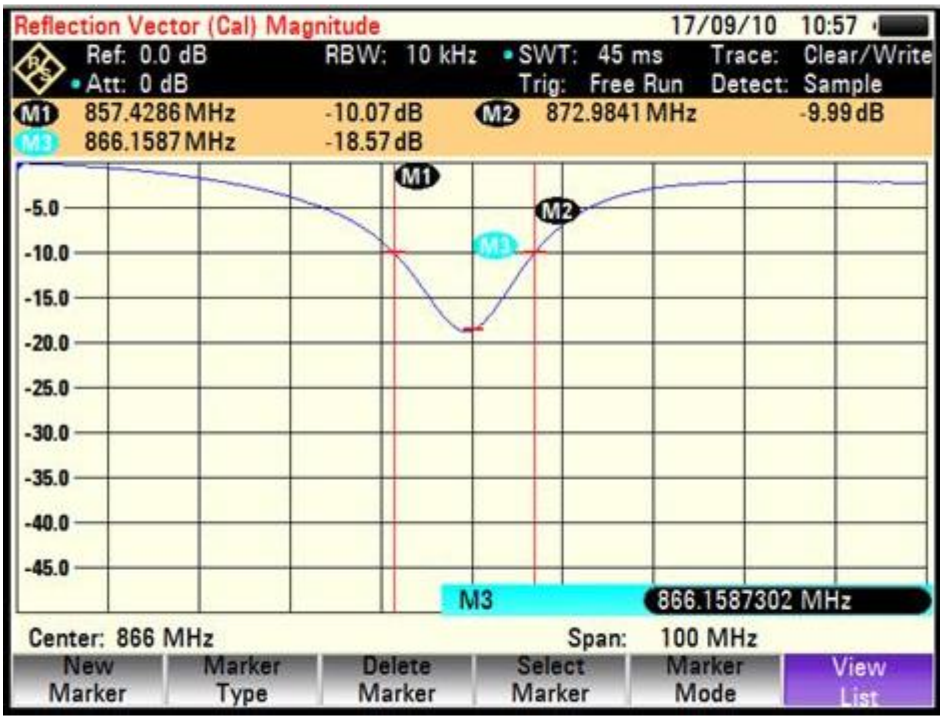


Figure 3-15 Measured Return Loss

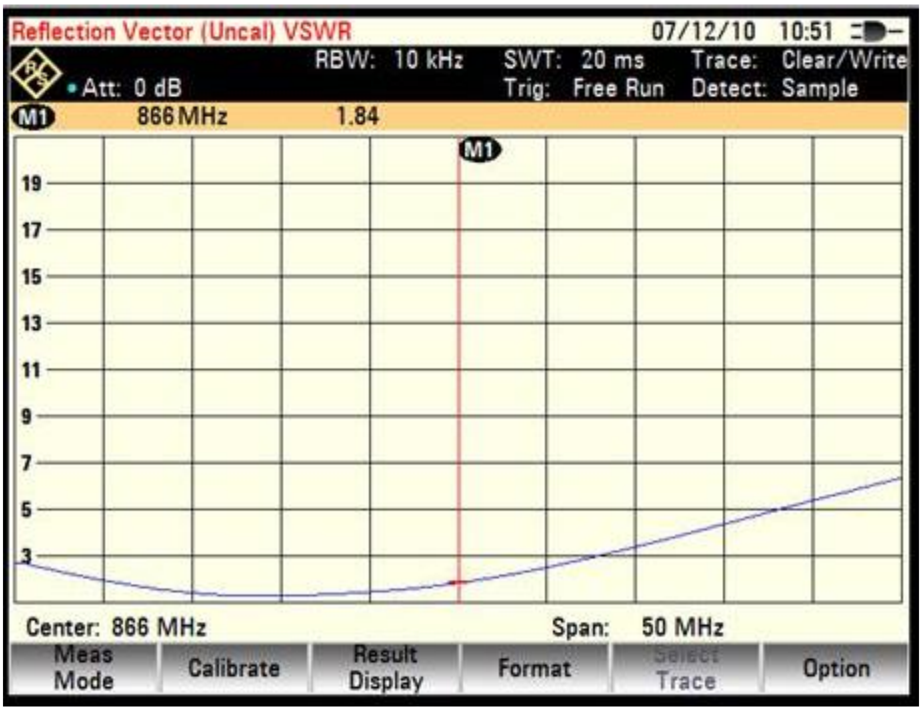


Figure 3-16 Measured VSWR

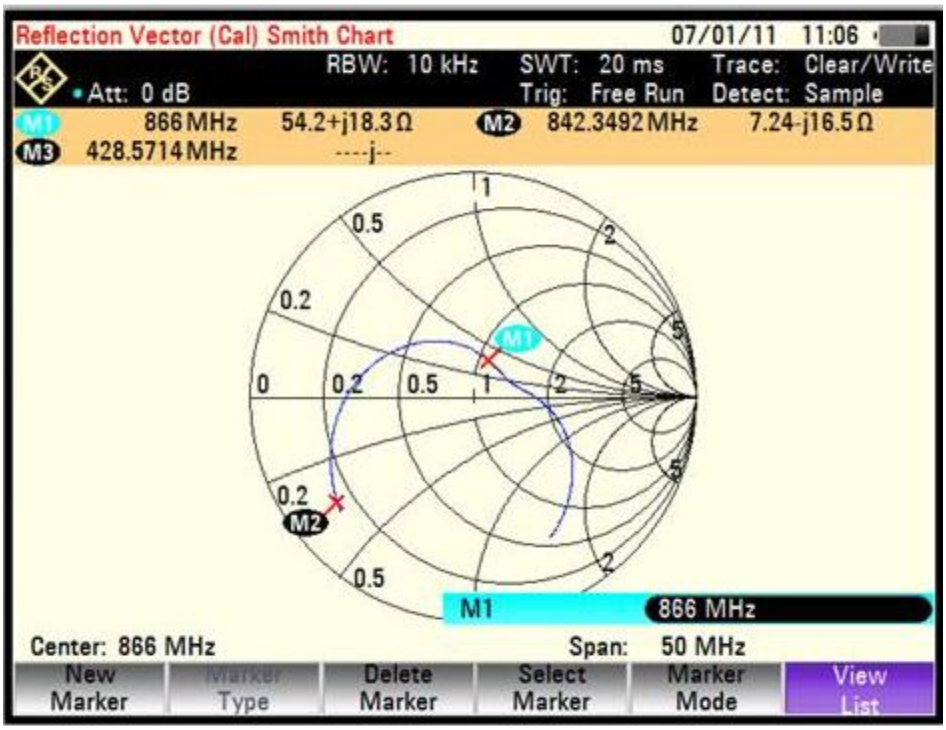


Figure 3-17 Measured Input Impedance

Gain and directivity measurements were experimentally measured. A reference and an antenna with known characteristics, Alien's antenna, with 5.5dBi gain, were used in the experimental setup. The results were obtained by comparing the designed antenna with the known antenna. Experiment setup can be seen in Figures 3-18, 3-19 and 3-20.

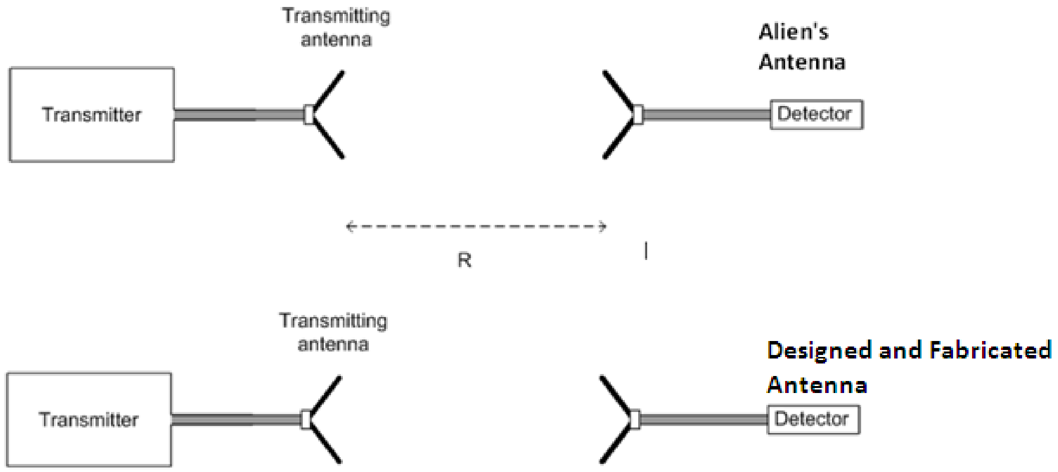


Figure 3-18 Experimental Setup for Measuring Antenna Gain

The reference antenna was connected to LFC-945 Signal Level Meter operating at 866 MHz which is labeled as the transmitting antenna. Alien's antenna was connected to Wavetek Signal Generator and was also operating at 866 MHz.

Gain of the designed antenna is calculated by using the Eq. 3.29. [36]

$$G_{designed}(dB) = P_{designed}(dBm) - P_{ref}(dBm) + G_{Alien}(dB) \quad \text{Eq. 3.29}$$

where;

$P_{designed}$; power received by the designed antenna

P_{ref} ; power received by the reference antenna

G_{Alien} ; Gain of the Alien's antenna which is 5.5 dB

Measured gain of the designed antenna is 5.4 dBi.

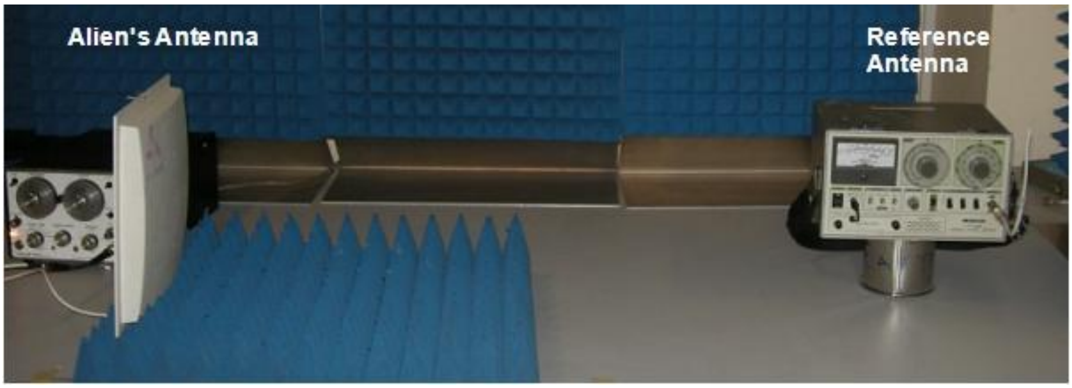


Figure 3-19 The Reference and the Alien’s Antennas

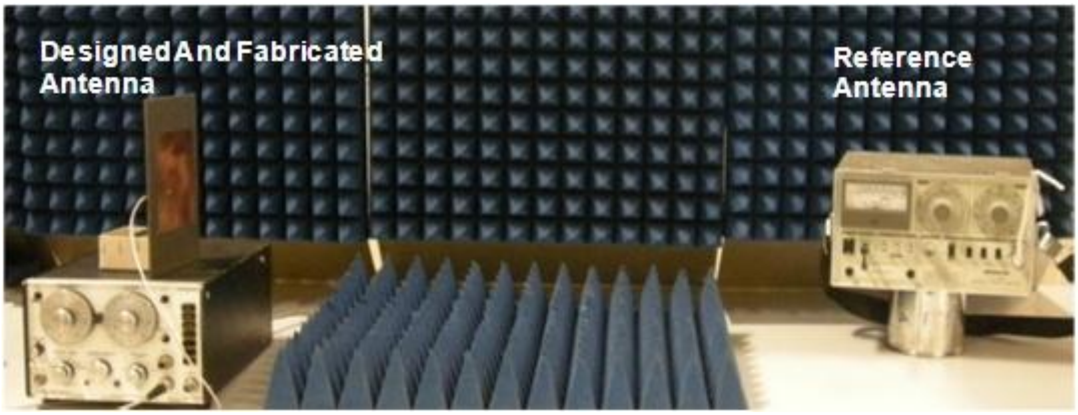


Figure 3-20 The Designed and the Reference Antennas

As a second step HPBW was measured by using a goniometer. While the antenna was rotating slowly, half power beam width points were labeled. Measured half power beam width is 70 degrees which is slightly lower than the simulated results.

Measured results of the designed microstrip patch antenna are summarized in Table-3-3.

Table 3-3Measured Results

Input impendace	54.2+j18.3
Return Loss	-18.57 dB
VSWR	1.84
Gain	5.4 dBi
HPBW	70^o

As seen in the table, the simulated and measured results are slightly different from each other. This variation could be attributed to the design imperfection in the prototype and errors caused due to the assumptions and approximations in measurements.

3.6.1 Read Range of the Designed Antenna

The maximum distance between the tag and the reader, where the tag can be detected properly by the reader, is called reading range. Reading range measurements of the fabricated antenna was performed at Maltepe University by pluged in the proposed antenna to UHF RFID reader to detect a UHF RFID tag. The Alien's RFID reader and its tags were used which operates 866 MHz. The maximum read range of 8 meters has been achieved.

3.7 Antenna Results

In this master thesis a microstrip patch antenna is designed and fabricated which can be used in UHF RFID system. In RFID applications low cost, low profile and easy to fabricate antennas are preferred, which completely matches with the designed antenna. As shown in the simulation and results sections, the read range goal of 8 meters has been achieved. The read range is maximum when the tag orientation is known and fixed, since the antenna is designed as linear polarized. Antenna gain is nearly the same with the simulated results and input impedance is around acceptable values.

4 MULTIPLEXER

4.1 The importance of Multiplexer in RFID Systems

RFID systems are used almost everywhere, from service supply chain to animal tracking systems. The main purpose of suppliers of RFID network is to increase the read range and the number of tags while keeping the cost minimum.AMR Research Inc.’s , a well known research company, research shows that the majority cost of an RFID system is the equipment costs. Average costs while shipping was 50 M cases per year are listed in Table 4-1. [55] (2005 results)

Table 4-1 Average Cost Dispersal of an RFID System [55]

Tags and readers	$5M to $10 M
System integration	$3M to $5M
Changes to existing supply chain applications	$3M to $5M
Storage and analytics of the large volumes of data	$2M to $3M

The most popular and effective way of increasing the reading zone is using multiple antennas which are located in different locations. Multi antenna in an RFID reader is very important feature to cover a wide RFID tag reading zone. In a multi antenna system, once the particular antenna is activated and populated the tags, the rest must sleep. Thus, any potential interference can be neglected while all the tags have been read in the related area. [53, 55, 56]

In this master thesis, a multiplexer circuit is designed for an RFID system to keep the equipment costs in minimum while increasing the reading zone. It is designed to scan tags sequentially from individual antenna ports.

Designed multiplexer circuit multiplies one port of the reader to two ports. There are two reader ports; one for input, one for output. The multiplexer multiplies each port to two ports.

A multiplexer circuit has been designed by using a special integrated circuit for RFID applications by an engineer under muRFID. [6] Using an integrated circuit increases the costs while making the replacement of components difficult in case of a failure. Another similar design has been presented by Skytek, a well known brand in RFID applications, in recent years. Skytek offers a 4 or 8 antenna port multiplexers. Control of the multiplexer is accomplished by a host processor or a reader module and the control voltage is provided by a CMOS circuit which makes the design complex and expensive. However, it has a narrow insertion loss, approximately 1.4 dB, in the range of 860-960 MHz. [59] In reference [60], another multiplexer for RFID applications is presented. The designed system includes an antenna array and a multiplexer coupled to this array. The antenna selection is controlled by the RFID reader. Since the antenna array and the multiplexer have been mounted on the same substrate, the structure is hard to implement.

This new design presents an innovation to the existing ones in terms of cost, fabrication and component base.

4.2 Multiplexer and its Test Circuit

A multiplexer, or simply a "MUX", is a device that selects an output signal from a number of input signals and is used to increase the data transmission rate by combining one or more data sources in the transmission path. [54] In the simplest multiplexer design, there are two input signals, one control input and one output. In this master thesis, the designed multiplexer multiplexes one reader port to two ports.

A multiplexer circuit is designed for UHF RFID reader. A test circuit is added to the design to control the propagation of the signal. Four identical antennas are used which are connected to the multiplexer ports, while two output ports are connected to the RFID reader. Antenna switch is done, using a PIC circuit. Each antenna rests in reading mode for an estimated time programmed by a PIC16F84A. A reset button is placed for a manual switch. By pressing this switch, the multiplexer switches to the determined antenna determined by the software of the PIC.

A certain time, 1.3ms, is needed to activate the passive tag and extract the information. [53] During this time interval, the multiplexer must wait before switching to the next antenna. Although the estimated time to read a tag for an UHF RFID reader is presented as 1.3ms, 10sec is selected in this master thesis.

4.3 Final Design of the Multiplexer

A multiplexer which multiplexes one UHR RFID antenna port to two ports is designed and fabricated in this master thesis. A driver circuit is designed to select the active antenna and supply the control voltage. The designed multiplexer circuit is connected to the reader port which supplies 866 MHz AC voltage. DC control voltage is coming from the output pins of PIC16F84A which are designed in another PCB. 4 linear antennas are connected to ends of the circuit to receive or transmit signals.

The aim is to obtain maximum isolation and minimum insertion loss. Capacitors behave like open circuit in DC and short circuit in AC when the frequency is increased. Inductors, contrary to the capacitors behavior, behave like open circuit in

AC and short circuit in DC. [58] In the designed multiplexer, in figure 4-2, an inductor, L1, is used to transmit DC voltage to the circuit by connecting between the DC voltage and the pin diode, second inductor, L2, is used to block DC voltage from the output and forward it to the ground. Capacitor, C1, is used as a protector for AC source and it blocks the DC voltage. Pin diodes are used in the multiplexer design due to their switching features. They are suitable for fast switching applications of RF systems. They behave as an almost pure resistance at RF frequencies. Pin diodes have minimized parasitic elements in RF frequencies. [54] In this master thesis, Infineon's BAR 67 series pin diodes are used. The specs of the BAR 67 pin diodes are presented in Table 4-2.

Table 4-2Pin Diode Specs [59]

Package	SOD323
Diode Reverse Voltage	50 V
Forward Current	100 mA
Breakdown Voltage (DC)	50 V (min)
Breakdown Current (DC)	5 µA
Reverse Current (DC)	10 nA
Reverse Voltage (DC)	35 V
Forward Voltage (DC)	0.95 V
Forward Current (DC)	100 mA

The resonant frequency of the design is 866 MHz. A test circuit is integrated to the design to confirm the signal propagation and the power loss. The circuit schematic can be seen in Figure 4-1.

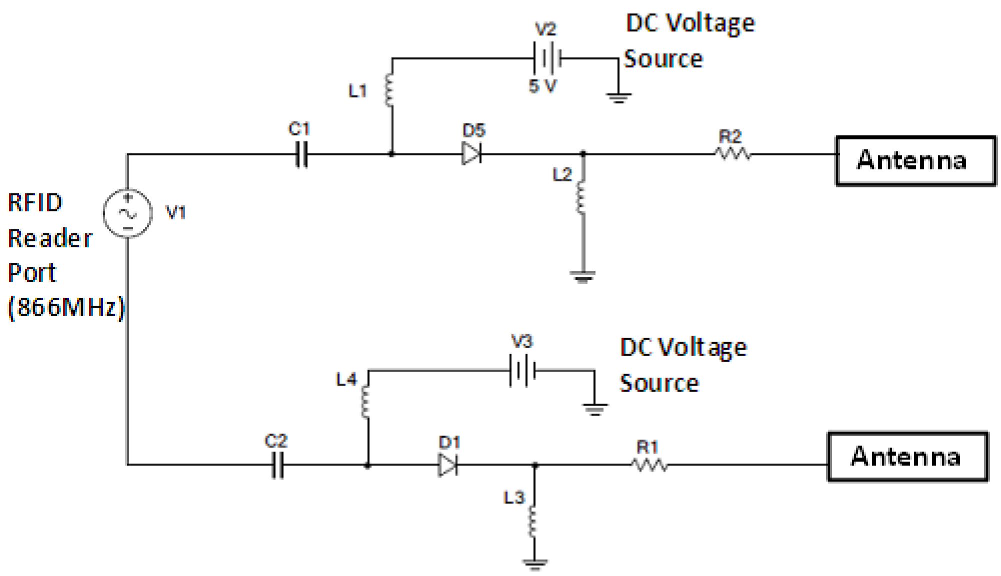


Figure 4-1Schematic of the MUX

The controller circuit and the multiplexer circuit are designed on different PCBs to eliminate the DC interferences. In RF design, line length affects the efficiency of the signal and the efficiency of the signal affects the radiation pattern of the antenna. The PCB designed as two sided, where both sides are covered with ground. Also lots of vias are added to the design to keep the RF signal and root it to the correct way. The fabricated version of the multiplexer can be seen in Figure 4-2.

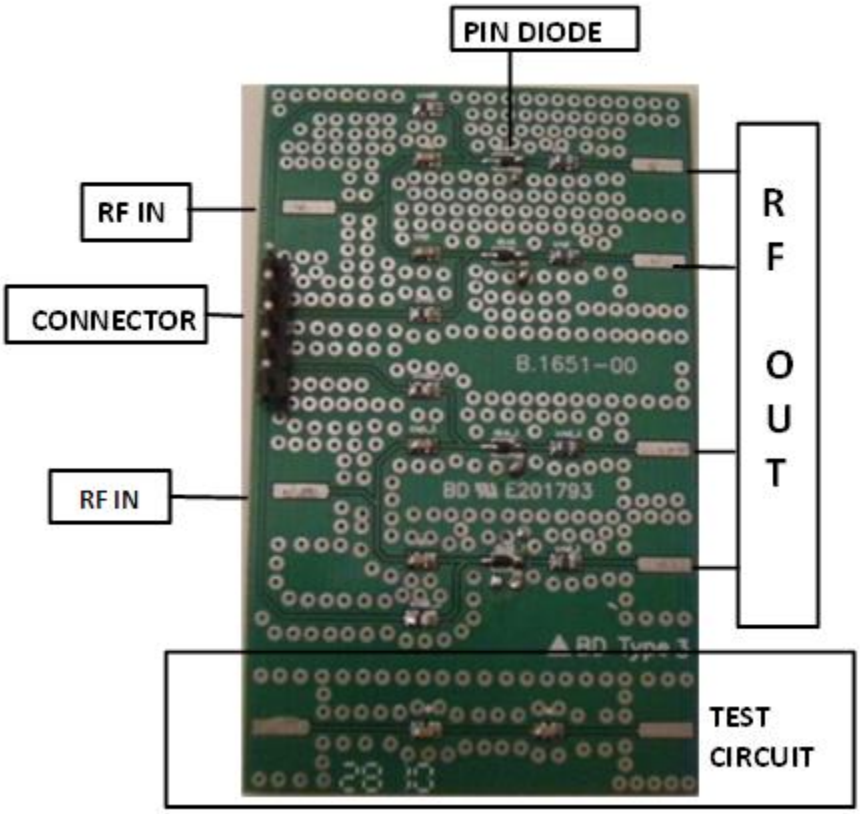


Figure 4-2 Fabricated MUX Circuit

4.4 Controller Circuit

The schematic of the DC controller circuit can be seen in Figure 4-3. This circuit is designed to supply a fixed 5 V to the multiplexer RF part for an estimated time. PIC16F84A is used as the microcontroller which is programmed in C (Program code can be found in Appendix 1). A LM7805 is added to the design to fix the DC voltage to 5V. The schematic of the circuit and the fabricated circuit can be seen in Figure 4-3 and Figure 4-4, respectively.

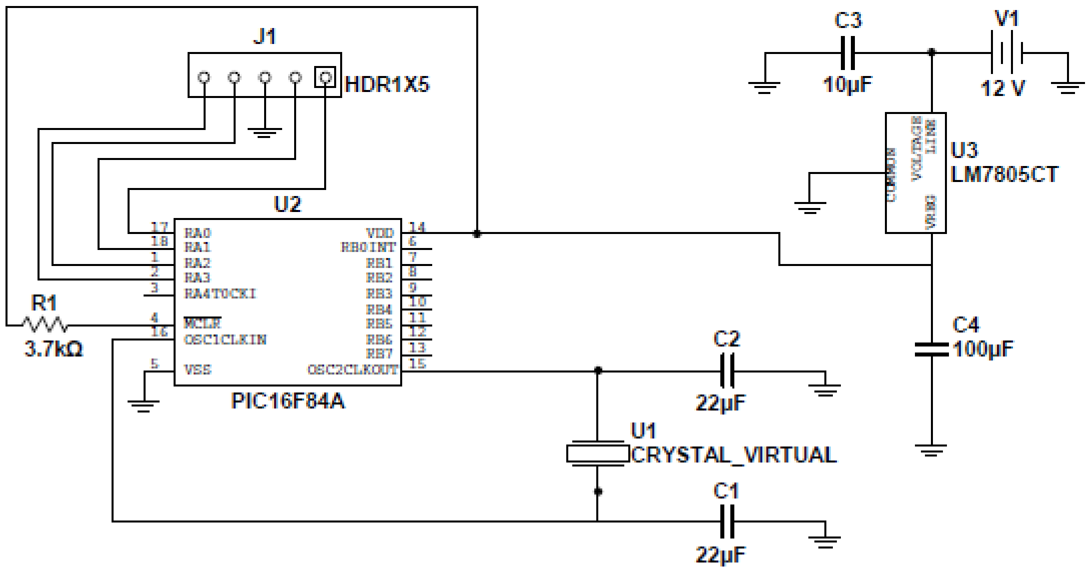


Figure 4-3 Schematic of the Controller Circuit

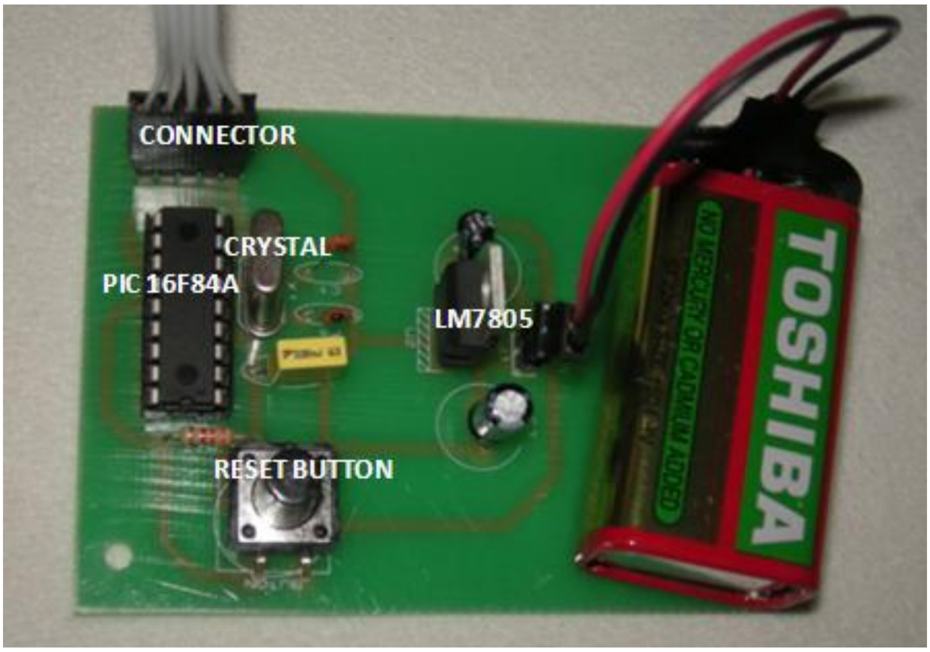


Figure 4-4 Fabricated Controller Circuit

4.5 Simulation Results of the Multiplexer Circuit

Simulation of the circuit is performed on AWR. The aim is to get 866 MHz in the output port of the circuit with a low power loss and measure the input voltage on the pin diode while the related current is flowing on the diode.

The schematic of the multiplexer circuit on AWR with the component values and simulation results can be found in Figures 4-5 and 4-6 respectively.

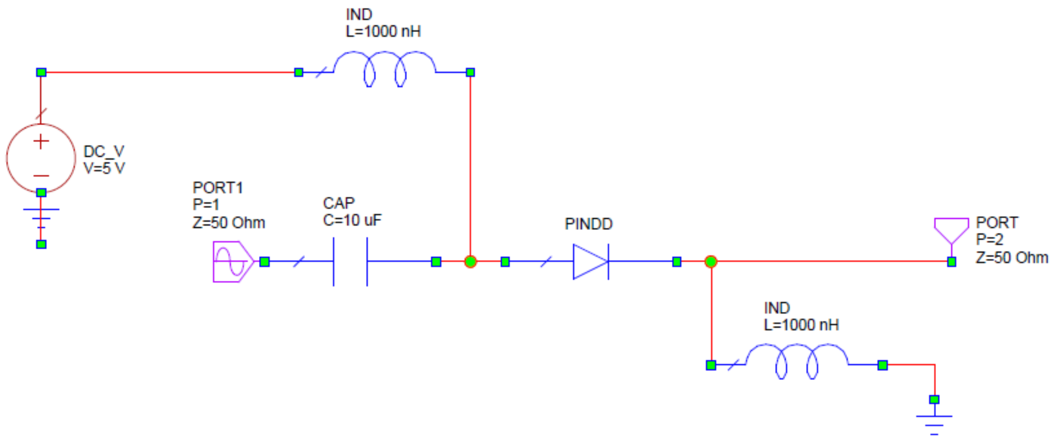


Figure 4-5Schematic of MUX with Component Values

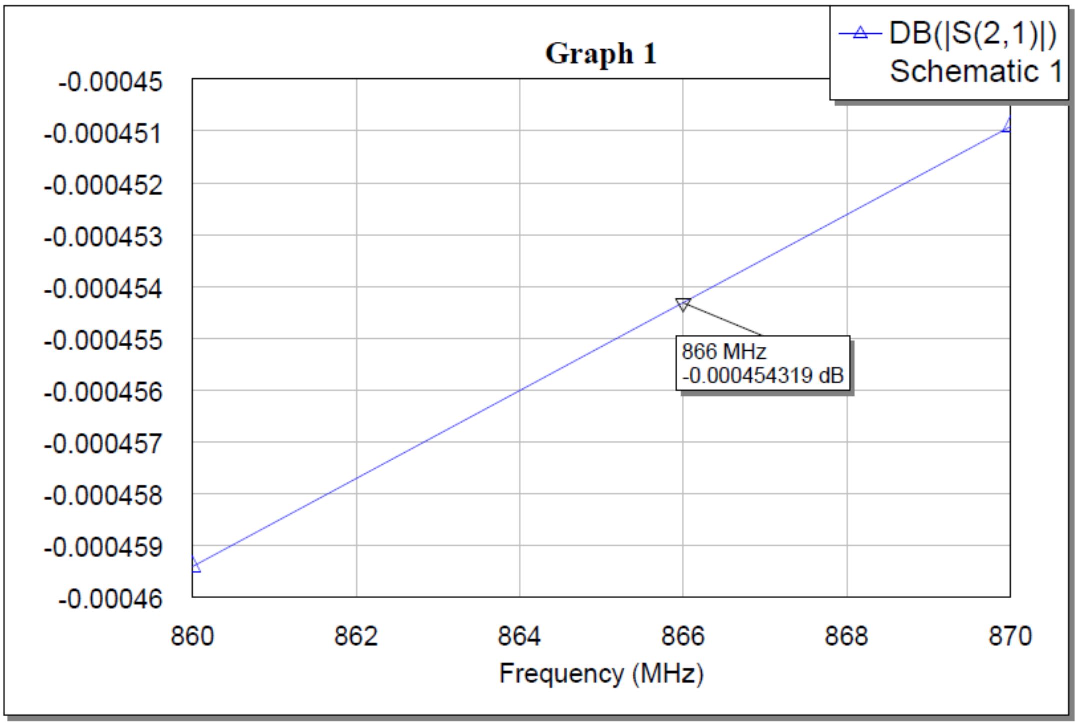


Figure 4-6 S(2,1) Results of the Multiplexer

As seen in Figure 4-6, the insertion loss is almost 0.

4.6 Measured Results of Multiplexer Circuit

The measurements are performed at ITU laboratories by using Network Analyzer. First, the input and output ports of the network analyzer are connected to the test circuit while the Network Analyzer was propagating RF signal at 866 MHz. The set up can be seen in Figure 4-7 and the screen shot of the Network Analyzer can be seen in Figure 4-8.

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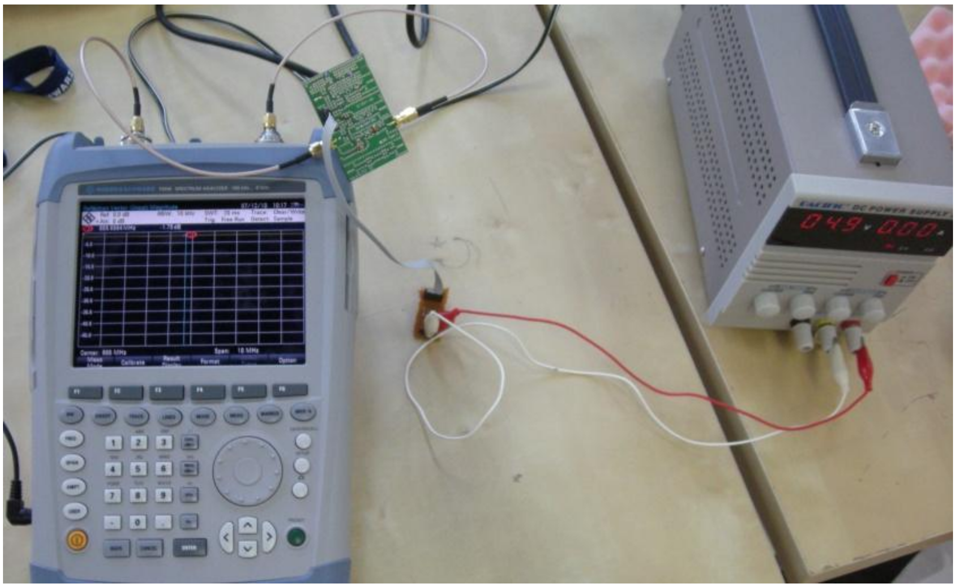

Figure 4-7 Measurement Setup

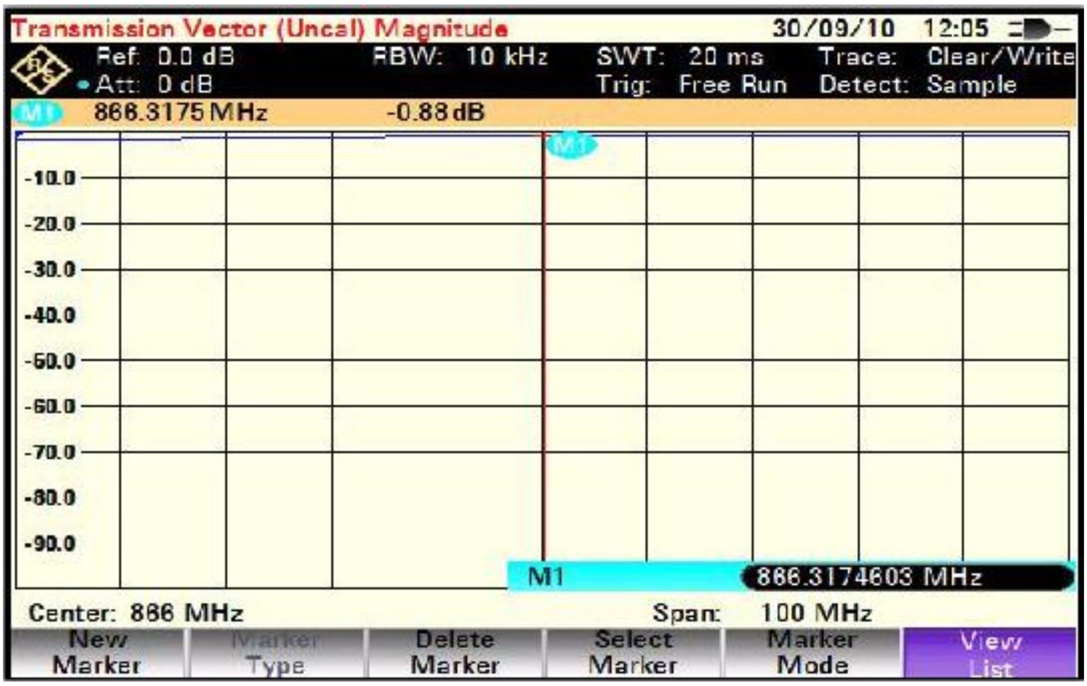

Figure 4-8 Test Circuit Measurement

As seen in the screen shot, the insertion loss is 0.88 dB.

After the propagation of the signal and losses of the antenna connectors are tested, the input and output ports of the Network Analyzer were connected to the multiplexer circuit inputs and outputs. 5 V DC voltage was applied to the DC input port. 1 kΩ resistance was used between the DC voltage source and the multiplexer circuit to protect the pin diode. The measurement setup can be seen in Figure 4-9. 866 MHz signal was propagated from the input port and the power loss was read from the output port at 866 MHZ as well.

The insertion loss was measured as 1.75 dB, the screen shot can be seen in Figure 4-10. This value is greater than the expected value. The losses are due to the insertion losses of the components, RF signal paths, cable loss and medium effects.

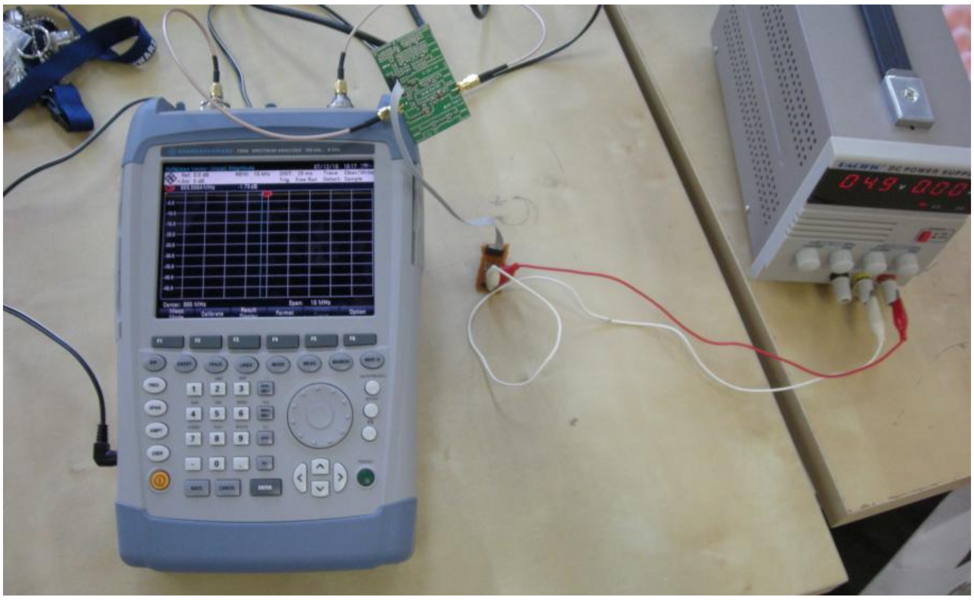

Figure 4-9 Measurement Setup

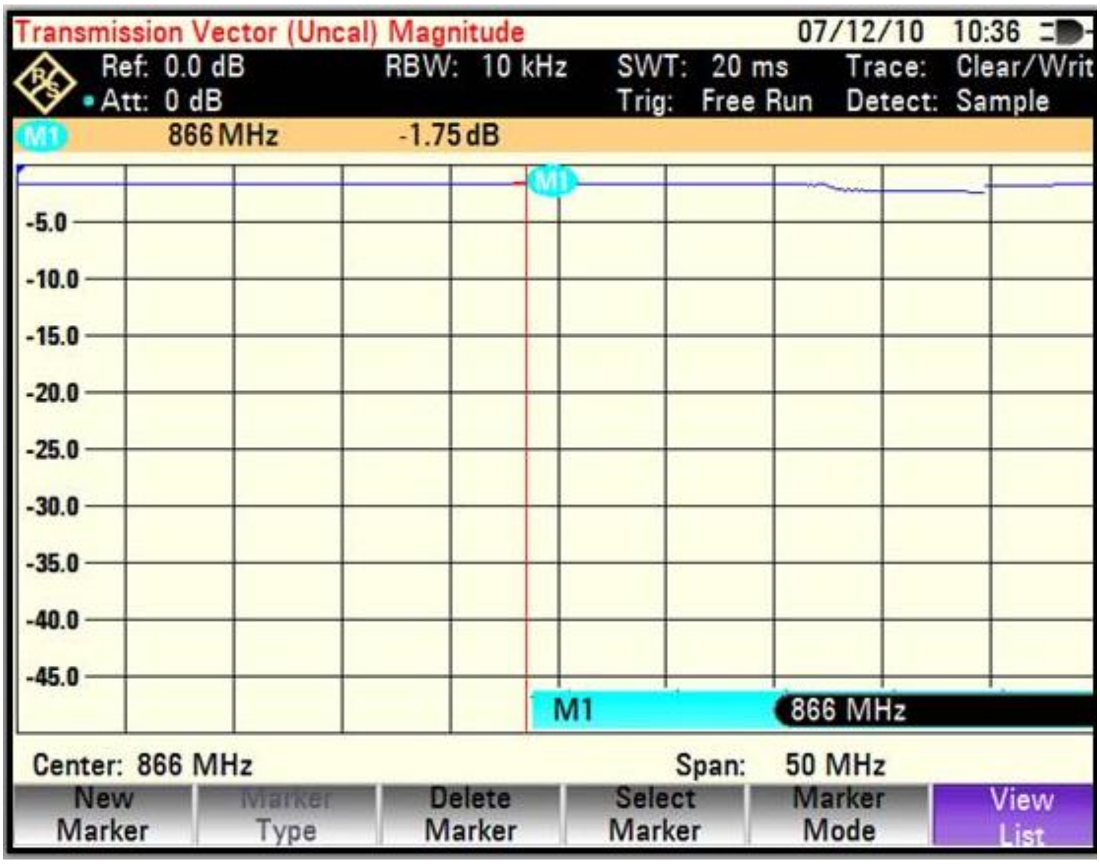

Figure 4-10MUX Measurement Result

4.7 Multiplexer Results

A multiplexer circuit and its controller circuit have been designed for UHF RFID applications in the scope of this master thesis. The designed and measured results are slightly different from each other. These differences are due to the insertion losses of the components, RF signal paths, cable loss and medium effects.

The aim of extending the reading range of an RFID antenna has been achieved while keeping the total system cost in minimum. It is possible to minimize the cost compared to the reading area by connecting multiple antennas to a single RFID reader. The multiplexer circuit consists of pin diodes which are very useful in antenna switching applications. They are very cheap, easy to find and replace. With this approach it is possible to use multiple antennas with single RFID reader which is one of the major costs of an RFID system.

5 CONCLUSION

RFID equipment costs are too high especially for wide reading range applications which requires multiple read-points thus multiple readers. In this master thesis, a linear microstrip patch antenna and a multiplexer with a driver circuit for RFID applications are designed and fabricated working at UHF frequencies which offers cost reduction.

The designed antenna is low cost, low profile and easy to fabricate which is completely matches with the RFID demands. The simulations and measurements of the designed antenna are performed and the results are summarized in Table 5-1.

Table 5-1 Comparasion of the Antenna Results

	Simulated	***Measured***
Input Impedance	$48.79 + j0.14\Omega$	$54.2 + j18.3\Omega$
Return Loss	-38.11 dB	-18.57dB
VSWR	1.025	1.84
Gain	5.9 dBi	5.4 dBi
HPBW	80^o	70^o

The designed antenna has $54.2 + j18.3\Omega$ input impedance, which is almost matched with the reader, narrow bandwidth, enough gain, 5.4 dBi and quite enough read range, 8 meters. The designed antenna has similar operational parameters as the antennas can be found from well known brands and/or presented in the literature. The most important difference of the designed antenna is its cost which is less than 1/10 of them. The aim of decreasing equipment costs has been achieved while the operation parameters keep similar.

The designed multiplexer circuit offers ease integration efforts for RFID applications which require multiple read-points to cover all the tags in the reading zone. Thus, the number of readers can be minimized while supporting multiple read-points. Since the costs of RFID systems are directly proportional to the equipment costs, the costs can be minimized by eliminating the usage of extra RFID readers. The multiplexer circuit consists of pin diodes which are very useful in antenna switching applications. They are very cheap, easy to find and replace in case of a component failure. The antenna read times are controlled by the user through a PIC circuit.

The measurement and simulated results can be seen in Chapter 4, Figures 4-6 and 4-10. The results proved that the designed multiplexer can be used in antenna switching applications. Thus, the cost is minimized compared to the reading area by connecting multiple antennas to a single RFID reader.

As a future work an antenna array can be designed to extend the read range. To increase the gain and directivity, phased array antenna can be build by using the presented patch. For this purpose, array feed network with power dividers can be added and implemented. For the multiplexer part, controller circuit can be designed which has a wireless LAN connection. The reader antenna can be switched from the server or the computer.

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APPENDICES

A.

Code for the controller circuit has been written in C code and compiled to hex code by using PIC C complier. This code determines the reading tine for each antenna.

```
#include <16f84a.h>

#fuses xt,nowdt,noprotect

#use delay(clock=4000000)

#use fast_io(a)

void main ()

{

set_tris_a(0x00);

output_a(0x00);

basla:

delay_ms(10);

output_high(pin_a0);

delay_ms(10);

output_low(pin_a0);

delay_ms(10);

output_high(pin_a1);

delay_ms(10);

output_low(pin_a1);

delay_ms(10);

output_high(pin_a2);

delay_ms(10);

output_low(pin_a2);

delay_ms(10);

output_high(pin_a3);
```

```
delay_ms(10);
output_low(pin_a3);
goto basla;
}
```

ÖZGEÇMİŞ

1984 yılında Balıkesir'de doğmuştur. 2007 yılı Gebze Yüksek Teknolojisi Enstitüsü Elektronik Mühendisliği mezunudur. 2008 yılından bu yana telekom sektöründe çalışmaktadır.