YAŞAR UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER’S THESIS

± 45° DUAL POLARIZED BASE STATION ANTENNA ENHANCED WITH PARASITIC ELEMENTS

ORHAN MURAT KADAĞAN

THESIS ADVISOR: ASSOC. PROF. DR. MUSTAFA SEÇMEN

ELECTRICAL AND ELECTRONICS ENGINEERING

PRESENTATION DATE: 28.08.2018

BORNOVA / İZMİR
AUGUST 2018

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Jury Members:	**Signature:**
Assoc. Prof. Dr. Mustafa SEÇMEN (Supervisor) Yaşar University	....
Asst. Prof. Dr. Nalan ÖZKURT Yaşar University	....
Prof. Dr. Korkut YEĞİN Ege University	....

Prof. Dr. Cüneyt GÜZELİŞ

Director of the Graduate School

ABSTRACT

± 45° DUAL POLARIZED BASE STATION ANTENNA ENHANCED WITH PARASITIC ELEMENTS

KADAĞAN, Orhan Murat
M.Sc., Electrical and Electronics Engineering
Advisor: Assoc. Prof. Dr. Mustafa SEÇMEN
August 2018

This thesis is related with the design of a ± 45° dual polarized base station antenna with improved cross-polarization discrimination (XPD) values. Parasitic elements are added to antenna design formed by orthogonal two compact meandered dipole above ground plane. The antenna designed with CST Microwave Studio program has VSWR ≤ 2 within 1.71-2.69 GHz frequency band, which covers GSM 1800/3G/LTE bands. The antenna has minimum of 0 dBi gain in the beamwidth of 120° (± 60°) at azimuth plane (ϕ = 0°) along the band, and XPD values being minimum of 2 dB at 1.71-2.4 GHz for ± 60° without parasitic elements are improved to 10 dB with parasitic elements. This design initially had two horizontal straight monopoles on the ground plane perpendicular to each other. Afterwards, antenna with microstrip balun feed applied but the XPD values were not appropriate to expected results. Because of that, by using image theory, vertical parasitic elements were added to get appropriate XPD values. Later, meandered structure used to make antenna smaller. Finally, according to base station applications, antenna frequencies optimized to 1.71 GHz and 2.69 GHz. The designed and optimized antenna produced and measured in laboratory environment. Return losses for port 1 and port 2 are measured above the 10 dB and isolation between the port 1 and port 2 are measured above the 20 dB. In addition, the maximum gain values are measured between 3 dB and 7 dB in 1.71 GHz and 2.69 GHz frequency band. Finally, XPD values are measured more than 10 dB in bandwidth.

Key Words: Base Station Antenna, Dual-Polarized Antenna, Cross-Polarization discrimination, XPD, Base Station, GSM

ÖZ

PARASİTİK ELEMANLAR İLE GELİŞTİRİLMİŞ ± 45° ÇİFT POLARİZELİ BAZ İSTASYONU ANTENİ

KADAĞAN, Orhan Murat
Yüksek Lisans, Elektrik Elektronik Mühendisliği
Danışman: Doç. Dr. Mustafa SEÇMEN
Ağustos 2018

Bu tez, çapraz polarizasyon ayrım (ÇPA) değerleri artırılmış bir ± 45° çift polarize baz istasyonu anteninin tasarımı ile ilgilidir. Toprak düzlem üzerinde birbirine dik konmuş iki kompakt kıvrımlı dipolden oluşan anten tasarımına dikey parazitik elemanlar eklenmiştir. CST Microwave Studio programı ile tasarlanan anten, GSM 1800/3G/LTE bantlarını kapsayacak şekilde 1.71-2.69 GHz frekans aralığında VSWR ≤ 2 değerlerine sahiptir. Azimut düzleminde (ϕ = 0°) bant boyunca 120° açı hüzmesinde (± 60°) en az 0 dBi kazancı bulunan antenin, 1.71-2.4 GHz frekans bandında ± 60° için parazitik elemanlar olmadan en az 2 dB olan ÇPA değerleri parazitik elemanlar ile 10 dB seviyelerine çıkarılmıştır. Antenin ilk tasarımı, toprak düzlem üzerinde birbirine dik iki yatay düz dipol anten şeklindedir. Bu anten, önce mikrostrip balun ile beslenmiştir, ancak ÇPA değerleri beklenen sonuçlara ulaşmadığından görüntü teorisi kullanılarak, dikey parazit elementler eklenmiştir. Daha sonra, meander dipol yapısı anteni küçültmek için uygulanmıştır. Son olarak, baz istasyonu uygulamalarına göre, anten frekansları 1.71 GHz ve 2.69 GHz'e optimize edilmiştir. Tasarlanan ve optimize edilen anten laboratuvar ortamında üretilmiş ve ölçülmüştür. Port 1 ve Port 2 için geri yansıma kayıpları 10 dB 'den fazladır ve portlar arası izolasyon değerleri 20 dB'den fazla ölçülmüştür. Ayrıca, maksimum kazanç değerleri band boyunca 3 ile 7 dB arasında ölçülmüştür. Son olarak antenin ÇPA değerleri band boyunca en az 10 dB ölçülmüştür.

Anahtar Kelimeler: Baz İstasyonu Anteni, Çift-Polarize Anten, Çapraz Polarizasyon Ayrımı (ÇPA), Base Station, GSM

ACKNOWLEDGEMENTS

I take this opportunity to express gratitude to all of the Electrical and Electronics Engineering Department members for their help and support.

Also, I am grateful to my advisor Assoc. Prof. Dr. Mustafa SEÇMEN for the continuous encouragement, sharing expertise and attention. Additionally, his guidance helped me in research, experimental practice and writing of this thesis.

I would also like to thank Asst. Prof. Dr. Nalan ÖZKURT and Prof. Dr. Korkut YEĞİN for the contribution to the evaluation of this thesis.

Finally, I would like to express my enduring love to my family and my wife, who are always devoted and supportive to me in my life.

Orhan Murat KADAĞAN
İzmir, 2018

TEXT OF OATH

I declare and honestly confirm that my study, titled "± 45° DUAL POLARIZED BASE STATION ANTENNA ENHANCED WITH PARASITIC ELEMENTS" and presented as a Master's Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Orhan Murat KADAĞAN

Signature

……………………………………..

September 25, 2018

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS:

GSM	Global System for Mobile communication
TDMA	Time Division Multiple Access
SIM	Subscriber Identity Module
HSCSD	High-Speed Circuit-Switched Data
GPRS	General Packet Radio System
EDGE	Enhanced Data GSM Environment
UMTS	Universal Mobile Telecommunications Service
BS	Base Station
BTS	Base Transceiver Station
BSC	Base Station Controller
TC	Transcoder
LTE	Long Time Evolution
MSC	Mobile Switching Center
PSTN	Public Switched Telephone Network
OMS	Operational Maintenance System
WCDMA	Wideband Code Division Multiple Access
LAN	Local Area Networks
LTE	Long Term Evolution
VSWR	Voltage Standing Wave Ratio
XPD	Cross Polar Discrimination
XPIC	Cross Polar Interference Cancellers

CHAPTER ONE
INTRODUCTION

1.1 Evolution of Communication

Communication is a system to communicate each other creatures and transmit their various feelings and thoughts to each other. Communication has always existed since the first time that the date has existed. Since people are needed the transfer of feelings and thoughts, various types of communication have been used for these necessity.

When we say communication, people understand that as communicating of people with each other but it is a false brief. Because it is known that, all creatures and even electronic devices are communicating with each other.

Throughout the history, many communication techniques have been used even smoke or pipe sound or pigeon have used a long time ago. Each day, communication techniques are varied with the developed technology.

The communication techniques, which are indispensable together with telegraph, telephone and Internet have reached to the top with wireless and whatever the case may be, communication is a necessity for people and will always continue to develop and to exist.

1.1.1 Mobil Communication

Mobile communication is known as talking, texting or sending data or image files over a wireless network. It is simply based on wireless communication. Wireless communication usually uses electromagnetic signals, which are produced by an enabled device with the air, physical environment or atmosphere ways. This enabled device can be sender or intermediate device, which is able to propagate wireless signals. The communication occurs when the signals transmitted and received between two device and wireless connection created.

Wireless communication has different types, technology and methods such as:

- Wireless communication
- Mobile communication
- Satellite communication
- Bluetooth communication
- Infrared communication

Theses communication technologies have different architecture; but, they do not have physical or wire connection to start or execute communication. In this thesis, mobile communication is focused on.

1.1.2 Global System for Mobile Communication (GSM)

GSM (Global System for Mobile communication) is a digital mobile telecommunication system that is using all around the world in these days. GSM technology is a variety of time division multiple access (TDMA) and is the commonly used of wireless technologies are given as GSM, TDMA and CDMA. GSM technology converts data signals to digital and compress after data signals are transmitted to the communication channel.

First mobile communication services were started in Finland in 1991 with the GSM technology. In these days, GSM services are using 213 countries with 690 service providers. Besides, 82.4% of total communication is supplied with GSM communications in world. In worldwide, more than two billion people are using mobile phone according to the record of GSM World. And, the mobile phone users record for the countries are given like; in China more than 370 million users, after that Russia with 145 million, India with 83 million and the USA with 78 million users.

Mobile phone users are generally can use their mobile phones when they travel because many GSM operators have agreement with each other. SIM cards (Subscriber Identity Module) using to access network configurations and identify the subscriber who has the mobile phone.

High-Speed Circuit-Switched Data (HSCSD), General Packet Radio System (GPRS), Enhanced Data GSM Environment (EDGE), and Universal Mobile Telecommunications Service (UMTS) are included to the GSM technologies and they are all the part of wireless communication.

At the beginning, GSM signals operate either at 900 MHz or 1800 MHz frequency band. However, currently, it is widely used between 1700 – 2700 MHz frequency bands with the 4G technology as shown in Table 1.1.

Table 1.1: Frequency Bands of GSM (Anatel, 2017)

Technology	Frequency Band	Uplink	Downlink
GSM 900	900 MHz	898-915 MHz	943-960 MHz
GSM 1800	1800 MHz	1710-1785 MHz	1805-1880 MHz
3G	2100 MHz	1920-1975 MHz	2210-2165 MHz
4G/LTE	2600 MHz	2500-2570 MHz	2620-2690 MHz

To transmit and receive wireless signal from mobile phone to other mobile phone, antennas must be used. Antennas are the devices that transmit and receive electromagnetic signal.

In GSM technology, base stations are used. They transmit and receive GSM signals with their electronic equipment and their antennas.

1.1.3 Cellular Network

Cellular network is a radio network occurred by several radio cells or just a cell each served by a fixed transmitter, known as base station. These cells are used to cover different areas in order to provide radio coverage over a wider area then the area of one cell. They are asymmetric with a set of fixed transceivers each serving a cell and a set of distributed transceivers, which supply service to the users. It has advantages like increased capacity, reduced power and better coverage.

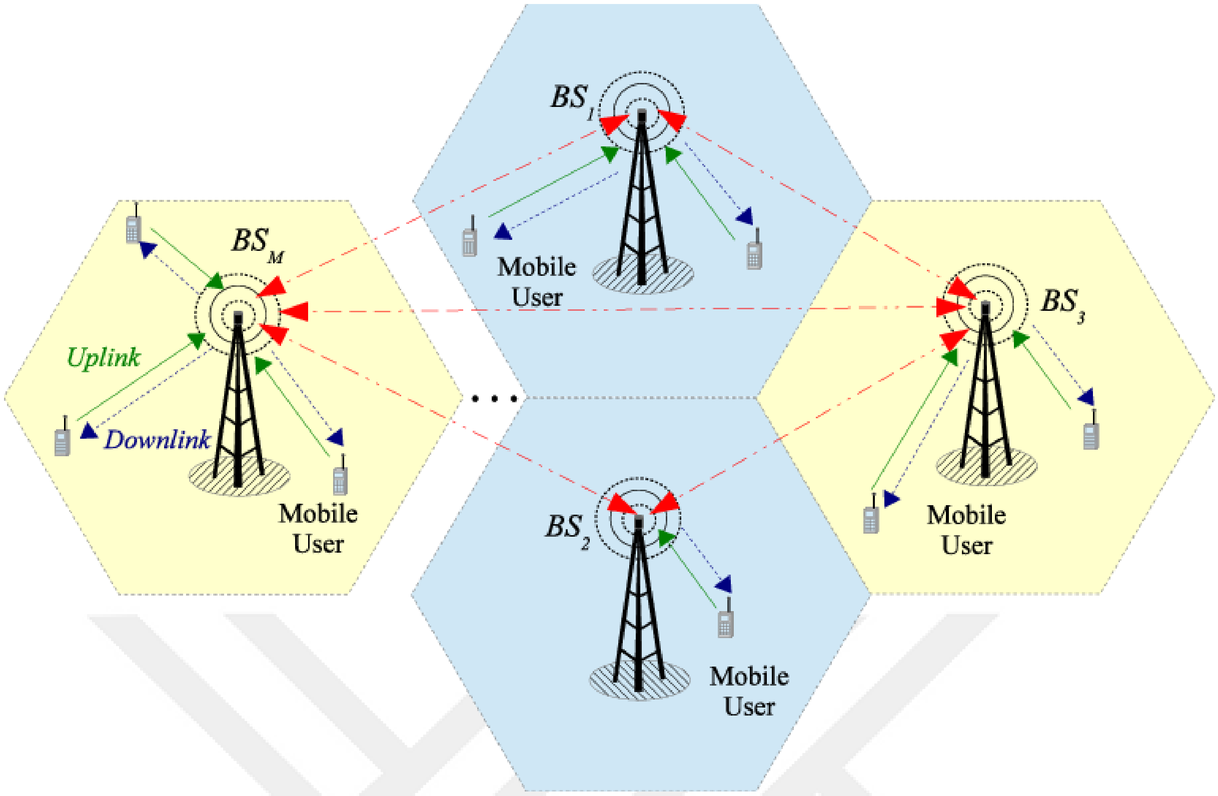


Figure 1.1: Diagram of Cellular Communication (Delgado, Rivera, Rojas, Gutierrez, 2017)

Base Transceiver Station (BTS), Mobile Switching Center (MSC), location register and Public Switched Telephone Network (PSTN) forms the hierarchical structure, which is supported by cellular network technology. Cellular devices are directly communicating with mobile phones with the help of BTS. The call routings are realized by transforming BTS unit to the Base Station Controller (BSC). Visitor Location Register (VLR) and Home Location Register (HLR) routings for the calls toward from different base center controllers are coordinating by Base Station Controller (BSC).

1.1.3.1 Cell Coverage

The environment and the output power of base station determine the cell coverage area. Buildings, trees or land formation can affect coverage area. There are generally many users and obstructions in city areas. Therefore, in order to compensate the coverage demand, there should be many base stations in the 2-5 km radius.

For several countries, which have large open space, the cell radius becomes 10-32 km for the base stations. Moreover, 80-200 km radius could be reachable with the extender cell technology. The cell coverage area is depicted in Figure 1.2.

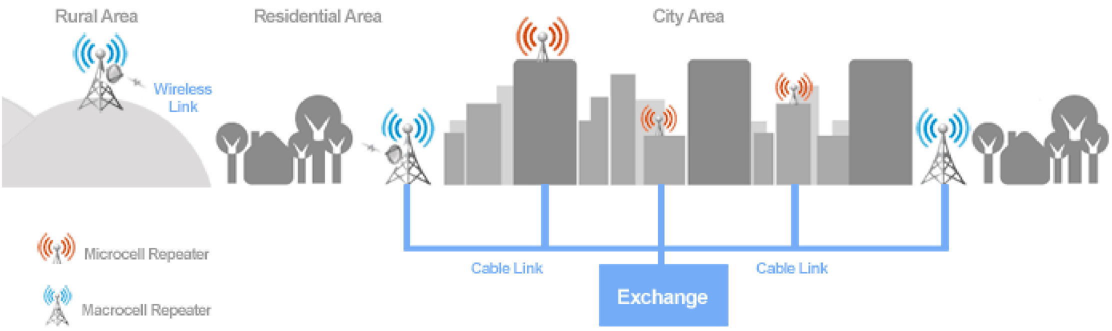


Figure 1.2: Cell Coverage (Mobilenet, 2017)

1.1.4 Base Station

A base station is a fixed communications location and is part of a network's wireless telephone system. It relays information to and from a transmitting/receiving unit, such as a mobile phone. Often referred to as a cell site, a base station allows mobile phones to work within a local area, as long as it is linked to a mobile or wireless service provider.

Figure 1.3: Base Station (CommsMEA, 2015)

Base stations send and receive radio signals and they are forming the cell area.

There are several part included to the typical cell tower such as;

- **The antennas**: Radio signals are transmitting and receiving in here.
- **The tower**: This can be a building or tower and it carries the antenna.
- **Hardware**: It is responsible for the operations of base stations and it is called BTS (Base Transceiver Station).
- **A link:** The medium for the communication signals flow and it could be wire or wireless connection.

1.1.4.1 Base Station Structure

There are three fundamental hardware systems in a base station. These are;

- Base Transceiver Station (BTS)
- Base Station Controller (BSC)
- Transcoder (TC)

Some of these systems are located in the cabins, which are separated under the base stations or in the antenna part, and some of them are located out of the cabins. Generally, remarkable equipment is located out of cabins. Base stations are usually found in cage-type towers, metal posts, either in the roof of the building or in various forms of camouflaged structures. Some sample base stations can be seen in Figure 1.4 and Figure 1.5.

Figure 1.4: Cage and Post Base Stations (F-Blog, 2012)

Figure 1.5: Base Station on Roof (Alamy, 2010)

Camouflaged base stations can be found in a variety of forms such that there are some base stations, which look like trees. Therefore, they may not be detected in the forest region though. Besides, they can be found as chimneys in the roof of the building. The antennas can be wall mounted, painted in the same color as the wall and even in wall patterns. One of the important parts of the base station is the antennas. They are using to transmit and to receive signals. Base station antennas are going to explain at the next parts in detail.

Cabins are places where the cables from all the antennas in the base station are collected as given in Figure 1.6. Inside the cabins, there are separate circuits for every incoming signal from antennas also BTS, BSC and transcoder systems are in there. Base Transceiver Station (BTS) has different and variable tasks. They manage the radio frequency and make the necessary radio channel allocations to talk and start talking. RF modulation for incoming and outgoing signals from antennas, channel coding, blending and ciphering operations are performed here.

Base Station Controller (BSC) is the intelligent management part of the base station system. The BSC may control more than one BTS under its command. The task is to connect transcoder and Operational Maintenance System (OMC) with BTS and perform radio frequency assignment and frequency management. The Transcoder (TC) transforms between the data transmission format used in GSM and the transmission formats used in other telecommunication systems.

Figure 1.6: Base Station Cabins (KUARK, 2013)

1.1.4.2 Capacity of Base Station

In base stations, the number of calls at one time is limited. For the standard base station, there are 168 voice channel and these channels could be reached to the top with in base station range. In addition, the base station has limited bandwidth available for the data and internet used.

With the smart phones technology, the channels and bandwidth are increased and base stations start to provide fast internet with in the pick periods.

When the bandwidth of channel becomes wider, the wider data could send. For example, in Australia, standard channel bandwidths are using by the carriers as 10 MHz or 15 MHz and Vodafone is planning to use 20 MHz for the 4G bandwidths.

1.1.4.3 Types of Base Station

According to their abilities and using area, there are several types of base station. These types and logic are given in Table 1.2, Figure 1.7 and Figure 1.8 in details.

Table 1.2: Types of Base Station (Mobilenetworkguide, 2017)

Base Station Type	Typical Coverage Radius	Typical Use
Femtocell	10m	home or office use
Domestic Repeater	100m	home, office or factory use
Picocell	200m	high rise building, hotel or car park use
Microcell	1-2km	shopping centers, transport hubs, mine sites, city block, temporary events or natural disasters.
Macrocell	5-32km	suburban, city and rural use
Macrocell - Extended Reach	50-150km using extender cell technology	suburban and rural use

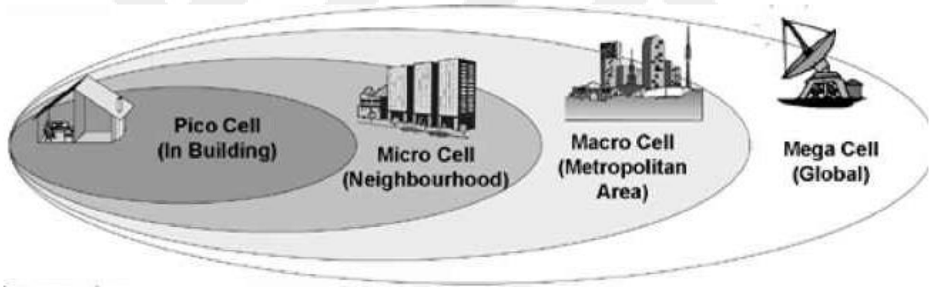


Figure 1.7: Logic of Base Station Types (Fishercom, 2017)

<u>Femtocell:</u>

Femtocell is a base station that runs on the licensed frequency of a low-powered mobile operator and connects the mobile phone user via the DSL to the mobile operator's core network. A typical household femtocell has an operating radius of about 10 meter.

<u>Domestic Repeater:</u>

Domestic Repeater is a device that increases the signal level of the base station, in other words, extends the coverage area of the base station. It has almost 100 meters coverage radius.

Picocell:

Picocell is a small base station that is an alternative solution to a repeater or distributed antenna system. It is using in buildings or the areas that network does not reached to extend wireless services. The local ranges of the picocells are about 200 meters.

Microcell:

Microcells are working like small cell towers that supply mobile connectivity to the internet enabled devices such as smartphones, tablets or laptops. Microcells has some advantages like, small size, require less maintenance and cheaper. They are generally using for network expanding applications. In addition, they have coverage radius between 5 and 35 km.

Macrocell –Extended Reach:

This technology occurred with the development of Macrocell. With this technology coverage area extended nearly to the 150 kilometers. It is using in the global communication with 4G and LTE technologies.

Figure 1.8: a) Alcatel-Lucent 9360 Femtocell (Alcatel-Lucent, 2014),
b) Panasonic Domestic Repeater (LIGO, 2018),
c) Huawei Picocell (Huawei, 2018),
d) AT&T Microcell (ATT, 2018)

1.1.4.4 Base Station Antenna

Base stations are transmitting and receiving radio signal with their antennas; therefore, base stations have towers to carry antennas. Panel antennas are using for communication with mobile phones in base stations. These antennas have certain angles and they only transmit or receive a signal from these angles. These panels direct the signal of the smaller antennas which is inside of it but the signal is directed only the direction that the panel is looking. The base station also has a number of panels depending on the angle, each of which looks in different directions. For example, three antennas each having 120 degrees beamwidth are used to achieve a 360-degree coverage and each is directed in different directions.

Panel antennas provide coverage with less power than multifaceted antennas and can be serviced three times more. In time, panel antennas developed and become dual band antenna. Dual band panel antennas are panel antennas that can broadcast two different frequencies in completely different ways. The small antennas inside the panels have different connections, or if their frequencies are different, their dimensions are also different. It is also useful for 2G or 3G GSM systems. You can see the picture of dual band panel antenna in Figure 1.9.

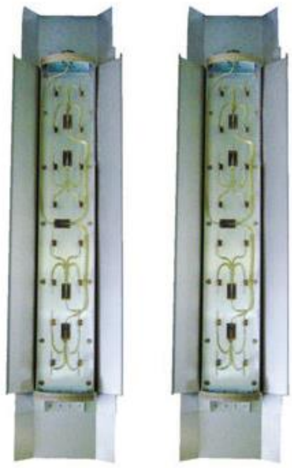


Figure 1.9: Dual Band Panel Antenna (Global, 2017)

1.2 Aim of Research and Literature Search

Nowadays, base stations become more important in digital communication depending to development of GSM Technologies. For this reason, base stations are getting better to supply clean communication signals and better cell coverage. Furthermore, reducing the size of base station becomes necessary with the new technologies and image pollution for the esthetics of cities.

In base stations, signals are transmitted and received with antennas. As understood, base station antenna is the most important part in base station. Thus, base station antennas are always remarkable for researchers and technology developers. In research, improving signal quality becomes a main topic and multipath propagation effect is fundamental issue for this topic.

According to their advantages and better attributes, polarization diversity techniques have been generally used in modern mobile communication systems. ±45º dual-polarized base station antennas are generally applied to unaffected multipath propagation effects and to improve signal reception quality. In these applications, Cross - Polarization Discrimination (XPD) parameter between two antennas is most important part for that system.

It is also important to reduce the dimensions of the base station antenna in new BSA system production. In the 90's, manufacturers are focused on designing flat panel antennas based on microstrip patches. After that, it is proved reducing the number of antenna is a good solution for BSA system size therefore dual-polarized antennas are designed for diversity.

This value is practically lower and drops quickly when a narrow frequency band around the center frequency exceeded. In the literature, there are ± 45 ° dual polarization antennas in different types of base stations (dipole, patch, slit etc.) (Kaboli, Abrishamian, Mirtaheri, Aboutorab, 2012), (Secmen, Hizal, 2010A), (Secmen, Hizal, 2010B)(İsenlik,Bilgiç,Yeğin,Çiydem,2011). In this studies, the frequency bands are narrow than 1.7 GHz and 2.7 GHz also bigger structures are designed for polarization besides in the majority of these studies only boresight XPD values in the frequency band are given and only a small number of studies (Oh, Lim, Chae, Lee, 2015).

Taking the above disadvantages into consideration, the aim of this study was to make a dual polarized antenna with broadband, high XPD, easy to manufacture and compact as possible. The aim of this project is to design and produce of ± 45° dual polarized base station antenna with improved cross-polarization discrimination (XPD) values. XPD values will be improved by adding vertical parasitic elements and the structure become smaller and compact with the help of meandered dipole.

The aims in terms of the specifications of the project are given;

- To have a VSWR ≤ 2,
- To have a wide frequency band within 1.71-2.69 GHz,
- To cover GSM 1800/3G/UMTS bands,

Also this designed antenna provide a lot of advantages for signal quality like, the antenna has minimum of 0 dBi gain in the beamwidth of 120° (± 60°) at azimuth plane (ϕ = 0°) along the band, and XPD values being minimum of 2 dB at 1.71-2.4 GHz for ± 60° without parasitic elements are improved to 10 dB with parasitic elements.

1.3 Outline of Thesis

In Chapter 1, a review of evolution in the parallel development of mobile communication systems, base stations and base station antennas are given with their examples and varieties.

In Chapter 2, important definitions are given also signal quality factors are given for base station and base station antennas.

In Chapter 3, expected antenna parameters are explained and antenna design, their structure and production methods are mentioned.

In Chapter 4, results are given in different forms such as, simulation results and measurement results. Also, these result forms are compared with each other in this part.

In Chapter 5, conclusion of thesis is mentioned in this part.

CHAPTER TWO
THE FUNDAMENTAL CONCEPTS FOR MOBILE COMMUNICATION WITH BASE STATION ANTENNAS

2.1 Radio Wave Propagation

Sending information from one location to another by using a transmitter at the origin and one or more receivers at destination points is the main goal of the radio services. The wireless connection provided with the transmitting antenna, propagation medium (free space, atmosphere), and receiving antenna. Radio waves or electromagnetic radiation propagates between the transmitting antenna and the receiving antenna by using propagation medium. The fundamental propagation medium is accepted as the earth's atmosphere (ionosphere and troposphere).

Radio signals propagate on free space at the speed of light (299792458 meters/second). Wavelength represent the distance, which is the RF signal travels during the period of one cycle. Because of that, wavelength = c/f, where c is velocity of electromagnetic waves expressed in meters per second and f is frequency expressed in cycles per second. As an example, a frequency of 1575.42 MHz will have a wavelength of almost 19 cm and the frequency of 1 MHz will have a wavelength of nearly 300 meters. Wavelength is an important parameter in signal propagation and reflection characteristics.

Sometimes the RF signal encounters with objects and the signal could reflect, refract, diffract or interfere. When the signal is reflected from an object, multiple wavefronts are occurred. As a result, some of these multiple wavefronts can reach the receiver. The multipath reflections are going to be mentioned in later (in Section 2.1.1).

By considering this fact, signal quality can be handled as an important issue for radiowave propagation. Thus, multipath effect causes reducing the quality of signals as mentioned before. There are some techniques against multipath effect and it is going to be mentioned in following parts.

2.1.1 Multipath Reflection

When the radio signal selects different way from source to a destination, multipath propagation occurs. In this situation, some parts of the signal goes to the destination while another part bounces off an obstruction, then goes on to the destination. As a result, some parts of the signal delay and travel a longer than others to the destination. Thus, signal quality distortions because of these effects.

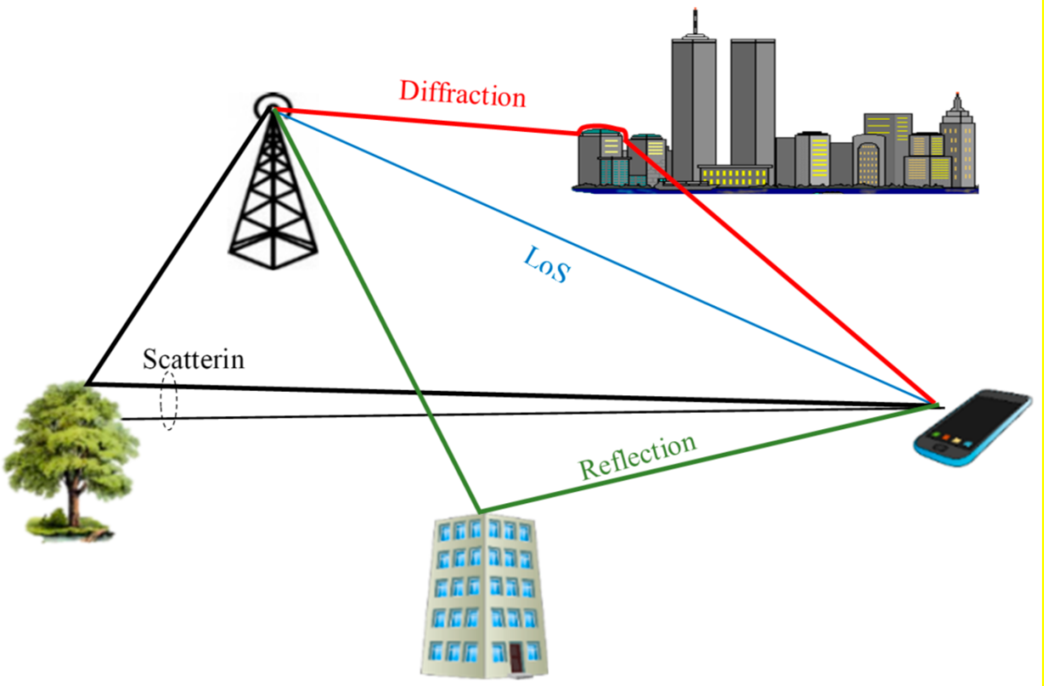


Figure 2.1: Multipath Reflection (Al-Barrak, Al-Sherbaz, Kanakis, Crockett, 2017)

Multipath distortion is a variety of RF interference that occurs when the radio signals have more than one path between the receiver and the transmitter. This occurs in cells with metallic or other RF-reflective surfaces, such as furniture, walls, buildings, trees or coated glass.

Multipath distortion cause to:

- Signal Nulling
- Data Corruption
- Increased Signal Amplitude

- Decreased Signal Amplitude

Reducing to these multipath effect, there are some hardware solutions such as;

- Antenna Site Selection
- Antenna Design
- Antenna Ground Plane

2.1.2. Diversity

Diversity explained as the use of two antennas for each radio, to increase the receiving a better signal on either of the antennas. The antennas supply a diversity solution this could be in the same physical housing or must be two separate but it must be equal antennas in the same location. Diversity gives solutions to a wireless network in a multipath scenario.

Physically separated diversity antennas are using for the radio and each other, to ensure that one encounters less multipath propagation effects than the other.

The cell coverage enhanced with diversity antennas but coverage range of a cell does not extended. The enhanced coverage is an effort to overcome issues that multipath distortion and signal nulls. Use of two antennas on an access point to cover two different cells can result in connectivity issues.

Diversity antennas solve the problem that two antennas in the same physical housing, there are two receiving and transmitting elements in that type of antenna.

In addition, there is a term for the diversity performance that is diversity gain. The diversity gain is expressed as how much the transmission power of the diversity-dependent-parasite ratio can be reduced by a performance loss.

2.1.2.1 Diversity Techniques

2.1.2.1.1 Space Diversity

In wireless systems, space diversity is the most popular diversity technique. It is also known as antenna diversity. The signal path between receiver and transmitter is not stable and the possibility of a number of scatters in the mobile environment suggests a Rayleigh fading signal (small-scale fading) for this technique. For the base station systems, when the multiple signals from base station antenna received on the mobile phones, with the help of space diversity technique, best signal is selected.

2.1.2.1.2 Time Diversity

In this technique, signals represent the same information that is send over the same channel at different times. Time Diversity repeats to transmit information at time spacing of the channel. Diversity is providing with multiple repetitions of the signal is received with multiple fading conditions.

2.1.2.1.3 Frequency Diversity

The same information signal is transmits and receive simultaneously on two or more independent carrier frequencies and that is the principle for that technique. Behind this technique, there is a way that frequencies separated by more than the coherence bandwidth of the channel will not experience the same fade. The probability of simultaneous fade will be the product of the individual fading probabilities. This technique requires that there are many receivers and there are channels used for the frequency diversity. Although for critical traffic, the expense may be justified.

2.1.2.1.4 Polarization Diversity

Polarization diversity provides the decorrelation of the two receive ports to diversity gain. Receiver ports must be cross-polarized.

The comparatively high cost of using space diversity at the base station prompts the consideration of using orthogonal polarization. Polarization diversity supplies two diversity branches and allows the antenna elements to be considered. In the early days of cellular radio, all subscriber units were mounted in vehicles or used vertical whip antennas **(**Beckman, Lindmark, 2007).

Today, however, over half of the subscriber units are portable. This means that most subscribers are no longer using vertical polarization due to hand-tilting when the portable cellular phone is used. This recent phenomenon has sparkled interest in polarization diversity at the base station (Webb, 1998).

2.1.3 Diversity Techniques Advantages And Disadvantages

The diversity communication technique supply us wireless link improvements and low cost. Diversity uses the radio signals which are randomly propagated by finding the best multiple independent incoming signals for the receiver. With diversity techniques, multipath effects are highly reduced. Also, some advantages and disadvantages are given in below with Table 2.1.

Table 2.1: Diversity Techniques Advantages and Disadvantages (Webb, 1998)

Diversity Scheme	Advantages	Disadvantages
Space diversity	Easy to design. Any number of diversity branches are (*L*) selectable. Neither extra power nor bandwidth is necessary. Applicable to macroscopic diversity.	Hardware size could be large (depends on device technologies). Large antenna spacing is necessary for microscopic diversity at the base station.
Polarization diversity	No space is necessary. No extra bandwidth is necessary.	Only two-branch diversity schemes are possible. Three decibels more power is necessary.
Frequency diversity	Any number of diversity branches (*L*) is selectable.	*L* times more power and spectrum are necessary.
Time diversity	No space is necessary. Any number of diversity branches (*L*) is selectable. Hardware is very simple.	*L* times more spectrum are necessary. Large buffer memory is necessary when is *fd* small.

2.3 Antenna Parameters

2.3.1 Reflection Coefficients and Scattering Parameters

In electrical transmission line, standing wave ratio is the ratio of maximum standing wave amplitude to minimum amplitude. All high frequency circuits have characteristic impedance. Similarly, electrical load, which is feeding from electronic circuit, has input impedance. In ideal situation, these two impedance values are equal but it is not possible in applications. The biggest impedance mismatches are open and short circuits (Pozar, 2012). Short circuit impedance is zero, while open circuit impedance is infinite.

Reflection coefficient Γ describes as;

$$\Gamma = Vy / Vg \quad \text{or} \quad Vy = \Gamma\, Vg \tag{1}$$

Here, Vg is going Vy is reflected voltage. Both voltages may have reactive components. If Γ = 0 there is no reflection and this circuit is ideal circuit. If Γ = 1 then it is open circuit. If Γ = -1 then the circuit is short circuit. In applications, the absolute value of Γ has a value between 0 and 1. Reflection loss is a value of reflection coefficient in decibel. Reflection loss is calculated as RL (dB) = − 20log |Γ|. In practical applications, more than 10 dB is enough for return loss.

“Scattering parameters,” which are commonly referred to as s-parameters, are a parameter set that relates to the traveling waves that are scattered or reflected when an n-port network is inserted into a transmission line. In this study, there are two port and it means that there are four S parameters that are going to mentioned such as S_{11}, S_{12}, S_{22}, and S_{21}.

S_{11} represent the input return loss in dB, S_{22} represent the output return loss in dB , S_{12} and S_{21} are off-diagonal terms represent voltage wave transmission coefficients (reverse and forward voltage gains, respectively), while S_{11} and S_{22} are the diagonal terms represent reflection coefficients.

The network is called reciprocal, if the transmission characteristics in either direction is the same (S_{12} = S_{21}). The network is called symmetrical, if the return losses at the input and the output are equal (S_{11} = S_{22}).

For this study, it is aimed to design antenna with return losses (S_{11} and S_{22}) at least 10 dB and S_{12} = S_{21} at least 20 dB along the bandwidth between 1.7 GHz and 2.7 GHz.

In the simulations, changing the parameters are giving different responses for return losses as same as frequency band. And these parameters are given as before as;

- Substrate lengths
- Meandered dipole lengths
- Feeding ground lengths
- Feeding balun lengths
- Parasitic elements lengths

Design steps and their results will be given in next parts. Also, graphs are given and explained in detail which belongs to parameters of antenna design.

2.3.2 VSWR

As you see that at the reflection loss, increases, the ratio of Vmax to Vmin increases, so a measure of the mismatch of a line, called the standing wave ratio (SWR) , can be defined as;

$$\text{SWR}= \frac{V_{max}}{V_{min}} = \frac{1+|\Gamma|}{1-|\Gamma|} \qquad (2)$$

This quantity is also known as the voltage standing wave ratio and is sometimes identified as VSWR. From (2) it is observed that SWR is a real number such that 1 ≤ VSWR ≤ ∞, where VSWR = 1 implies a matched load (Pozar, 2012).

The VSWR is always a real and positive number for antennas. The smaller VSWR is better the antenna is matched to the transmission line and more power delivered to the antenna. The minimum VSWR is 1. In this case, no power is reflected from the antennas, which is ideal.

For the antenna applications, VSWR values lower than two is suitable in practice. This situation means that antenna has a good matching. When someone says that the antenna is poorly matched, very often it means that the VSWR value exceeds 2 for a frequency of interest.

Another specific parameter is return loss and it covers more details for the antenna theory. A commonly required conversion is between return loss and VSWR, and some values are tabulated below, along with a graph of these values for quick reference (Mobilmark, 2018).

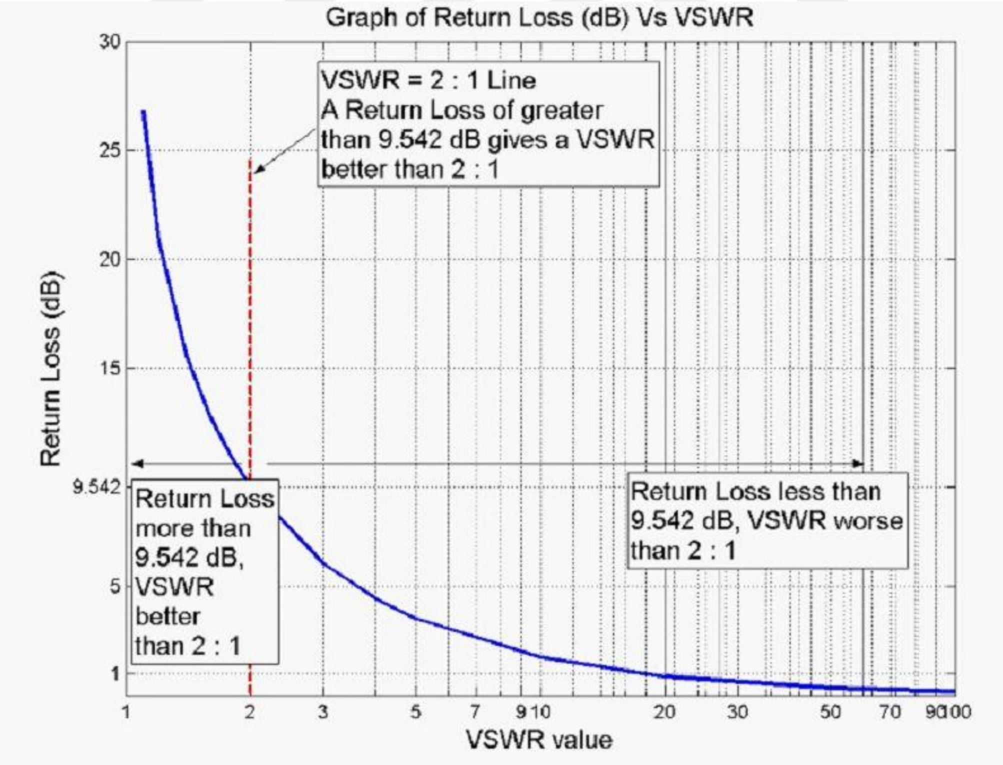


Figure 2.2: VSWR vs. Return Loss Graph (Mobilmark, 2018)

2.3.3 Radiation Pattern

The desired propagation characteristic of an antenna is obtained with mechanical and electrical designs. Radiation pattern determines to how good an antenna sends emission and takes. This pattern is a function of azimuth angle and elevation angle (Secmen, 2011) and it is given as graphically.

Cartesian and polar coordinates are using for radiation pattern. In graphical presentation, measurements are scaling as linear or logarithmic. Example radiation pattern is given in Figure 2.3.

The parts of radiation pattern are;

- Major lobe
- Minor and side lobes
- Back lobe
- First null beamwidth
- Half-power beamwidth

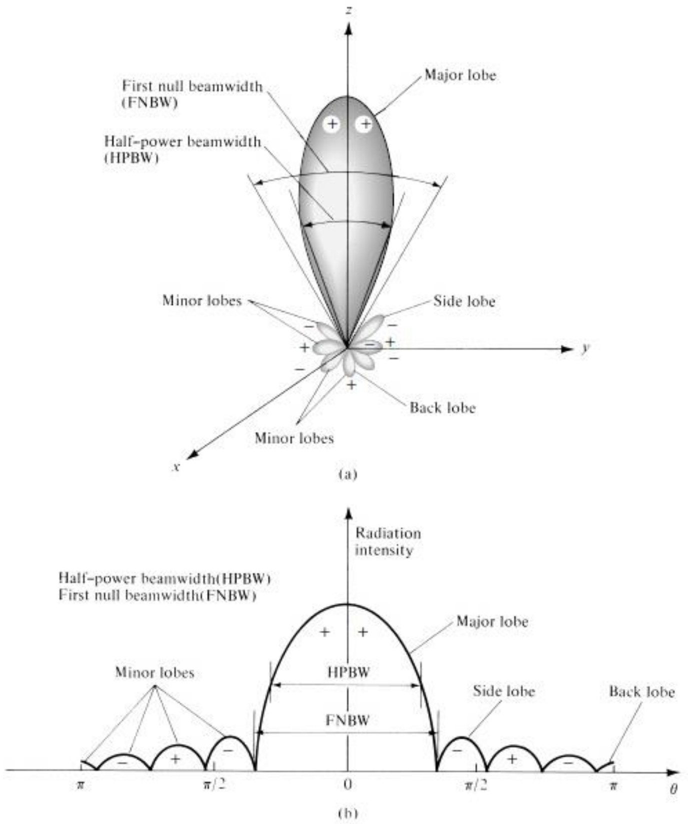


Figure 2.3: Example Radiation Pattern (Balanis, 2005)

2.3.4 Directivity and Gain

Directivity is described as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions (Chen, Luk, 2009). It is also one of the main antenna parameter. It shows that the direction of radiation pattern is. The directivity unit is dB. If an antenna radiates equally to the all directions, the directionality of antenna would be zero and the directivity of this type of antenna would be 1 (or 0 dB). Sometimes direction of the directivity is not identified. For this situation the direction of the maximum radiation intensity is suggested and the maximum directivity is given as;

$$D_{max} = \frac{U_{max}}{U_i} = \frac{4\pi U_{max}}{P_r} \tag{3}$$

where D_{max} is the maximum directivity and U_{max} is the maximum radiation intensity.

Directivity of the antenna is measured with gain parameter. The propagation density of a antenna may be directed to a specific direction with a special design. Antenna gain can describe like the directivity ability measurement of lossless antenna. In antenna description besides the real antenna, there are reference antennas. Generally isotropic antenna or basic dipole antenna is using as reference antenna. If we want to define, isotropic antenna is a imaginary antenna which propagates to each direction with same magnitude. In summary, antenna gain or power gain is ratio between propagation magnitude of antenna in given direction and average propagation intensity in each direction (Secmen, 2011).

The propagation density of an antenna may be directed to a specific direction with a special design. Antenna gain can describe like the directivity ability measurement of lossless antenna.

In antenna description besides the real antenna, there is one reference antenna. Generally, isotropic antenna or basic dipole antenna is used as reference antenna. If we want to define, isotropic antenna can be defined as an imaginary antenna that propagates to each direction with same magnitude. In summary, antenna gain or power gain is ratio between propagation magnitude of antenna in given direction and average propagation intensity in each direction is same. (Secmen, 2011).

Gain of an antenna for a given direction is described as “the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π’’ (Balanis, 2005).

In equation form this can be expressed as**;**

$$Gain = 4\pi \frac{radiation\ intensity}{total\ input\ power} = 4\pi \frac{U(\theta,\varphi)}{P_{in}} \tag{4}$$

In the simulations, the parameters which are mentioned before also affect the gain. The best gain values are obtained in design and they will be given next parts.

2.3.5 Polarization

Polarization is an important factor for antenna design. Some antennas are horizontally polarized some antennas are vertically polarized. The other types of antennas have different forms for polarization. Antennas, which have a particular polarization, will not have sufficiently receiving electromagnetic signals with a different polarization.

Usually for many antennas, it is very easy to detect the polarization. It is simply in the same coordinate plane as the antenna. As an example, a horizontal antenna will receive horizontally polarized signals and a vertical antenna will receive vertically polarized signals. Matching the polarization of the antenna and the incoming signal is very important. With this situation, the maximum signal is obtain. If the antenna polarization does not match with the signal, the level of the signal decreases correspondingly. It is reduces by a factor of cosine of the angle between the polarization of the antenna and the signal.

In communication applications, even after a signal has been transmitted, its polarization does not change in unbounded (unobstructed) medium. However, reflections from objects in the path can change the polarization. As the received signal is the sum of the direct signal plus a number of reflected signals, the overall polarization of the signal can change slightly although it stay the same.

There are different categories for polarization such as;

- Linear polarization: This is the most prevalent form for antenna polarization. It has different types like horizontal, vertical and slant/dual polarization.

-Horizontal polarization: If the antenna has horizontal elements, this form occurred. It transmits and radiates horizontally polarized signals, for example in the horizontal plane electromagnetic waves with the electric field.

-Vertical polarization: If the antenna has vertical elements, this form occurred. In addition, it can be a single vertical element. There is a one important reason to use vertical polarization that is antenna, which contains of a single vertical element can radiate equally around it in the horizontal plane.

-Slant/Dual polarization: It the antenna has the angle to horizontal and vertical planes, it means the antenna has slant or dual polarization. With this situation, both vertical and horizontally polarized antennas are able to receive the signal.

- Circular polarization: This polarization type gives us some benefits generally for satellite applications which preserve the effects of propagation anomalies, ground reflections and the effects of the spin that occur on satellites.

In circular polarization, it is more difficult to visualize than linear polarization. There are types for circular polarization such as;

-Right hand circular polarization: This is form of circular polarization where the electric field vector rotates in a right-handed fashion.

-Left hand circular polarization: This is form of circular polarization, the vector rotates in a left-handed fashion or opposite to right handed.

- Elliptical polarization: It occurs when the antenna has neither linear nor circular polarization.

2.3.6 Cross-Polarization Discrimination

The ratio between polar component at the given polarization and orthogonal cross-polar component is representing the cross polarization discrimination (XPD). XPD is the ratio of signal, which is transmit in orthogonal polarization in, transmit mode and it is required. For the receive mode, the XPD is the antenna ability to maintain the incident signal polarization purity.

For instance, when a perfect vertical (without horizontal component) polarized signal were incident upon a single polarized antenna, the mechanical and electrical imperfections will show a small amount of elliptical polarization of the signal. By considering the signal known as having vertical and horizontal components, XPD is the ratio of the significant horizontal to vertical components.

The XPD described, as “Cross-Polarization Discrimination, in dB, is the difference between the peak of the co-polarized main beam, and the maximum cross-polarized signal over an angle twice the 3dB beamwidth of the co-polarized main beam” in practice.

Especially in dual-polarized systems, XPD is an important characteristic factor while cross-talk between polarizations can frustrate the system quality objectives which is achieved. In radio systems, to isolate polarization and compensate the link induced coupling, cross-polar interference cancellers (XPICs) are using. Besides, good polarization purity from the antenna is important to allow the XPICs maximum flexibility to compensate for these dynamic variations.

CHAPTER THREE

THEORY OF DESIGN

3.1 Desired Specifications in the Designed Antenna

Diversity techniques are widely used in modern mobile communication systems to reduce the effect of multipath propagation and to increase the quality of signal reception. The two antennas, which are usually perpendicular to each other in the most frequently used polarization diversity of these techniques, are placed to give ± 45 ° double polarization (Lempiainen, Laiho-Steffens, 1998). At least 3 antennas are placed in the base stations for all space coverage in different geographical and residential scenarios (such as city, suburban and rural areas). Depending on the application and the number of antennas placed on these antennas or an array, the azimuth plane angular widths vary between 65 and 120 degrees and are more or less 65 ° (+/- 32.5°) in the city and more 120° (+/- 60 °) in the rural area look at their performance (Chen, Luk, 2009).

One of the most important parameters to be investigated in base station systems where ± 45° dual polarization antennas are used is the cross polarization discrimination (XPD) value between the two antennas. In most countries, it is desirable that the XPD value is at least 20 dB in the azimuth plane along the frequency band and at least 10 dB in the desired beamwidth. When the standard dipole antenna is placed in the form of two antennas perpendicular to each other, giving a ± 45 ° dual polarization, the theoretical center frequency in the azimuth plane (φ = 0 °) and 120 ° (+/- 60 °) angle the XPD value in its XPD value in its spectrum is about 9.5 dB minimum.

This value is practically lower and drops quickly when a narrow frequency band around the center frequency is exceeded. In the literature, there are ± 45 ° dual polarization antennas in different types of base stations (dipole, patch, slit etc.), but in the majority of these studies only boresight XPD values in the frequency band are given and only a small number of studies (Oh, Lim, Chae, Lee, 2015).

The mobile communication technologies are developing every day. With this development, the antenna technologies are also improving. The antenna technology has shown an important progress in parallel to improvement of new base-station antenna systems. For this situation, antenna design part becomes one of the important progresses. In this study, we aim to design ± 45° dual polarized base station antenna with improved cross-polarization discrimination (XPD) values.

Recent mobile phones can cover frequency bands of systems such as GSM (800, 900, 1800, and 1900 MHz bands), LTE (1.8, 1.9, 2.1, 2.5 GHz bands). At the beginning, GSM signals were operated between 900-1800 MHz frequency band. However, nowadays, it is widely used between 1700 – 2700 MHz frequency bands with the 4G technology.

With this information, the antenna is designed to work from 1.7 GHz to 2.7 GHz. This provides a wide frequency coverage for GSM 1800/3G/LTE frequency band. To get this wide frequency band different design techniques are used.

Some techniques are applied directly but some techniques are also designed for the antenna. In the design and simulation process, CST Microwave program is used and drawings were added parametrically. In the simulations, changing the parameters gives different responses for frequency band.

In this thesis, there are some important parameters that we focus on such as;

- Wide frequency band between 1.7 GHz – 2.7 GHz,
- Low reflection loss,
- Dual polarization,
- Improved cross-polarization discrimination,
- Wide beamwidth,
- Moderate gain,
- Compact size,
- High antenna efficiency,

According to these parameters, the antenna is designed, simulated and produced.

3.2 Structure Design

3.2.1 Image Theory

To provide image theory, dipole antennas are used for this antenna design. The height from the ground is calculated according to the λ/4 rule and dipole length is calculated according to the λ/2 rule at the center frequency. Figure 3.1 explains that.

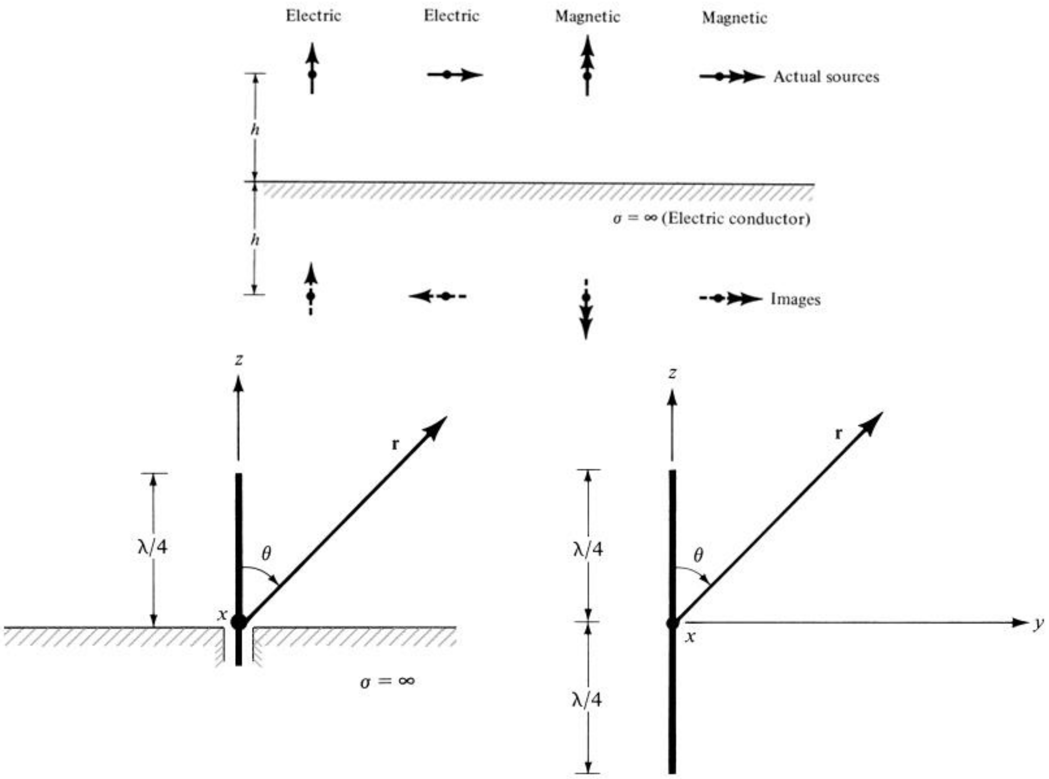


Figure 3.1: Image Theory (Balanis, 2005)

In this study, it is aimed to design more compact size, easier to assemble and superior in terms of its technical properties when compared to its examples. Because of these reasons, it is first added parasitic elements to the production, benefiting from the image theory and ensuring that E_θ and E_φ are equal. In Figure 3.2, there is a schematic diagram of the proposed ±45° dual-polarized base station antenna with four vertical parasitic elements. A + 45º polarized dipole given in #1 and #2, and a -45º polarized dipole is given in #3 and #4 are located parallel to the xy-plane. E_θ and E_φ are the θ and φ components of electric field.

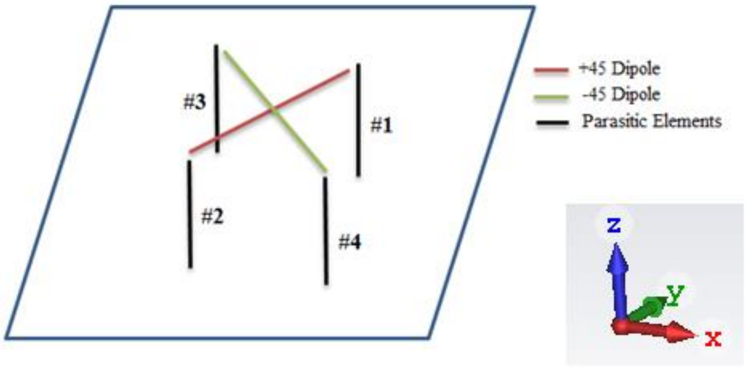


Figure 3.2: Parasitic Element Schematic

After that, the current distribution of the antenna is given in Figure 3.3. When the -45º polarized dipole and parasitic elements #3 and #4 are placed orthogonal to the +45º polarized dipole, no currents are induced. So, only images of the two vertical parasitic element (#1 and #2) and the +45º polarized dipole needed shown in figure below. The images of the parasitic elements are in phase with the original parasitic elements whereas the image of the +45º polarized dipole is out of phase with the original +45º polarized dipole. The +45º polarized dipole can be decomposed into its x and y components as shown in Figure 3.3.

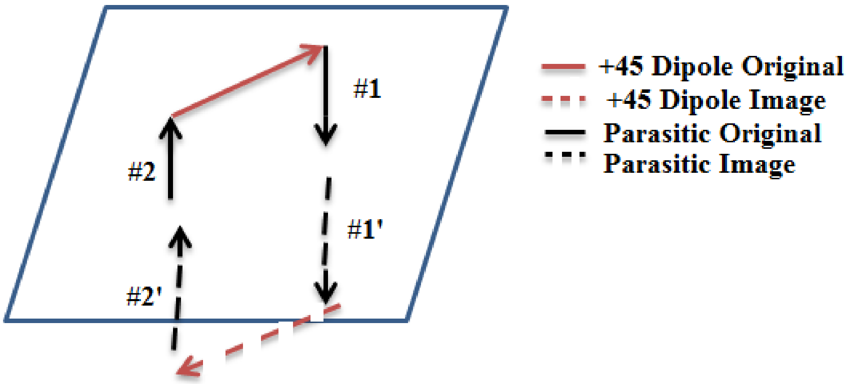


Figure 3.3: Image Theory Schematic

To use image theory vertical parasitic elements are added to the designed antenna. Parasitic element is an element or a length of wire or conductor placed near by a dipole or other conventional radiating antenna. This element is not connected directly to the feeder. It helps to increase the radiation indirectly.

In feed line, energy transmitted derives into the dipole antenna. It is sometimes called driven element. In addition, the radiation pattern of antenna will be maximum at right angles to that element in all direction to the perpendicular to the antenna axis. The gain increased for dipole antenna by adding parasitic elements. The elements, which has not an electrical connection to the driven element or the feed they called parasitic element.

There are two ways to get that, and the first way is adding a director element in front of antenna. It is called the director because it directs the radiation, energy, and response in the direction relative to the driven element. Moreover, the antenna radiates to the parasitic element and main lobe comes to that direction. It is generally 5% shorter than the driven.

The second way is to add parasitic elements and reflector behind the driven element. It is generally 5% longer than driven element. It acts like a way as to direct the energy back away from itself.

In this thesis, parasitic element are used to get better return loss, The VSWR band (reflection coefficient <9.54 dB) has parasitic elements added by parasitic elements in a narrow band of about 2.45-2.8 GHz when it has a broad band of 1.71-2.69 GHz, including GSM 1800 / 3G / LTE bands.

In addition, for the parasitic element structure, it was found to be higher than 23 dB without parasitic element in the frequency band in this case which is higher than 30 dB in the 1.71-2.69 GHz band.

Although, in the structure part, there are various parameters that affect the expected results and these will be mentioned in next parts. The meander structure to enhance the polarization of our antenna and it supplies compact size, also stated that the parasitic elements expand their positions and sizes. After the optimizations made, we will make measurements related to our antenna.

3.2.2 Meandered Dipole

Meander antennas are using for reducing the resonant length of antenna. In this study, meander antenna structure is designed to have compact size and small antenna.

The meander monopole is almost 20% to 30% smaller than a conventional monopole antenna. In addition, input impedance of the meander monopole is less than that of a conventional monopole.

The number of meander sections is calculated according to the wavelength. With that, the antenna is matched to the transmission line. For example, firstly the antenna was designed with standard dipole in this study after that, for reducing antenna size it becomes meander dipole. It is shown in Figure 3.4 below.

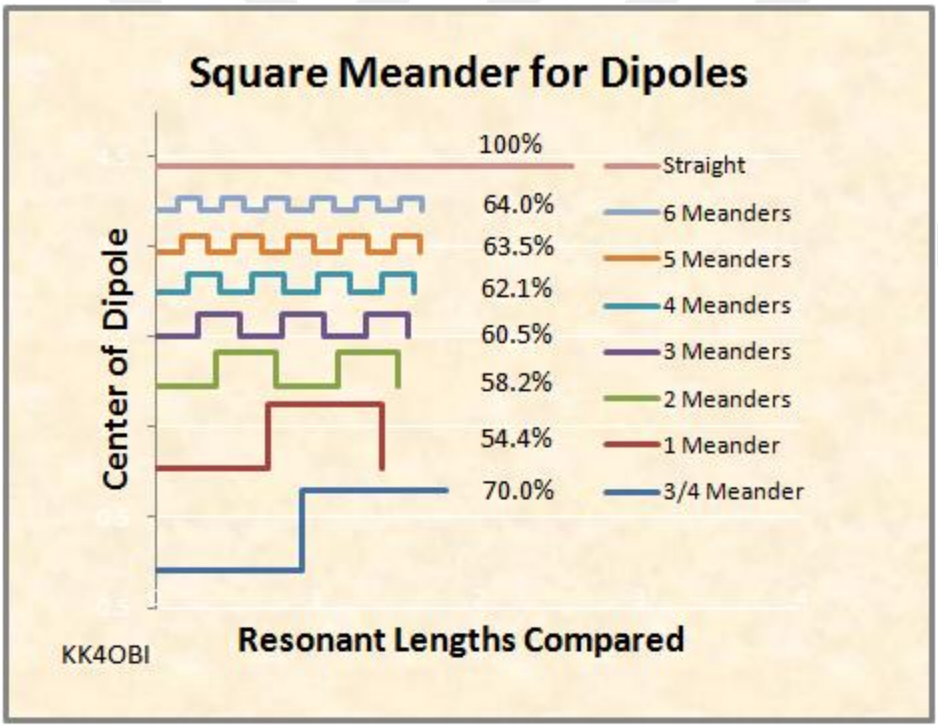


Figure 3.4: Meander Lengths (QSL, 2017)

3.2.3 Robert's Balun

The dipoles that are mentioned in image theory are given as wire dipole. In this study, printed dipoles are used for easy manufacturing and strength. Because of this reason, microstrip feed is necessary.

Dipole antennas are generally balanced structures and must be driven through some form of balun. In microstrip printed dipole antennas, one of the most popular choices is Robert's Balun (or sometimes it is called hairpin balun), which is given in Figure 3.5 as an example.

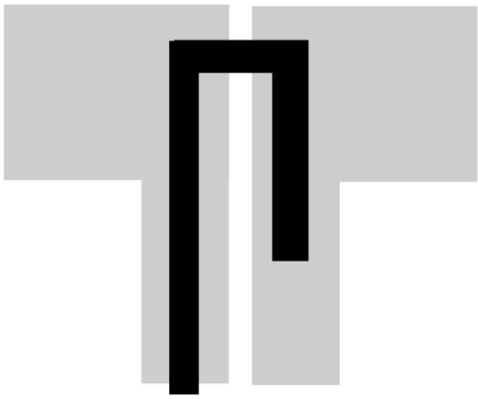


Figure 3.5: Robert's Balun (Chen, Luk, 2009)

In the studies, it is found that for the crossed – dipole antennas or Robert's Baluns are usually mounted. It supports the dipoles $\lambda/4$ above the reflecting plane, and it also supplies both a high balance ratio and effective impedance compensation over the necessary extended bandwidths (Chen, Luk, 2009).

CHAPTER FOUR

DESIGN OF THE ANTENNA AND SIMULATION RESULTS

For this thesis, CST Microwave Studio is used for design, simulations and optimizations. CST Microwave Studio simulation program provides us to make 3D electromagnetic simulation in high frequencies (CST, 2018). Especially, the program that is used for designing of antenna and microwave structures gives us rapid and reliable results.

4.1 Preliminary Design without Parasitic Element

In this design, the proposed antenna is initially designed without parasitic element as given in Figure 4.1. The designed antenna consists of two substrates (RO4003C, h = 0.813 mm, ε_r = 3.55, tan δ = 0.027) perpendicular to each other on a ground plane floor of 140 mm × 140 mm. At the beginning, ground plane dimensions were 160 mm × 160 mm.

The horizontal dipole dimensions were 7 cm at the beginning and this values is almost equal lambda/2 at the center frequency 2.2 GHz. According to the image theory, the height of the vertical dipoles from ground is equal to lambda/4 at the center frequency again. Some other dimensions are given in Figure 4.1

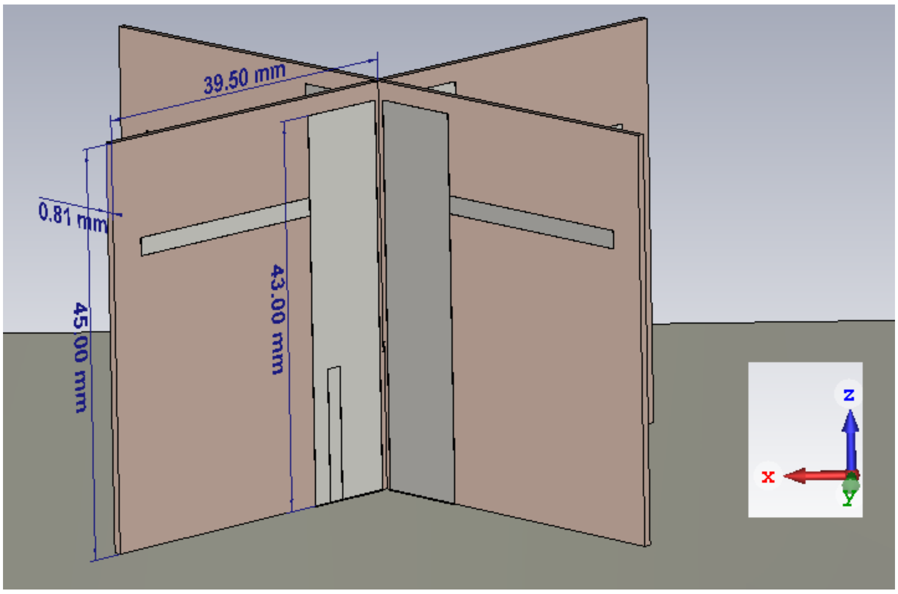


Figure 4.1: Designed Antenna without Parasitic Element

Balun structure is used for feeding the antenna. The dimensions of the designed balun, which are optimized, are given in Figure 4.2.

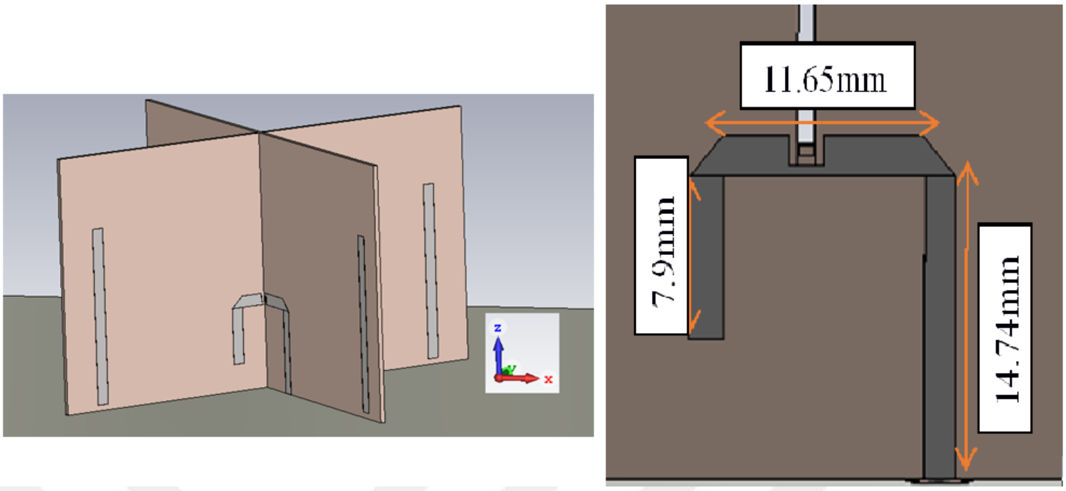


Figure 4.2: Designed Balun

The results of reflection loss and port isolation performance of the antenna are shown in Figure 4.1 without parasitic element.

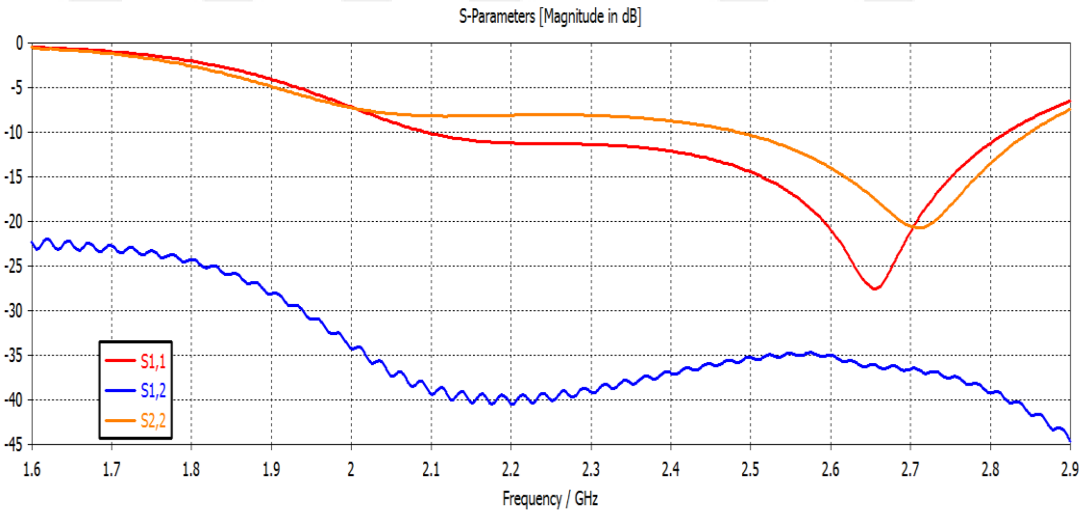


Figure 4.3: S Parameters without Parasitic Element

It can be seen in Figure 4.3, the frequency band for reflection coefficient values lower than -10 dB is between the frequency of 2.5 GHz and 2.8 GHz. This value is not sufficient (too narrow) for GSM 1800, 3G and 4G bands.

4.2 Parasitic Trials

Due to the insufficient results obtained in Section 4.1, parasitic element designs become necessary. Firstly, thin parasitic element is designed and after that, it is tried with two parasitic elements. However, the results are not enough for the expected results.

Parasitic element is located to their positions with the optimization where parasitic element width (w) and length (L) are 2 and 31 mm, respectively. The view of parasitic elements is depicted in Figure 4.4.

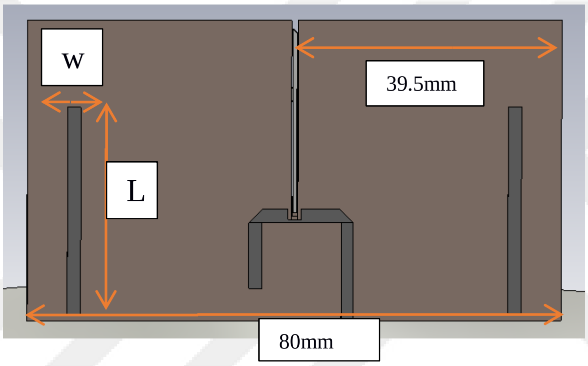


Figure 4.4: Predesigned Structure of Parasitic Element

Afterwards, two parasitic elements as shown in Figure 4.5 are tried, and corresponding simulations are performed. It is given in Figure 4.5 with structure and S parameters.

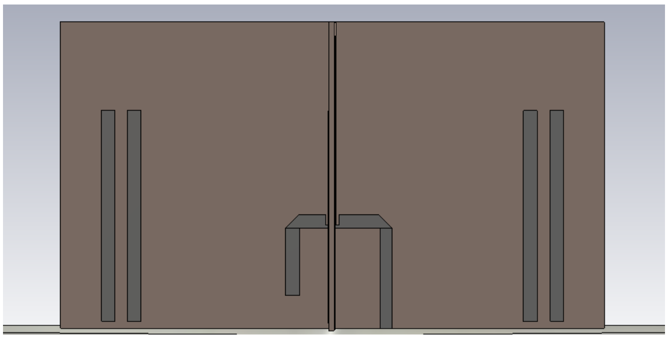


Figure 4.5: The Structure with Two Closely Spaced Parasitic Elements

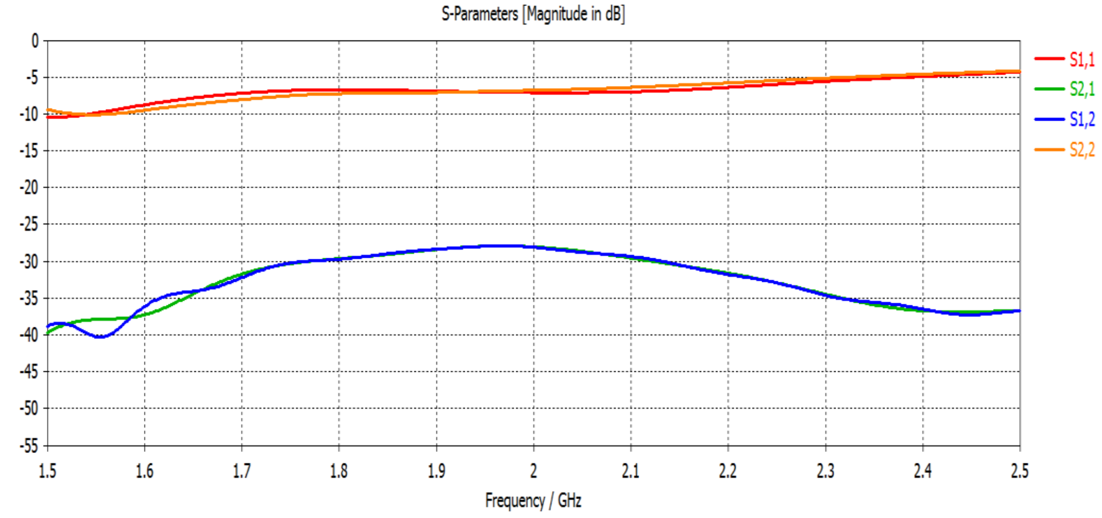


Figure 4.6: The results of S Parameters for the Structure With 2 Parasitic Elements in Figure 4.5

It can be observed from the results in Figure 4.6 that the usage of two thin parasitic elements does not work. In the next trial, the width of the parasitic element is increased to the 6 mm, and the simulations belonging to structure in Figure 4.7 are realized.

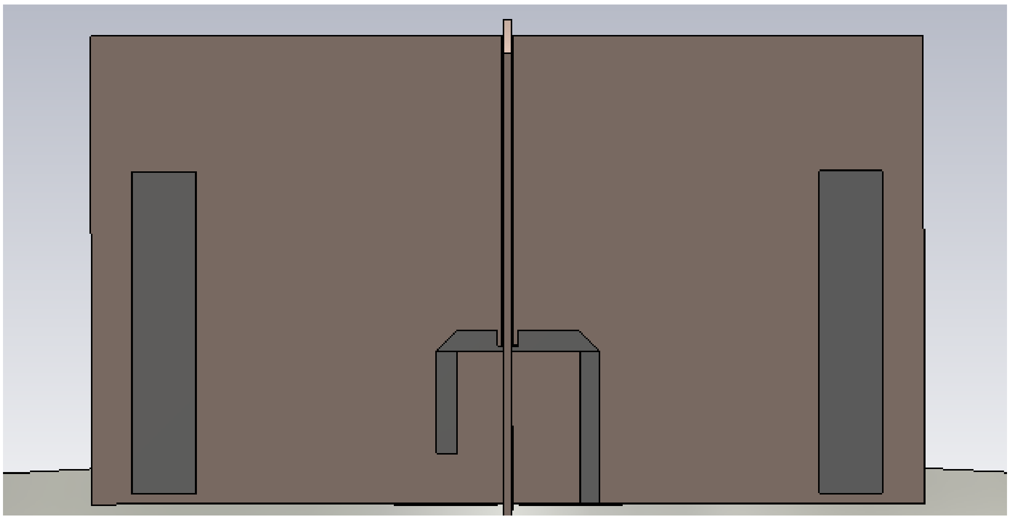


Figure 4.7: Wider Parasitic Element Structure

After the mentioned simulations, it is found that using wider parasitic element gives better result against using two parasitic elements.

Some techniques are tried at “Section 4.2 Parasitic Trials” part, and the best results are obtained with wider parasitic structure, which is given in Figure 4.7. S parameter results are given for wider parasitic structure in Figure 4.8.

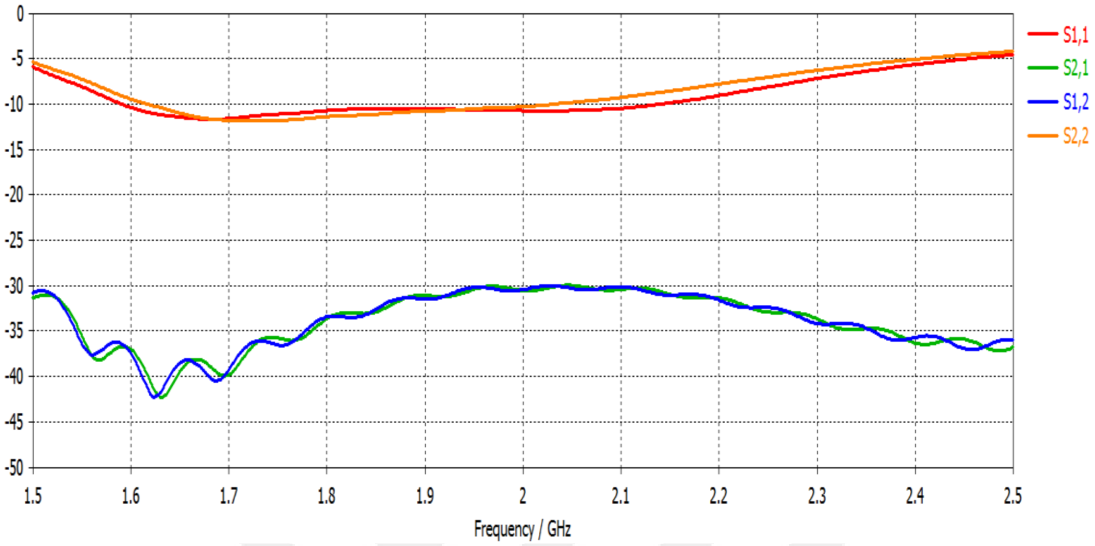


Figure 4. 8: S Parameter Results for Wider Parasitic Element

Considering both antennas together (port 1 and port 2)

- Return losses < -10 dB $\Rightarrow$ 1.6-2.05 GHz
- Insufficient results for 1.71-2.69 GHz band

4.3 Meandered Dipole Modification and Final Structure

In order to make the structure as compact as possible, a work was done by keeping Rogers' width constant in the previous design. Since parasitic were placed at the extreme points of the dipoles, parasitic could not exceed a certain thickness. As a rule of antennas, one of the ways to make an antenna with broadband was to increase the thickness of the parasitic element with the idea of using thick structures (Seçmen, 2011). For this purpose, reducing the horizontal length of the dipole antenna may increase the thickness of the parasitic element starting from the exact end point of the antenna. In addition, Rogers' width can be reduced by this method. For this purpose, the meandered dipole technique, which reduces the horizontal length mentioned in Section 3.2.2, is used.

Meander structure is also one of the main structures that have effect on the antenna results. For that, meander dipole lengths are the important parameter in this study. Initially, antenna is designed with the standard dipole antenna. Afterwards, in order to have small and compact size, dipole structure is modified to the meander dipole.

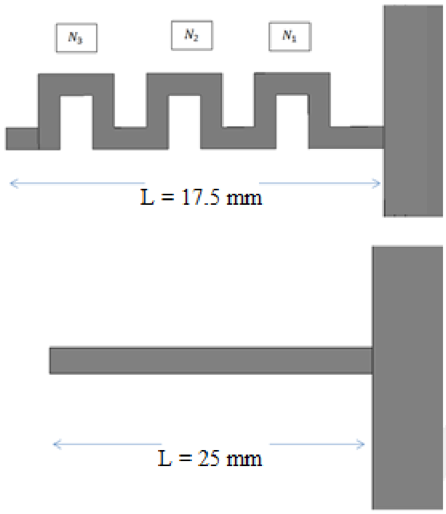


Figure 4.9: Dipole Length vs. Meander Length

In Figure 4.9, as you see that, when the dipole length was 25 mm it becomes 17.5 mm with the meander structure. It gives 7.5 mm length reduction and it means meander is 20 % smaller then dipole structure. That is the mean reason for selection of meandered dipole in this thesis.

The meander structure designed according to the $\lambda/2$ logic. First λ must be calculated.

$$c = \lambda . f \tag{5}$$

Here, c is equal to speed of light which is equal to 3.10^8 m/sec and our center frequency is almost equal to 2.2 GHz because it between 1.7 GHz and 2.7 GHz. After these calculations, λ is found as ≅ 13 cm. and the $\lambda/2$ is almost ≅ 6.5 cm, after other calculations and simulation optimizations meandered dipole length is designed in given values.

The optimization of all dimensions and final dimensions are made with CST

Microwave Studio program. The dimensions of parasitic elements are also modified by optimizing together with meandered structure. The dimensions of the final design (final antenna) are depicted from Figure 4.10 to Figure 4.12.

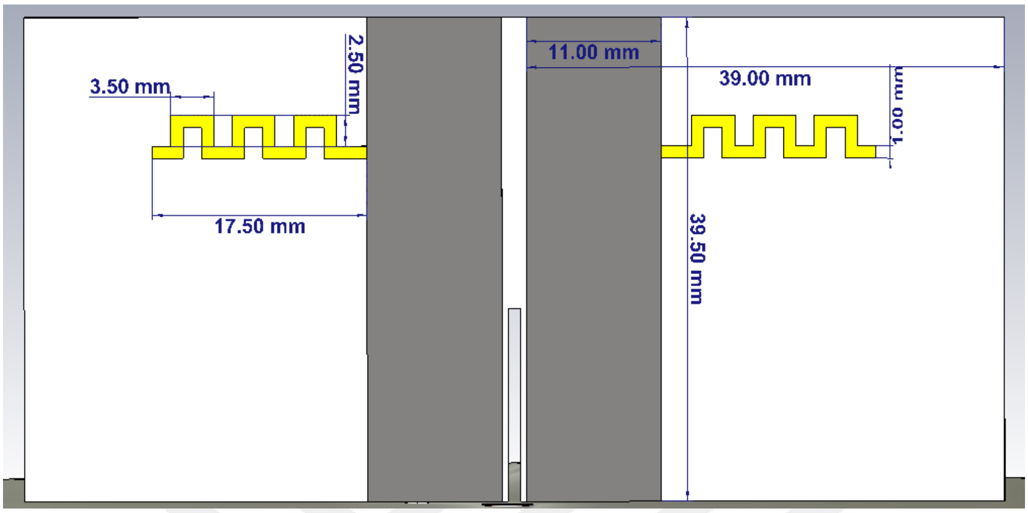


Figure 4.10: Meander Structure

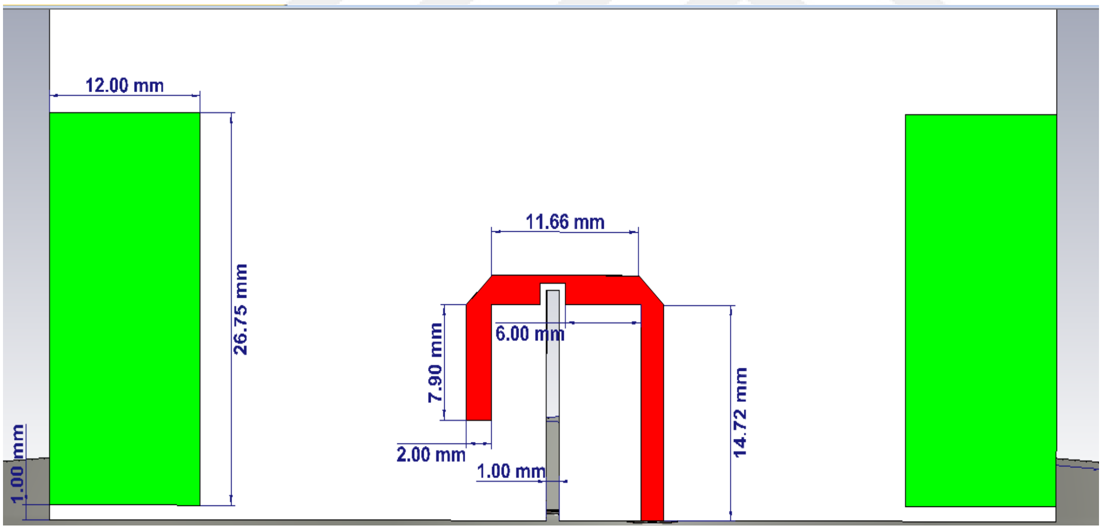


Figure 4.11: Final Design of Parasitic Element and Balun Side

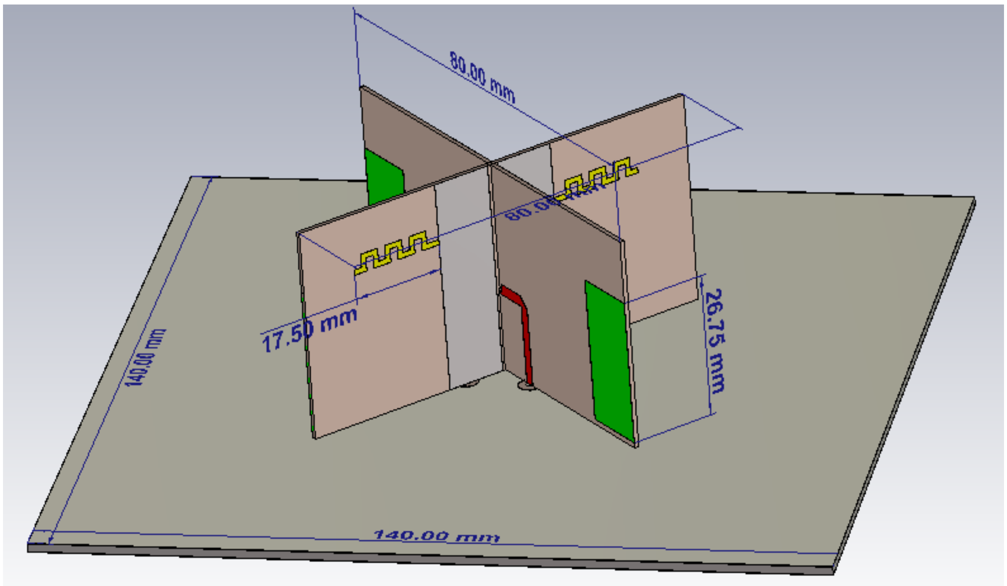


Figure 4.12: Final Designed Antenna

By considering the dimensions given in Figure 4.10, Figure 4.11 and Figure 4.12;

- For Standard dipole, the length was nearly λ/2 ≅7 cm at center frequency (2.2 GHz) with the optimized meandered dipole it become 5.8 cm from end to end. It means that, almost %20 size reduction with that Rogers substrate and ground plane become smaller.
- The ground plane dimensions are 14 cm x 14 cm (λ x λ at the center frequency fc = 2.2 GHz), it become smaller with the meandered structure.

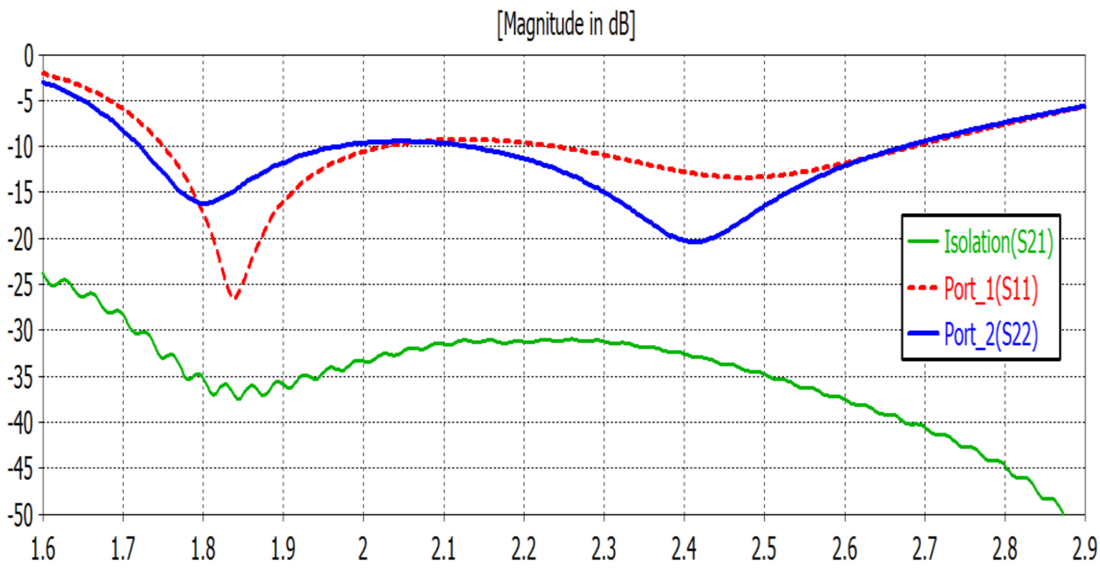


Figure 4.13: S Parameters for the Final Antenna Design

The simulations with parasitic elements in the final design are also repeated to show the effect of parasitic elements (by removing green parasites in Figure 4.11 and 4.12). The compared S parameters are given in the following Figure 4.14.

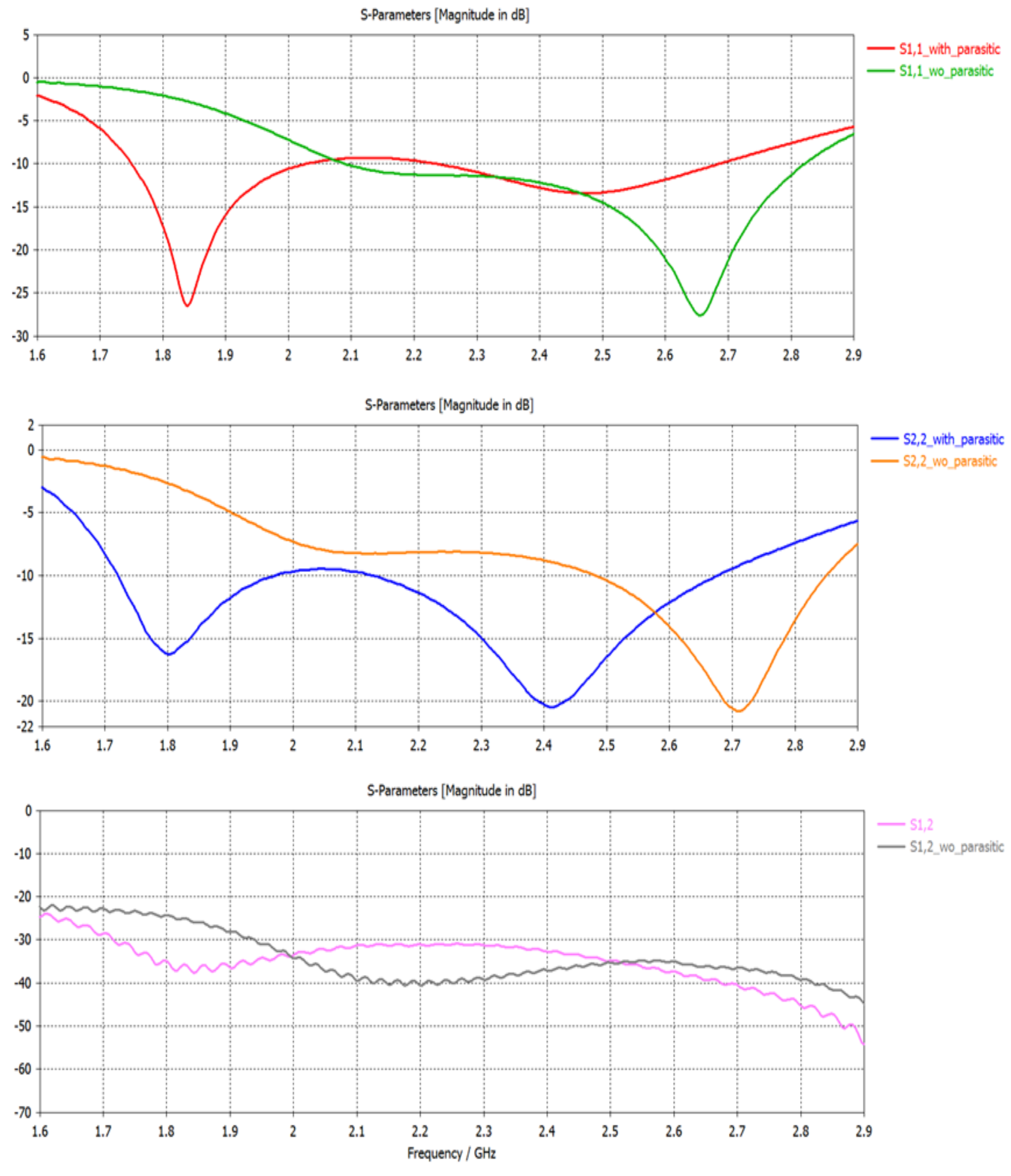


Figure 4.14: S Parameter Simulations with Parasitic vs. without Parasitic Elements

For Figure 4.14, it is are observed that,

- Return losses are $\leq$ -10 dB (VSWR 2:1 for band)
  Without parasitic element, the frequency band above -10 dB is 2.45-2.8 GHz, with parasitic elements these frequency band becomes 1.74-2.69 GHz

- Isolation between port1 and port 2 is more than 20 dB without parasitic elements between 1.71-2.69 GHz bands, this values become more than 30 dB with parasitic elements.

As you see that, S11 and S22 values for the port 1 and port 2 do not give effective values between 1.7 GHz and 2.7 GHz. Without parasitic element VSWR band (reflection coefficient ≤ 9.54dB), it has narrow band as between 2.45 GHz and 2.8 GHz. However, when the parasitic elements are added and dimensions are optimized to the antenna with the wide band of 1.71-2.69 GHz, including GSM 1800 / 3G / LTE bands. It can be seen in Figure 4.8 below.

S parameters have better results when we added parasitic elements to the structure. It can be seen in Figure 4.10.

4.4 The Simulation Results for Gain and Radiation Pattern

In the design part, another important parameter is gain value. Due to the dual polarization, in simulations and measurements, there are two types of results like co-polar and cross-polar for radiation pattern and also for gains. For the first designed antenna with the standard dipole and small parasitic elements (Figure 4.2), the antenna realized gains and patterns were given in Table 4.1 and Table 4.2 and Figures 4.13-4.20 for port 1 below.

Table 4.1: Realized Gains of Standard Dipole Design for Port 1 and Port 2

	Port 1		Port 2	
Realized Gains	Co-polar	Cross-polar	Cross-polar	Co-polar
1.8 GHz	6.88 dB	-15.8 dB	-15.5 dB	6.91 dB
2.0 GHz	6 dB	-14 dB	-13.6 dB	5.9 dB
2.2 GHz	3.84 dB	-10.1 dB	-9.93 dB	3.47 dB
2.4 GHz	2.22 dB	-6.47 dB	-6.52 dB	2.03 dB

Table 4.2: Realized Gains of Final Antenna Design For Port 1 and Port 2

	Port 1		Port 2	
Realized Gains	Co-polar	Cross-polar	Cross-polar	Co-polar
1.8 GHz	7.4 dB	-15.4 dB	-15.5 dB	7.29 dB
2.0 GHz	6.12 dB	-13.7 dB	-13.3 dB	5.87 dB
2.2 GHz	4.23 dB	-9.68 dB	-9.02 dB	4.14 dB
2.4 GHz	3.46 dB	-6.29 dB	-5.74 dB	3.5 dB

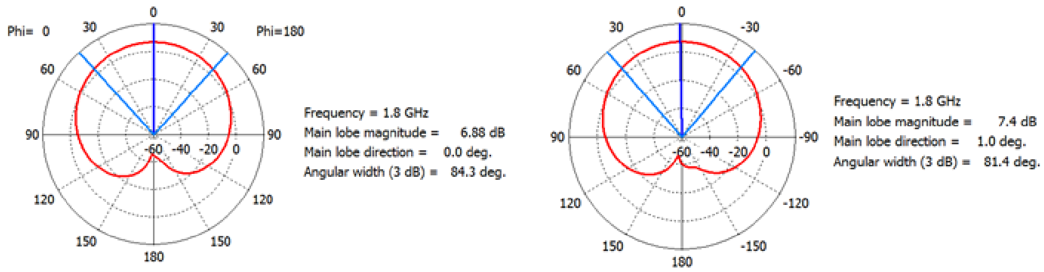


Figure 4.15: 1.8 GHz Co-polar Realized Gain and Radiation Patterns Initial vs. Final Design

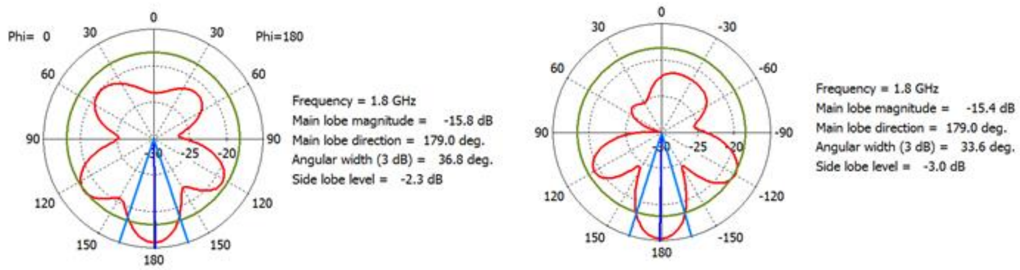


Figure 4.16: 1.8 GHz Cross-polar Realized Gain and Radiation Patterns Initial vs. Final Design

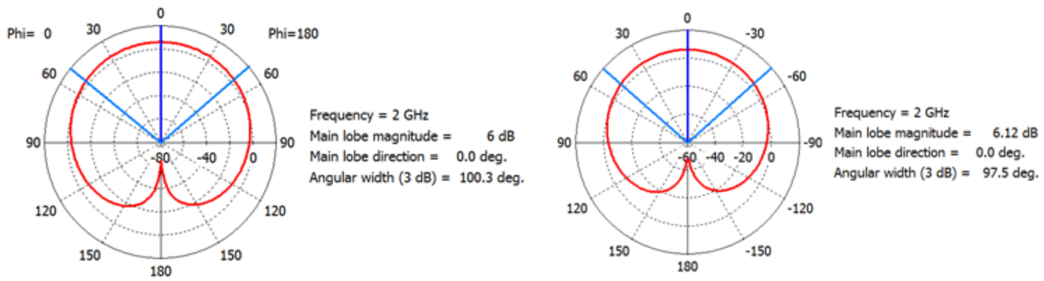


Figure 4.17: 2.0 GHz Co-polar Realized Gain and Radiation Patterns Initial vs. Final Design

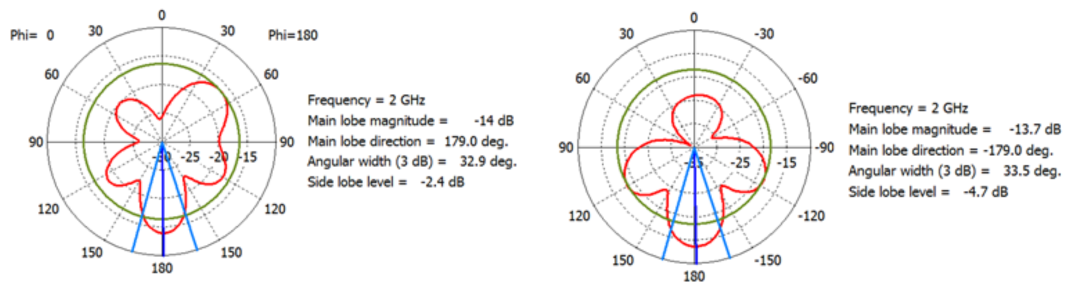


Figure 4.18: 2.0 GHz Cross-polar Realized Gain and Radiation Patterns Initial vs. Final Design

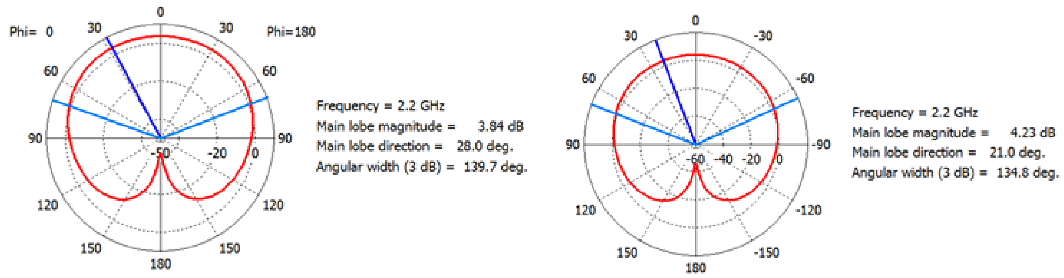


Figure 4.19: 2.2 GHz Co-polar Realized Gain and Radiation Patterns Initial vs. Final Design

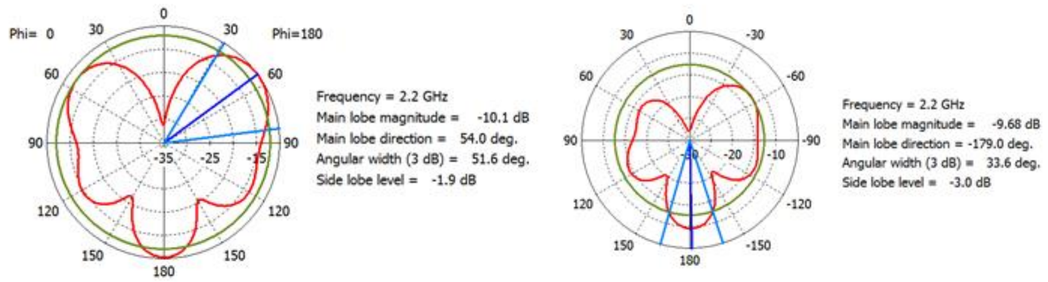


Figure 4.20: 2.2 GHz Cross-polar Realized Gain and Radiation Patterns Initial vs. Final Design

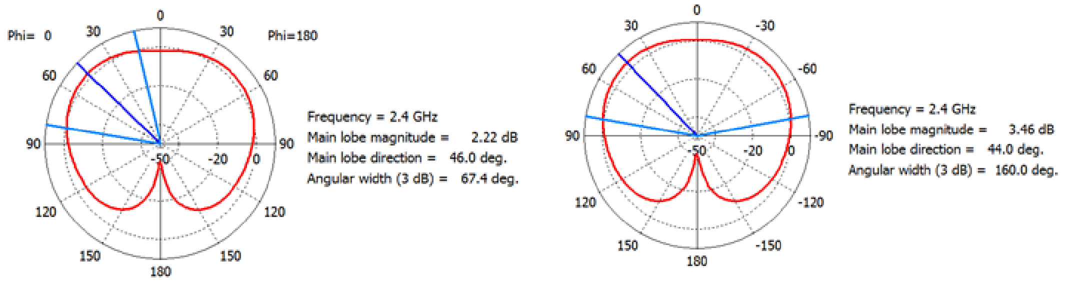


Figure 4.21: 2.4 GHz Co-polar Realized Gain and Radiation Patterns Initial vs. Final Design

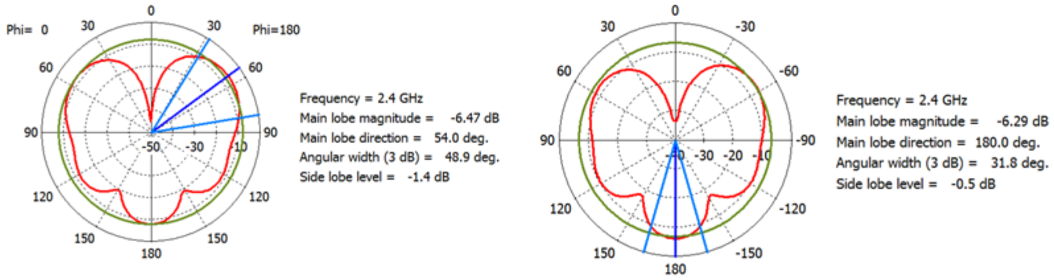


Figure 4.22: 2.4 GHz Cross-polar Realized Gain and Radiation Patterns Initial vs. Final Design

Radiation pattern characteristics and cross-pol levels are close for both antennas but especially co-pol levels for designed antenna are better than the antenna with standard dipoles.

As it can be observed from Table 4.1 and Table 4.2, standard dipole antenna design does not give effective values for the gain. After that, with the new parasitic elements and meandered dipole structure the antenna gains become better. Realized gains and radiation patterns are given below for the final design.

It is obviously seen that the final antenna design with the suggested parasitic elements and meandered dipole structures, gives the effective values better than other design.

4.5 XPD Simulations

One of the most important parameters to be investigated in base station systems in which ±45° dual polarization antennas are used is the cross polarization discrimination (XPD) value between the two antennas. Generally, in most countries the XPD value is required to be at least 20 dB in the azimuth plane (boresight) along the frequency band and at least 10 dB in the desired beamwidth.

In this study, to broaden the frequency band by attracting to the desired lower frequencies of the antenna operation and to seriously improve the XPD values, thick parasitic elements starting from the end of the horizontally curved dipole structures and having a vertical shape are added.

Finally, vertical parasitic elements acting as monolithic structures have been added, especially due to the inadequate frequency band and XPD performance. These monolithic parasitic elements behave like a vertical dipole when considering the ground plane and image theory.

Thus, the structure will have both horizontal and vertical dipoles at the same time. This is the main reason for the improvement of XPD values. The results of the simulation and measurement of the values will be also given in the next chapter; on the other hand, some simulation results for radiation pattern performance are given in Table 4.3.

Table 4.3: Radiation Pattern Performance of Antenna With and Without Parasitic

	1.71-2.69 GHz 120° beamwidth Minimum Gain	1.71-2.69 GHz 65° beamwidth Minimum Gain	1.71-2.69 GHz 120° beamwidth Minimum XPD	1.71-2.69 GHz 65° beamwidth Minimum XPD	1.71-2.4 GHz 120° beamwidth Minimum XPD
With Parasitic Element	~ 0 dBi	~ 0 dBi	~ 7 dB	~ 10 dB	~ 10 dB
Without Parasitic Element	~ -9.5 dBi	~ -2 dBi	~ 2 dB	~ 12 dB	~ 2 dB

According to the these information;

- The minimum gain values of the parasitic element structure within the band and beam are higher than the parasitic structure.
- The minimum XPD values of the parasitic structure at 120° beam are better than the without parasitic structure, minimum XPD values at 65° beam are close.
- Elevation of the designed antenna in band 3-dB (half-power) gain beam at least 78°.

  The minimum gain of the frequency band and beam is 10 dBi if this antenna is used in the form of an array with a beam of 7° in the elevation.

CHAPTER FIVE
PRODUCTION AND THE RESULTS

After the design of the proposed antenna is completed with the given dimensions and structure described in Chapter 4; the antenna is manufactured, and the measurement results are obtained and compared with simulation results.

5.1 The Production of the Antenna

The manufacturing of the antenna contains three main parts; the fabrication of antenna parts above ground, form of the ground plane, and the assembly of antenna parts, ground plane and SMA connectors.

As described in the design of the antenna; the printed meandered dipoles, parasitic elements and balun structure are placed on the substrates, which are placed mutually perpendicular to each other and ground plane. Rogers RO4003C (h = 0.813 mm, ε_r = 3.55, tan δ = 0.027) material is selected as a substrate. As the first step of the manufacturing, the parts above ground are produced in Yaşar University Antenna Laboratory. Figure 5.1 shows for the production system with MITS Autolab (MITSPCB, 2018).

The second step of the manufacturing is about the ground plane and SMA connectors' assembly. In the design and simulations, ground plane is selected as perfect electric conductor (PEC) with the thickness of about 4 mm. However, a copper with the dimensions of 140 mm x 140 mm x 4 mm becomes too heavy for the production and measurement systems. Therefore, for ground plane selection pure copper plate is replaced with FR4 material having nearly 35 μm copper thickness values on each side in order to get much lighter antenna in weight. Therefore, the antenna becomes more compatible with the measurement setup.

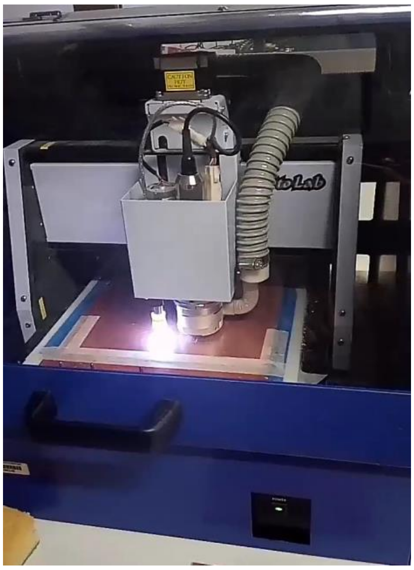


Figure 5.1: The Production of Parts of the Antenna above Ground.

In order to get suitable ground thickness at around 4 mm, two pieces of FR4 substrate each having 1.6 mm total thickness are connected to each other and soldered. This ground are drilled with 0.635 mm radius and inner parts of SMA connectors are passed through the ground, and SMA connectors are soldered to the microstrip balun and ground. After this manufacturing step, antenna parts are soldered and combined with ground and SMA connectors, which is third and final step of the production. Finally, the realization of the antenna is completed as depicted in Figure 5.2.

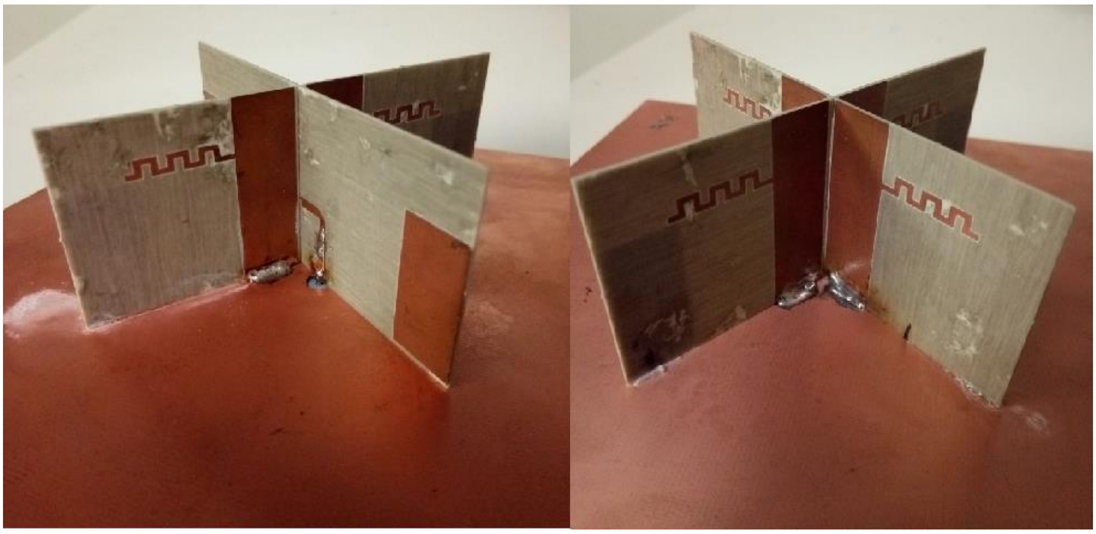


Figure 5.2: The Manufactured Antenna

5.2 Measurement Results of Antenna

After the production of the proposed antenna is completed, the performance of the antenna is measured. Yaşar University Antenna Laboratory is used for these measurements. The measurement steps can be summarized as given below.

- N9912 Fieldfox RF Analyzer: Return loss and gain of the designed antenna is measured with this analyzer.

-Radiation Pattern Measurement Set (ME1300 Dreamcatcher): Radiation patterns of the designed antenna and corresponding gain patterns are obtained by using this set.

5.2.2 S Parameters Measurement

For S-parameter measurements, Agilent N9912A Fieldfox RF Analyzer is used and the values are exported to the graphics with help of MATLAB and CST Microwave Studio programs. The measurement setup for S-parameter is given in in Figure 5.3.

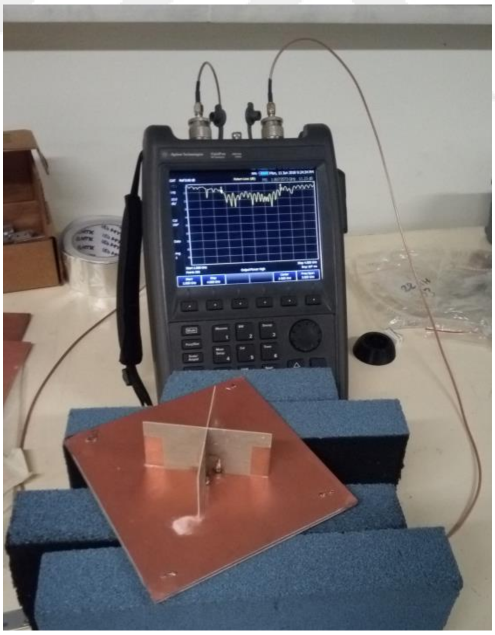


Figure 5.3: Experimental Setup for S-Parameter Measurements

As it can be shown in Figure 5.3, ports of the network analyzer are connected to the antenna port 1 and port 2 at the same time. Then, frequency range of the measurement is arranged between 1.5 GHz and 3.5 GHz. Finally, the results are obtained from device as shown in Figure 5.4, which is a sample measurement result belonging to return loss of port 1 (S11).

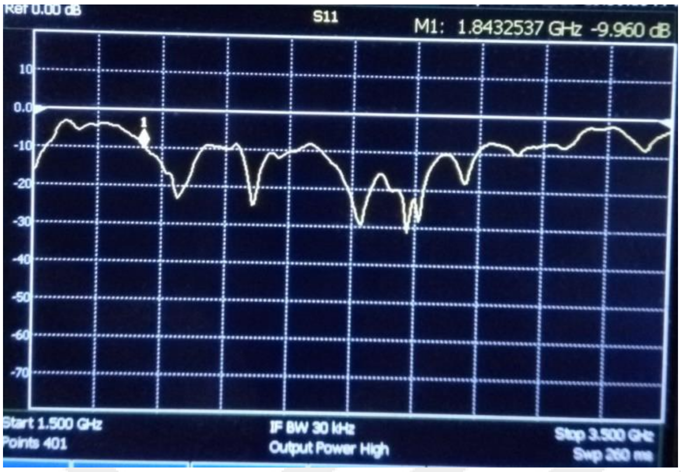
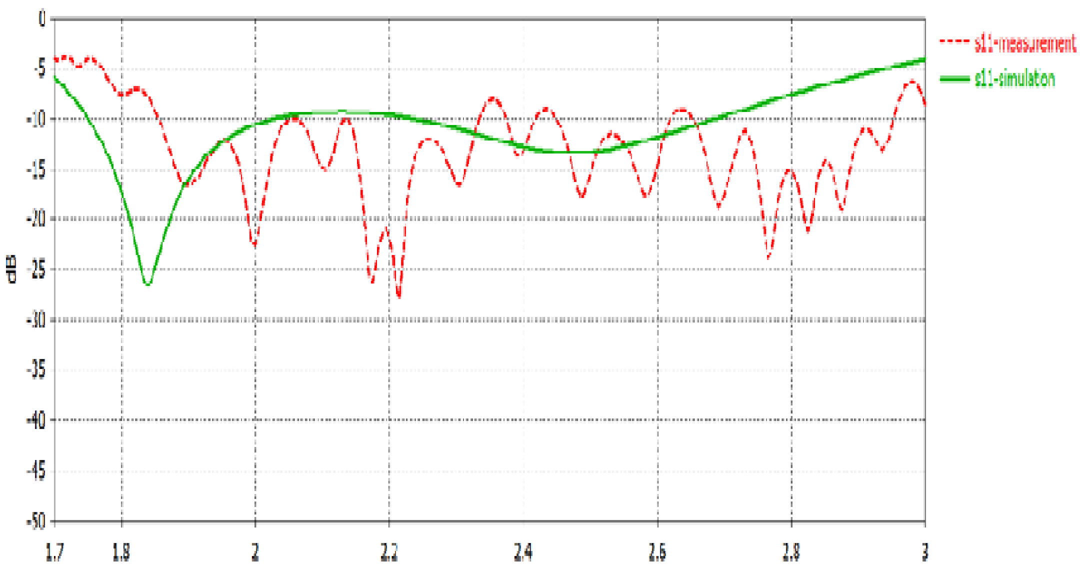


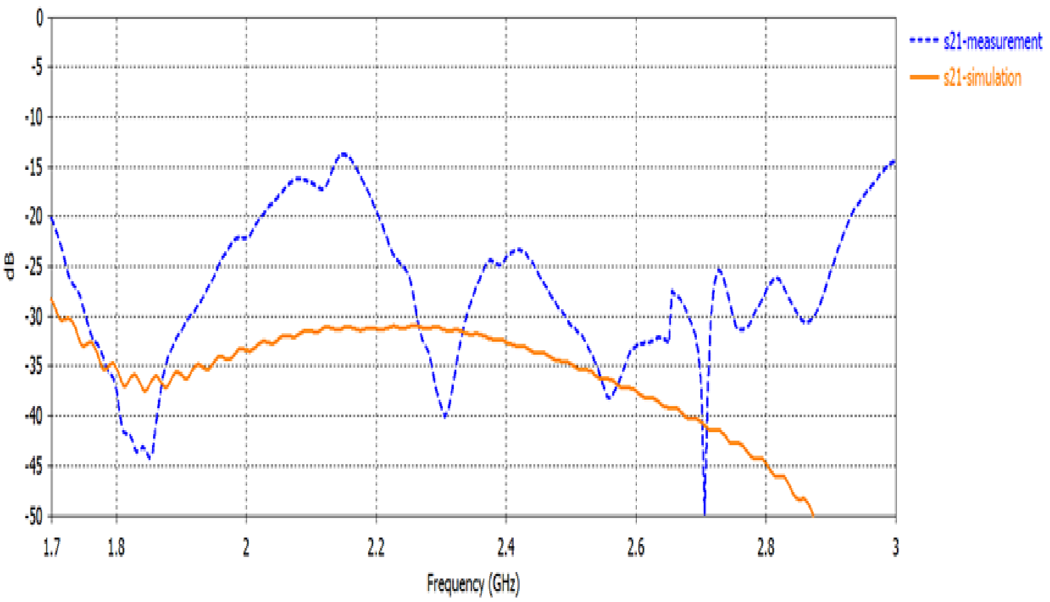
Figure 5.4: Measurement Result with Agilent N9912A for S11

After the measurement of S-parameters of the antenna, S-parameter values obtained with simulations and measurements are compared in Figure 5.5.

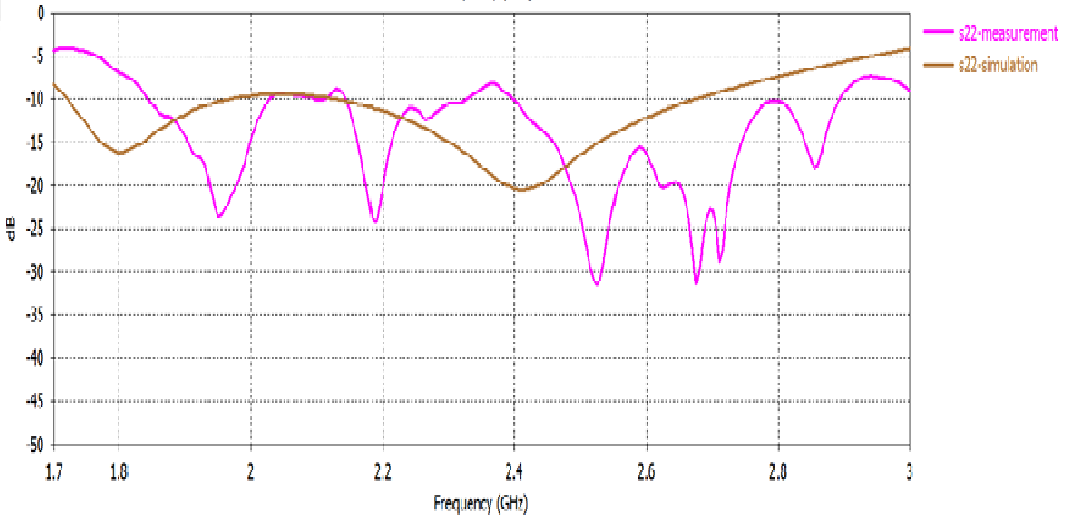
According to the measurement results, both ports are thought to have a 10 dB return loss band as wide as 1.84-2.9 GHz. In addition, according to the measurement results, inter-port isolation is better than 20 dB in almost all frequency bands (1.7-2.9 GHz).



(a)



(b)



(c)

Figure 5.5: Comparison of S Parameters a) S11 results simulation vs. measurement, b) S21 results simulation vs. measurement, c) S22 results simulation vs. measurement

Although there are certain consistencies between the measurement and the simulations, there are differences due to the faults caused by the production and soldering. While port 1 is more consistent (frequency shift), more frequency shift is observed at port 2 because it has more defect on the balun feed part microstrip line and the solder is almost at the end of the live end. In the isolation, especially from the production errors in balun feed points (the thickness of the solder) values were higher than the desired ones.

As it shown in Figure 5.5, return loss values for port 1 and port 2 are above the 10 dB, and isolation value between ports is measured above 20 dB between 1.7 and 2.7 GHz frequency band.

5.2.3 Gain and Radiation Pattern Measurements

Gain and XPD values are measured in Yaşar University Antenna Laboratory and. The measurements are realized only for two frequencies of 1.8 GHz and 2.4 GHz. Gain measurement system is shown in Figure 5.6. The blue antenna is reference antenna Aaronia Hyperlog 60180 (Aaronia, 2018). The blue antenna was rotated 45 degrees relative to the ground to measure the co-pol in the Phi = 0 plane. In the cross-pol, the antenna's direction was turned 45 degrees in the opposite direction (90 degrees perpendicular to the Figure 5.6).

Figure 5. 6: Gain Measurement System

The gain and XPD values at 1.8 GHz and 2.4 GHz are given in Table 5.1.

Table 5.1: Measured Gains

	Co-polar (maximum gain) measurement/simulation	Cross-polar (maximum gain) measurement/simulation	XPD (at boresight) measurement
1.8 GHz	6.5 dB / 7.4 dB	-15.4 dB / -19 dB	19 dB
2.4GHz	3 dB / 3.46 dB	-6.29 dB / 10 dB	10 dB

Gains are measured between 3 dB and 7 dB in the bandwidth. There is a consistency between measurement and simulation results. In addition, the radiation diagrams are given in Figure 5.10 and Figure 5.11.

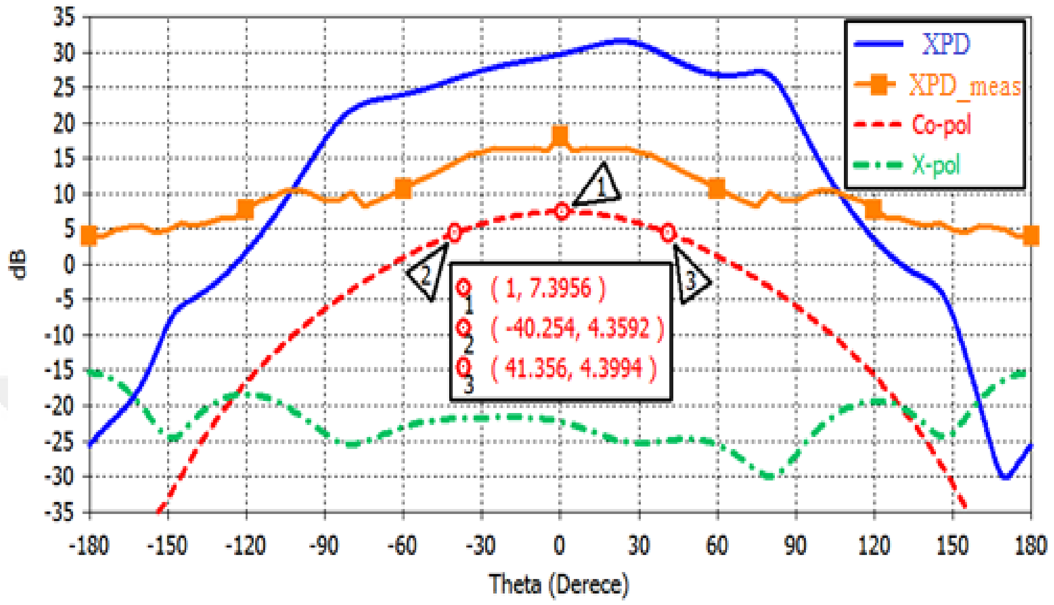


Figure 5.7: Radiation Patterns for 1.8 GHz

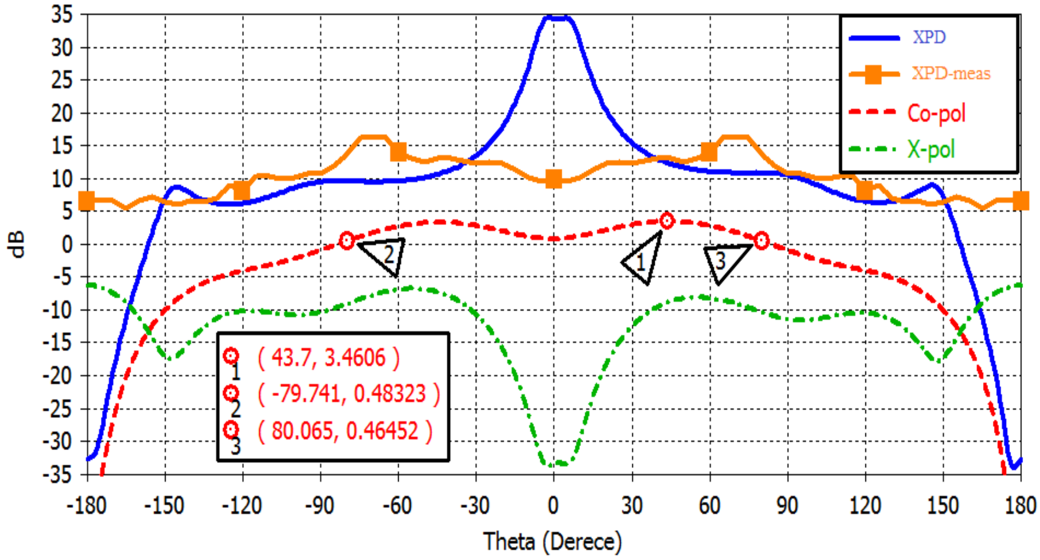


Figure 5.8: Radiation Patterns for 2.4 GHz

Two important frequencies within the frequency band are for 1.8 GHz (GSM 1800) and 2.4 GHz (Wi-Fi) are measured. The XPD values (+/- 60°) were measured at least 10 dB in a 120° beam.

Thanks to the added parasitic elements, a VSWR <2 value and a 10 dB value at a beamwidth of 65° were found in the band 1.71-2.69 GHz. In the 1.71-2.4 GHz band, XPD values of 2 dB were obtained without parasitic elements at a beamwidth of 120°, where XPD values of approximately 10 dB were obtained with parasitic elements.

The radiation patterns obtained with simulations are mentioned in the previous sections. The radiation patterns are measured with ME1300 Dreamcatcher pattern measurement device and it is shown in figure 5.9. As it can be seen in Figure 5.10 and 5.11, for two important frequencies that are 1.8 GHz (GSM 1800) and 2.4 GHz (Wi-Fi), measured co-pol and cross-pol radiation gain patterns are given.

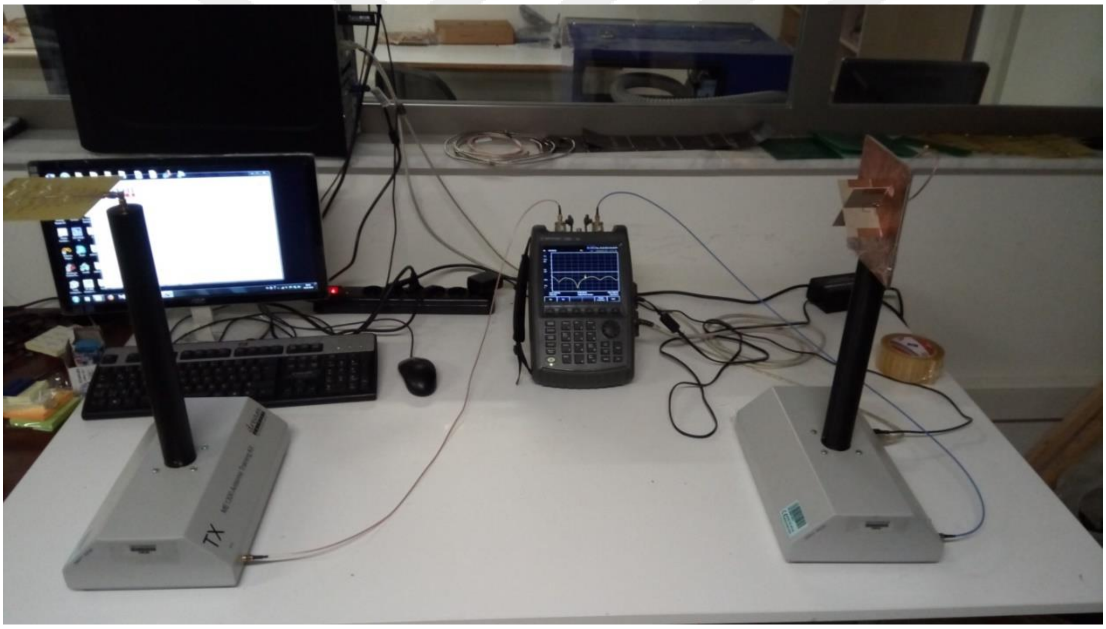


Figure 5.9: Radiation Pattern Measurement System

In Figure 5.10 and 5.11, it can be seen the maximum and minimum cross-pol and co-pol radiation patterns. At 1.8 GHz, maximum radiation is directly towards boresight; while there is a little shift in the main beam at 2.4 GHz.

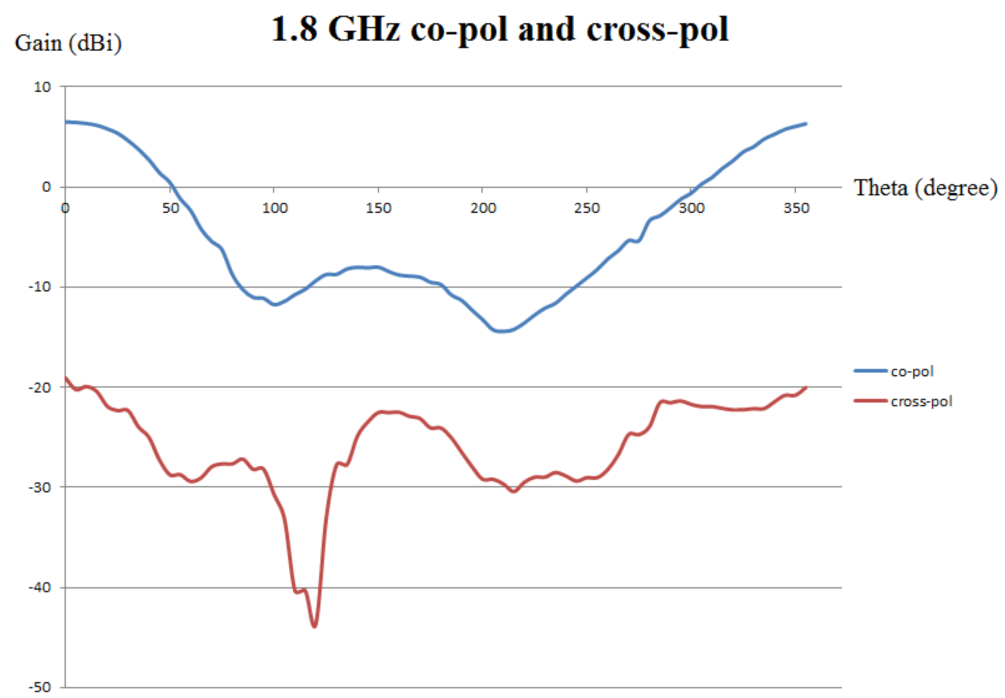


Figure 5. 10: Measured Patterns for 2.4 GHz Port1 Co-Pol and Cross-Pol

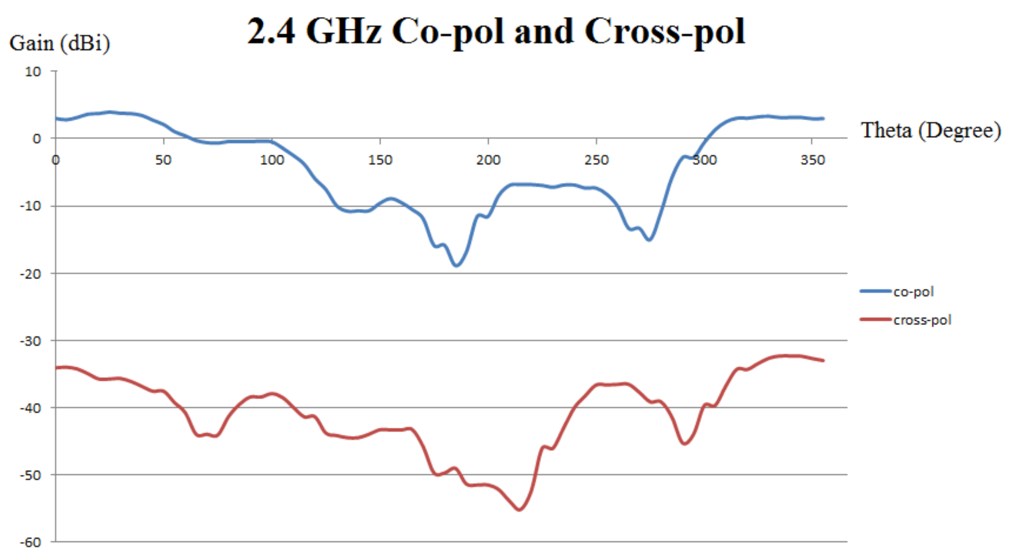


Figure 5. 11: Measured Patterns for 2.4 GHz Port1 Co-Pol and Cross-Pol

Backlobe level is measured more than expected from simulations. This is because not enough ground plane effect is observed due to the fact that two combined FR4 substrates is used instead of 4 mm pure copper.

5.3 Results

In this study, the antenna designed for operation between 1.71-2.69 GHz is based mainly on the dipole structure printed on two substrates placed horizontally and vertically on one ground plane. This printed double dipole structure, modified in the form of meandered, in particular to reduce the total structure, provides the desired performance in a frequency band relatively narrow from the desired frequency band (2.45-2.8 GHz) as mentioned above.

With the seriously improve the XPD values by decreasing the frequency band to 2 dB in the azimuth plane (ϕ = 0 °) and 120 ° (+/- 60 °) in the lower frequencies, the horizontal bend dipole thick parasitic elements starting from the end of the structures and being in the vertical direction are added.

With the addition of these parasitic elements, an antenna with gain values greater than 0 dBi was obtained at 1.71-2.69 GHz band, VSWR value below 2, isolation value between ports of more than 30 dB and 120° azimuth plane angle gain. The XPD values of the antenna are better than 10 dB in the range of 1.71-2.4 GHz and 120 ° angle and above 10 dB in the entire band (1.71-2.69 GHz) at an angle of 65°.

CHAPTER SIX
CONCLUSIONS

In this study, the design and results of a ± 45 ° dual polarization antenna, which can be used in base stations for GSM 1800 / 3G / LTE bands, are shown. The antenna consists of two printed and twisted dipoles perpendicular to each other on the ground plane to have a compact structure.

In order to increase the XPD values, which is an important parameter in double polarized antennas, vertical parasitic elements acting as monopole in the structure are added. Thanks to these added parasitic elements, a VSWR <2 value in the 1.71-2.69 GHz band and a 10 dB XPD value in the angle of 65° are found. In the 1.71-2.4 GHz band and for 120° beamwidth, XPD value of minimum 2 dB are obtained without parasitic elements while this value is about 10 dB for the structure with parasitic elements.

The antenna designed with CST Microwave Studio program has VSWR ≤ 2 within 1.71-2.69 GHz frequency band, which covers GSM 1800/3G/LTE bands. The antenna has minimum of 0 dBi gain in the beamwidth of 120° (± 60°) at azimuth plane (ϕ = 0°) along the band, and XPD values being minimum of 2 dB at 1.71-2.4 GHz for ± 60° without parasitic elements are improved to 10 dB with parasitic elements

With this thesis, it is obtained that, a ± 45° dual polarized base station antenna with improved cross-polarization discrimination (XPD) values, with compact size and wide frequency band.

For the future studies, the antenna is going to be produced professionally and result will be replied especially for the for incompatible simulation and measurement results. After that, the antenna will be used in an array like 1×2 or 1×3 and the performance will be measured for more realistic base station antenna.

REFERENCES

Aaronia, 2018 - https://www.aaronia.com/products/antennas/HyperLog-60180/

Alamy, 2010 - https://www.alamy.com/stock-photo/lte-base-station.html

Al-Barrak, A., Al-Sherbaz, A., Kanakis, T., & Crockett, R. (2017). Enhancing BER Performance Limit of BCH and RS Codes Using Multipath Diversity. Computers, 6(2), 21.

Alcatel-Lucent , 2014 http://www.tmcnet.com/tmc/whitepapers/documents/whitepapers/2014/10163-alcatel-lucent-9360-small-cell-solution-the-home.pdf

Anatel, 2017 - http://www.anatel.gov.br/grandeseventos/en/mobile-services-for-foreigners-i-e-imt

ATT, 2018 - https://www.att.com/att/microcell/

Beckman, C., & Lindmark, B. (2007, September). The evolution of base station antennas for mobile communications. In Electromagnetics in Advanced Applications, 2007. ICEAA 2007. International Conference on (pp. 85-92). IEEE.

C. A. Balanis, (2005). "Antenna Theory: Analysis and Design", 3rd Edition, John Wiley & Sons Inc.

Campos-Delgado, D. U., Luna-Rivera, J. M., Rojas, A. J., & Gutierrez, C. A. (2017). Power allocation in mobile cellular communication under multiplicative noise and interference uncertainty. IEEE Transactions on Control of Network Systems, 4(3), 451-461.

Chen, Z.-N. ve Luk K.-M.,(2009). Antennas for Base Stations in Wireless Communications. McGraw-Hill, New York, A.B.D., CommsMEA, 2015 - https://www.commsmea.com/15067-comba-telecom-launches-4g-lte-base-station-antennas

CST, 2018 - http://www.cst.com/Content/Products/MWS/Overview.aspx

D. M. Pozar, (2012). “Microwave Engineering”, 4th Edition, John Wiley & Sons Inc.

Mobilemark, 2018 - https://www.mobilemark.com/faqs/what-is-meant-by-the-vswr-of-an-antenna/

EMRSS, 2018 - https://www.emrss.com/products/sma-malefemale-adapter-rf-explorer-3

F-Blog, 2012- http://www.f-blog.info/baz-istasyonu-sistemi-bss-base-station-subsystem/

Fisher, 2017- http://www.fishercom.xyz/wireless-networks-2/introduction-kkb.html

Global, 2017-
http://www.globalsources.com/si/AS/Electronics-and/6008817493698/pdtl/Dipole-Array-Base-Station-Antenna/1123835242.htm

Gunapandian, P., Nandhitha, R., & Manimegalai, B. (2013). Design of Dual Polarized Basestation Antenna for CELL Band Application using Parasitic Conductor. International Journal of Computer Applications, 10-14.

Huawei,2018-http://carrier.huawei.com/en/products/wireless-network/SmallCell/Pico

İsenlik, T., Bilgiç, M. M., Yeğin, K., & Çiydem, M. (2011, August). GSM/UMTS dual polarization base station antenna design. In General Assembly and Scientific Symposium, 2011 XXXth URSI(pp. 1-4). IEEE.

Kaboli M., Abrishamian M. S., Mirtaheri S. A. ve Aboutorab S. M., “High-isolation XX-polar antenna”, IEEE Trans. Antennas Propag., vol. 60, no.9, s.4046-4055, Eylül 2012.

KUARK,2013 - http://www.kuark.org/2013/11/baz-istasyonlari-ve-radyasyon/

Lempiainen J. J. A. ve Laiho-Steffens J. K., “The performance of polarization diversity schemes at a base station in small/micro cells at 1800 MHz”, IEEE Trans. Vech. Tech.,Vol.47 no.3, s.1087-1092, 1998.

LIGO, 2018 - https://www.ligo.co.uk/panasonic-kx-a-405-repeater

MITSPCB, 2018 -http://www.mitspcb.com/edoc/autolab.htm

Mobilenet, 2017 – http://mobilenetworkguide.com.au/mobile_base_stations.html

Oestges, C., Clerckx, B., Guillaud, M., & Debbah, M. (2008). Dual-polarized wireless communications: from propagation models to system performance evaluation. IEEE Transactions on Wireless Communications, 7(10).

Oh T., Lim Y. G., Chae C.-B. and Lee Y., “Dual-polarization slot antenna with high cross polarization discrimination for indoor small-cell MIMO system”, IEEE Antennas and Wireless Propagation Letters, Vol.14, s.374-377, February 2015.

QSL,2017 - https://www.qsl.net/kk4obi/Meander%20Dipole.html

Secmen, M., & Hizal, A. (2010). A dual-polarized wide-band patch antenna for indoor mobile communication applications. Progress In Electromagnetics Research, 100, 189-200.

Secmen M. and Hizal A., “An inverted L-shape fed microstrip patch antenna for mobile communication”, International Symp. on Personal Indoor and Mobile Radio Comm., İstanbul, Turkey, s. 1002-1006, September 2010.

Secmen M., “Multiband and Wideband Antennas for Mobile Communication Systems”, Recent Developments in Mobile Communications – A Multidisciplinary Approach, s. 158-159, Intech, 2011

Singh, J. (2013). Comprehensive Study of Mobile Networks. International Journal of Innovative Research in Computer and Communication Engineering, 1(3).

TESTE,2018- http://www.testequipmentdepot.com/usedequipment/hewlettpackard/spectrumanalyzers/n9912a.htm

UTDALLAS, 2017 - http://www.utdallas.edu/~saquib/EE4365/Diversity/diversity-EE4365.pdf

Vallozzi, L. (2016, April). Patch antenna with slanted±45° dual polarization and performance comparison with H/V diversity. In Antennas and Propagation (EuCAP), 2016 10th European Conference on (pp. 1-5). IEEE.

Webb, W. E. (1998). Introduction to wireless local loop. Artech House, Inc..

Winters, J. H. (1998). The diversity gain of transmit diversity in wireless systems with Rayleigh fading. IEEE Transactions on Vehicular Technology, 47(1), 119-123.