ANALYSIS OF ELECTROMAGNETIC INTERFERENCE BETWEEN ANTENNAS

SAMİ DURUKAN

JULY, 2012

Title of the Thesis : **Analysis of Electromagnetic Interference between Antennas**

Submitted by **Sami DURUKAN**

Approval of the Graduate School of Natural and Applied Sciences, Çankaya University

Prof. Dr. Taner ALTUNOK
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Celal Zaim ÇİL
Head of Department

This is to certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Prof. Dr. Yusuf Ziya UMUL
Supervisor

Examination Date: July 16, 2012

Examining Committee Members

Name	**Inst.**	
Assoc. Prof. Dr. Halil. T. EYYÜBOĞLU	(Çankaya Univ.)	
Prof. Dr. Yusuf Ziya UMUL	(Çankaya Univ.)	
Assist. Prof. Dr. Nursel AKÇAM	(Gazi Univ.)	

STATEMENT OF NON-PLAGIARISM

Hereby I declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name	: Sami DURUKAN
Signature	:
Date	: July 16, 2012

ABSTRACT

ANALYSIS OF ELECTROMAGNETIC INTERFERENCE BETWEEN ANTENNAS

Sami DURUKAN

M.S.c., Department of Electronics and Communication Engineering

Supervisor: Prof. Dr. Yusuf Ziya UMUL

July 2012, 52 pages

In an electromagnetic interference (EMI) phenomenon, there is at least a transmitter antenna, and a receiver antenna which is also called as a victim system. To be able to understand this phenomenon analytically, power radiation from the transmitter and power received by the victim antenna should be evaluated. Electric fields of the antennas are used for power intensity calculations. Pattern function with respect to the spherical coordinates is a very important factor in the evaluation of an antenna's electric field.

In this thesis, two fundamental cases for EMI analysis are studied. First, a dipole antenna is considered as a transmitter and a microstrip patch antenna is considered as a victim receiver.

Secondly, a circular loop antenna and a microstrip patch antenna are taken into consideration as a transmitter and a receiver, respectively.

For both cases, their interference mechanisms are shown analytically. The results of the calculations are shown graphically in the MATLAB simulations.

Keywords: Dipole Antenna, Microstrip Patch Antenna, Electromagnetic Interference

ÖZ

ANTENLER ARASINDAKİ ELEKTROMANYETİK GİRİŞİMLERİN ANALİZİ

Sami DURUKAN
Yüksek Lisans, Elektronik ve Haberleşme Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Yusuf Ziya UMUL

Temmuz, 2012

Elektromanyetik girişim (EMI) olayında, en azından bir verici anten ve etkilenen sistem olarak da adlandırılan bir alıcı anten işin içindedir. Bu olayı analitik olarak anlaşılır kılmak için, vericiden ışıyan ve alıcı tarafından alınan güçler hesaplanmalıdır. Güç yoğunluğu hesaplamaları için antenlerin elektrik alanları kullanılır. Küresel koordinatlara göre verilen patern fonksiyonu ise, bir antenin elektrik alanının hesaplanmasında kullanılan en önemli parametredir.

Bu tezde, EMI analizi için iki temel durum üzerinde çalışılmıştır. İlk olarak, verici olarak bir dipol anten ve alıcı olarak bir mikroşerit yama anten ele alınmıştır. İkinci durumda ise, verici anten olarak bir dairesel çevrim anteni ve alıcı olarak da yine mikroşerit yama anteni üzerinde durulmuştur.

Her iki durum için de, girişim mekanizmaları çözümlemeli olarak gösterilmiştir. Hesaplamaların sonuçları, benzetimlerde grafik olarak gösterilmiştir.

Anahtar Kelimeler: Dipol Anten, Mikroşerit Yama Anteni, Elektromanyetik Girişim

ACKNOWLEDGMENTS

I would like to tell my biggest gratefulness and thanks to my supervisor, Prof. Yusuf Ziya UMUL who had helped and guided me at every phases of this thesis work with his invaluable comments and suggestions.

I would also like to thank my wife for her patience and support during my thesis studies.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

Antennas are the main issue in electromagnetic interference analysis that’s why a lot of subjects related with antennas shall be studied in the next sections of this thesis. In this chapter, a historical introduction to the topics Antennas and EMC (Electromagnetic Compatibility) both shall be done. In addition to this, a short overview of this thesis shall be given at the end of this chapter.

1.1 Introduction to Antennas

Antennas are very important elements in electrical engineering. They are also called as a transducer which converts electrical energy into electromagnetic energy, and vice versa. The IEEE definition for an antenna is that conductive and special shaped part of a transmitting or receiving system that is designed to radiate or receive the electromagnetic waves. They are used in all *wireless* communication/radar systems and electromagnetic compatibility test and measurement equipment as a very critical component. If the antenna of a communication system is designed well, so the system performance improves directly.

In the modern wireless communication systems, the antennas act with the same performance on transmitting and receiving. Moreover, antenna science and engineering has improved over a hundred years of study and experimental experience.

1.1.1 History of Antennas

It can be said that antenna science and antenna engineering started with Scottish Scientist James Clerk Maxwell. He developed the electromagnetic theory and published the paper "A Dynamical Theory of Electromagnetic Field" in 1864 where he demonstrated that there is matter in motion by which the electromagnetic phenomena are produced with the space in the neighborhood of the electric and magnetic bodies, [1]. In 1873, he also unified the theories of electricity and magnetism, and eloquently represented their relations through a set of profound equations best known as Maxwell's Equations [2].

German Physicist Heinrich Hertz firstly started to worked out with electromagnetic waves experimentally in the late times of 1800s. He implemented the first wireless electromagnetic system by using $\lambda/2$ dipole transmitter and a nearby loop receiver. It was an Italian inventor, Guglielmo Marconi who worked out on sending signals over long distances. In 1901, Marconi performed the first transatlantic electromagnetic transmission from Poldhu in Cornwall, England, to St. John's, Newfoundland, Canada. He used the radiated signals in MF (Medium Frequency) band around 850 kHz. His transmitter consisted of 50 vertical wire antennas and receiver was 152.4-meter kite-supported antenna. It was a very simple system, but was a landmark in wireless communication technology. Some people accept this invention as the starting point of electrical engineering.

From the beginning of 1900s with Marconi's experiments to 1940s, antenna scientists and engineers focused on wire type antennas with the radiation frequency up to a couple of hundred megahertz (UHF).

Along with the World War II, the technology improved very fast and a new era launched in antennas. During the period between 1940-1960, new types of antennas like apertures, horns, reflectors, etc. were firstly introduced with the evolution of microwave components and sources.

Another big advances in antenna technology occurred in the early 1970s when the microstrip patch antennas were invented. It was a low-cost and low-profile, but had some disadvantages including low efficiency, narrow bandwidth, and low power handling capabilities [2].

Antenna theory is a well-founded major field of a study in electrical engineering, and there are very good classic books about it (some of them are listed in references). Today, engineers and scientists are still working on it to improve its performance and capabilities.

1.2 Introduction to Electromagnetic Compatibility (EMC)

Since the first experimental studies with the electromagnetic waves, it has been known that these waves may cause interference in some electrical and electronic equipment like radio receivers and telephone communication systems. The other sources of electromagnetic interference are lighting, relays, dc motors, etc. An electronic system that is able to function compatibly with other electronic systems and not produce or be susceptible to interference is said to be electromagnetically compatible with its environment [8]. Hence, EMC profession deals with the generation, transmission and reception of electromagnetic energy. It is also concerned with the effects of electromagnetic interference on electronic components and devices.

1.2.1 History of EMC

In the first experiments with the radio waves, interference problems were very simple because the radio receivers were very few and far away from each other. However, some major problems raised around 1920s and technical journals began to appear regarding the radio interference. During the WW II, so many electronic devices like radar, radios, navigators, etc. were developed and used together. Because of the less usage of electronic components like vacuum tubes in devices, interference problems were being corrected easily by reassigning the operating frequencies of such transmitters or moving cables away from sources in an uncrowded electromagnetic spectrum [8]. In the 1950s, the bipolar transistors were started to use much in electronic devices. The integrated circuits and microprocessors were also used first in devices in 1960s and 1970s with high density in resulting to increase the interference problem. While those achievements continue so fast in electronic industry, the electromagnetic frequency spectrum was becoming more complex and crowded simultaneously.

In 1933, International Special Committee on Radio Interference (CISPR) was established at a meeting of International Electro-technical Commission in Paris. Afterwards, the committee published many documents to deal with EMI problem. In the early 1960s, the military community in the United States prepared MIL-STD-461 standard explaining the limits on the electromagnetic emissions of electronic systems to avoid EMI. In 1979, because of the so many interference problems in digital wired and wireless communication systems, the Federal Communication Commission (FCC) in the USA proposed some limits that all electromagnetic radiations from digital devices must be below those limits.

Recently, with the evolution of technology, intentional electromagnetic interference which is studied later on this thesis became the most important threat for the electronic devices and also countries in terms of military applications.

Those regulations and technological achievements have made EMC and interference considerations as very important aspect.

1.3 Thesis Overview

The aim of this thesis is to provide an analysis method for electromagnetic interference phenomenon between some kinds of antennas. In terms of this method, analytical investigations shall be done for such antennas like dipole, circular loop and microstrip patch antenna.

In Chapter 1, first of all, an introduction on the topics antennas and electromagnetic compatibility (EMC) are given.

In Chapter 2, some basic properties of the antennas are given. Coordinates systems, far and near fields, radiation pattern, directivity, gain parameters and radiation characteristics for an antenna are explained shortly.

In Chapter 3, electromagnetic interference is defined. Electric fields of dipole, circular loop and microstrip patch antennas are derived. Electromagnetic interactions between dipole and microstrip patch antenna and circular loop antenna-microstrip patch antenna are inspected.

In Chapter 4, some simulation results of electromagnetic interference explained in the previous chapter are given.

In Chapter 5 finally, the thesis study is summarized at a glance.

CHAPTER 2

FUNDAMENTALS OF ANTENNAS

In this chapter, some important parameters of the antennas are given shortly. Typical antenna parameters are radiation pattern, gain, directivity and polarization. Radiation characteristics of the antennas in the far field are also discussed later in this chapter.

2.1 Coordinate Systems

In this study, for antenna calculations, a three dimensional (3-D) Cartesian coordinate system with the axis notations x, y, and z will be used together with the spherical coordinates which are the polar angle (θ), the azimuthal angle (ϕ), and the radius or radial distance (r) as shown in Fig. 2-1 below. If we choose the point *O* as the origin of xyz coordinate system, and *P* as any point in this coordinate system, so the spherical coordinates can be defined as the followings:

- The polar angle, θ, is the angle between the zenith direction and the line segment *OP*.
- The azimuthal angle, ϕ, is the signed angle measured from the azimuth reference direction to the orthogonal projection of the line segment OP on the reference plane.
- The radial distance is, r, the Euclidean distance from the origin O to P.

From the Fig. 2-1, the Cartesian coordinates can be defined as

$$x = r\sin\theta\cos\phi \qquad (1.a)$$

$$y = r\sin\theta\sin\phi \quad (1.b)$$

$$z = r\cos\theta \quad (1.c)$$

where $0 \le \theta \le \pi$, $0 \le \phi \le 2\pi$, and $r \ge 0$ [4].

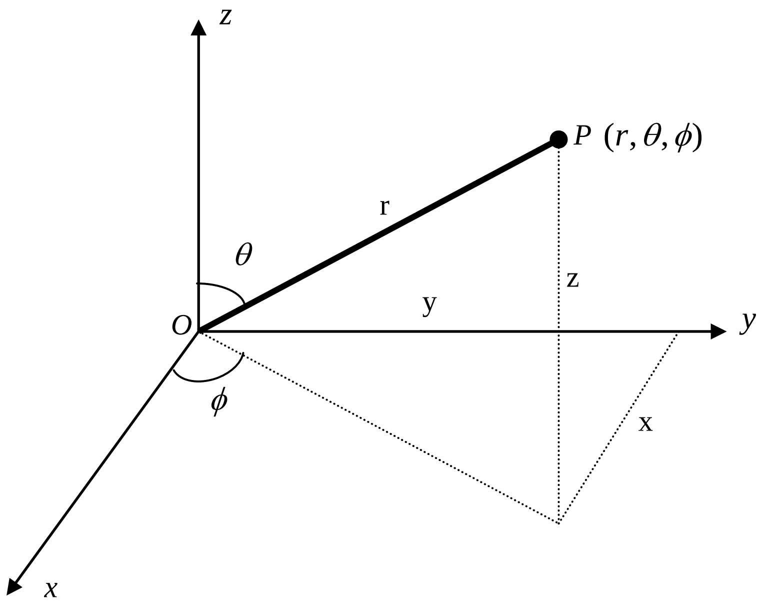

Figure 2.1. Spherical coordinates

2.2 Near and Far Fields of an Antenna

Far-field region of an antenna is defined as "that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna" [5]. If the maximum length of an antenna is D, so the far field of this antenna exists at distances bigger than $2D^2/\lambda$, where λ is the wavelength. This distance is the boundary between the near field and the *far field*. Therefore, the distance less than $2D^2/\lambda$ is in the near field region.

The near field region is divided into two sub-regions as "Reactive Near Field" and "Radiating Near Field". The reactive near field region is defined by one wavelength distance from the antenna while the radiating near field region is defined by a distance greater than one wavelength but less than $2D^2/\lambda$ showed in Fig 2.2.

2.3 Radiation Pattern

Because of the fact that the antennas do not radiate equally in all directions, they have some directional properties. An antenna radiation pattern or antenna pattern is defined as “a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates [5].

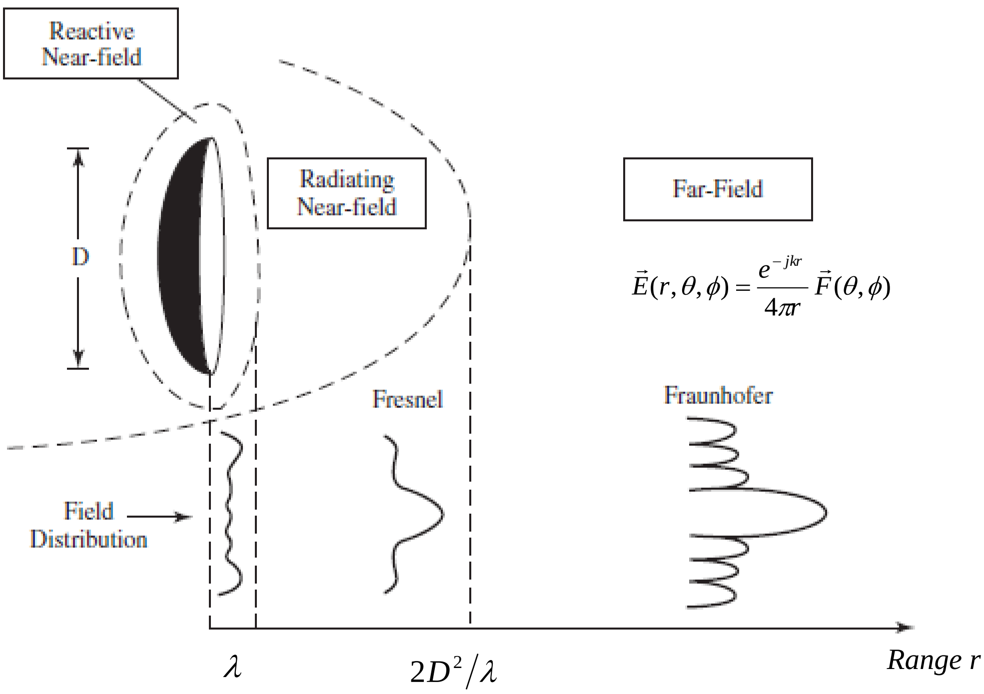

Figure 2.2. Antenna near and far fields [6]

As seen from Fig. 2-3 below, the main lobe (*or boresight axis*) contains the maximum radiation power of the antenna. A side lobe is defined as a radiation lobe in any direction other than the intended lobe. The opposite side lobe, which is also called as a back lobe, is defined as a radiation lobe whose axis makes an angle of approximately 180° with respect to the main lobe of an antenna [5].

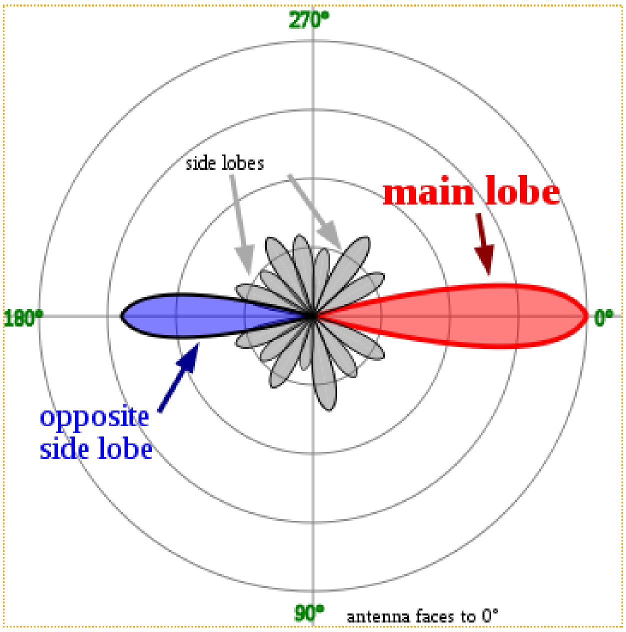

Figure 2.3. Polar representation of radiation pattern of an antenna [7]

It can be seen from the radiation pattern of an antenna in Fig. 2.4 below, the maximum radiation power level is in the main beam.

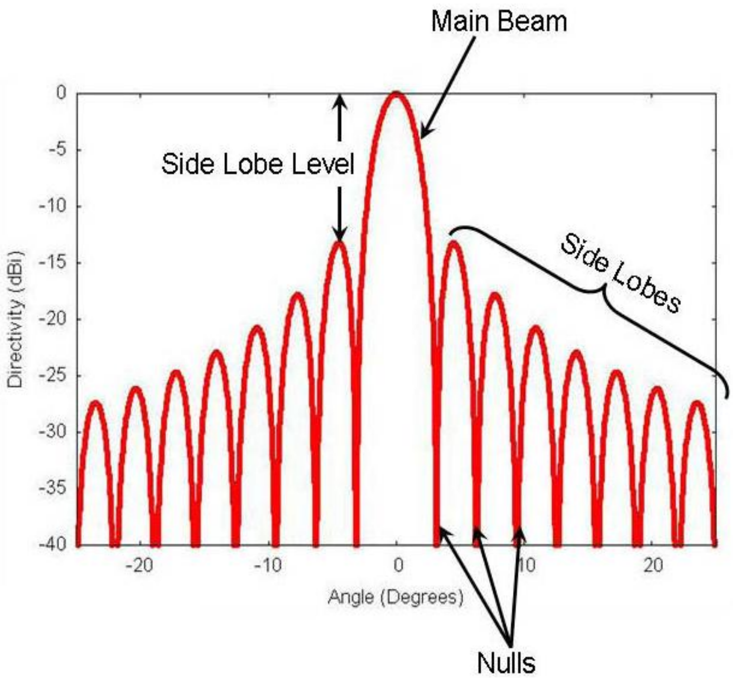

Figure 2.4. Rectangular representation of radiation pattern of an antenna [7]

2.4 Directivity

The directivity of an antenna is defined by IEEE (Institute of Electrical and Electronics Engineers) Standard Definitions of Terms for Antennas 1983 version as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. In other words, it is a measure of how 'directional' an antenna's radiation pattern is. For example, an isotropic antenna, which radiates equally in all directions, has a zero directionality; that means the directivity for this antenna is 1 or 0 dB. It can be defined mathematically as

$$D = D_{max} = \frac{U}{U_0} = \frac{U_{max}}{U_0} = \frac{4\pi U_{max}}{P_{rad}} \tag{2}$$

where D is directivity (unitless), D_{max} is maximum directivity, U is radiation intensity (Watt/unit solid angle), U_0 is radiation intensity of isotropic source, U_{max} maximum radiation intensity, P_{rad} total radiated power (Watt). The maximum directivity can written as [5]

$$D_0 = \frac{4\pi}{\left(\int_0^{2\pi}\int_0^{\pi} F(\theta,\phi)\sin\theta\, d\theta d\phi \right) / \left. F(\theta,\phi)\right|_{max}} \tag{3}$$

where $F(\theta,\phi)$ is the pattern function of the antenna. If the direction of any antenna is not specified, it is considered as the direction of maximum radiation intensity.

2.5 Gain

Gain of an antenna (in a given direction) is defined 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 [5]. In other words, it is a measure of how much power is radiated in the direction of maximum radiation to that of an ideally isotropic antenna; that is also called as a *relative gain*. Hence,

$$G = \frac{4\pi U(\theta,\phi)}{P_{in}\,(idealisotropicsource)} \tag{4}$$

which is also defined as

$$G(\theta,\phi) = e_{cd}\; D(\theta,\phi) \tag{5}$$

where e_{cd} is the antenna radiation efficiency (unitless), and $D(\theta,\phi)$ is the directivity with respect to the spherical angles [5].

2.6 Radiation Characteristics of Antennas in the Far Field

The transmitting antenna of an interference source can be thought as a point source in the far field. Next with this assumption, electric field of antennas in the far field is calculated.

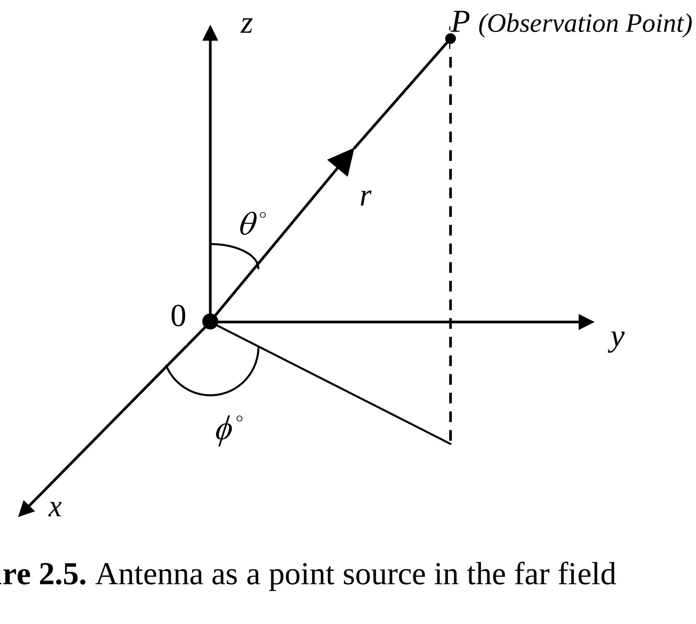

Figure 2.5. Antenna as a point source in the far field

Let's assume that there is an antenna on the origin of the coordinate plane in the Fig. 2.5. In the far-field, we can assume the antenna to be a point source. So, we can describe the electric field radiated from this antenna as

$$\vec{E} = f(\theta,\phi)\frac{\exp(-jkr)}{r}\vec{e}_t \qquad (6)$$

where, $f(\theta,\phi)$ is the pattern function of the radiating antenna with respect to the angles, $\vec{e}_t$ is the unit vector that is polarization of the field, $k = 2\pi/\lambda$ is the wave number, r is the distance from the antenna to the observation point, and –j indicates the direction of propagation that is from the origin outwards. The equation (6) includes the gain of the antenna in the pattern function as well.

We will next derive the power received to a receiver antenna from a transmitter antenna in the far field by using the electric field equations of both transmitter and receiver.

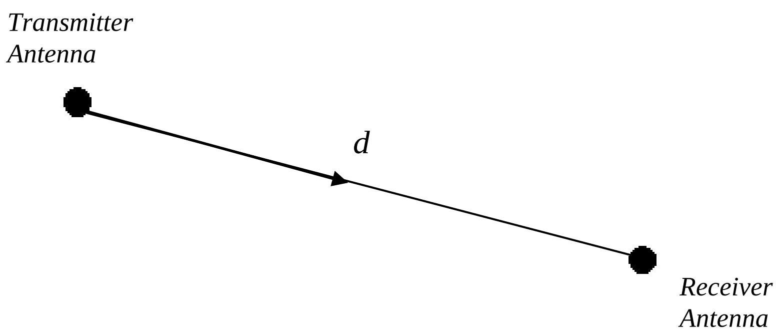

Figure 2.6. Distance between transmitter and receiver antennas

The electric field radiated from a transmitter antenna is

$$\vec{E}_t = f(\theta_t,\phi_t)\frac{\exp(-jkr_t)}{r_t}\vec{e}_t\,. \qquad (7)$$

We can assume the receiver antenna to be a transmitter and obtain its electric field as

$$\vec{E}_r = g(\theta_r, \phi_r) \frac{\exp(-jkr_r)}{r_r} \vec{e}_r \tag{8}$$

where r_t, θ_t, ϕ_t and r_r, θ_r, ϕ_r are the spherical parameters of a coordinate system having an antenna on the origin for a transmitter and a receiver system respectively.

From equation (8), the electric field of the received wave in a receiver which is showed in Fig. 2.6 can be defined as

$$E_{received} = f(\theta_{t0}, \phi_{t0}) g(\theta_{r0}, \phi_{r0}) \frac{\exp(-jkd)}{d} (\vec{e}_t . \vec{e}_r). \tag{9}$$

The power intensity in the receiver antenna is then defined as

$$P = \frac{E_{received} E^*_{received}}{2Z_0} \tag{10}$$

where $E^*_{received}$ is the complex conjugate of $E_{received}$ and Z_0 is the impedance of free space which is defined as

$$Z_0 = \mu_0 c_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = \frac{1}{\varepsilon_0 c_0} \tag{11}$$

where

μ_0 = permeability of free space,

ε_0 = permittivity of free space, and

c_0 = speed of light in free space.

Hence, we now obtain the total received power in the receiver as

$$P_{total} = PA_e \tag{12}$$

for A_e is the effective area of the antenna.

CHAPTER 3

ELECTROMAGNETIC INTERFERENCE (EMI)

In this chapter, definition of electromagnetic interference is done, and the methods of mathematical analysis for EMI between antennas are provided.

3.1 Introduction

Because of the fact that electromagnetic environment becomes more and more complex rapidly, such electronic systems using electromagnetic radiation like radars, satellites, etc. are at risk and they come under various electromagnetic interference (EMI). In order for that kind of systems to guarantee their correct functionality, signal integrity and electromagnetic compatibility analysis should be considered on the focus of electromagnetic propagation and interference.

3.2 Definition of EMI

Electromagnetic interference can be defined as undesirable electromagnetic energy or radiation which is able to couple into a victim antenna and/or system. EMI is radiated from such sources which are manmade and not of natural origin like transmitters of communication devices, jammers, and other intentional electromagnetic radiators. EMI is generally considered as the effect of unwanted energy in a victim system, rather than energy itself. Interference can cause serious degradation, destruction, or repeated interruption in the victim antenna and/or system if the power of EMI exceeds the minimum detectable signal level of the receiver [9]. EMI is mostly thought as a receiver issue. The main part of any receiver in a system is an antenna. If any unwanted signal enters into the receiver front-end, so it may cause some reduction in sensitivity or ends up its functionality with false alarm.

On the other hand, the unwanted or interfering signal does not have to be coupled into receiving channel. If its signal power is strong enough, it may block the system or damage its electronic components. In Fig. 3.1 below, the coupling ways of interfering signals on a victim system are illustrated.

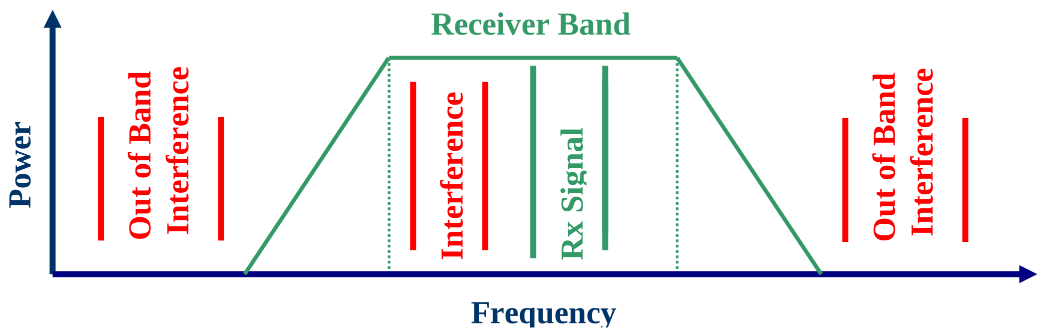

Figure 3.1. Coupling ways of EMI

3.3 Types of EMI

EMI types can be classified in two main categories as intentional and unintentional threats. Intentional EM Interferences can be classified into sub-groups as "High-Power EMI" and "Low Power Jamming". Intentional EMI can damage and/or lock the victim system [10]. On the other hand, unintentional EM Interferences can also be classified into sub-groups as "Direct Radiation", "Intermodulation", and "Clutter". This type of interference is an operational frequency-related overlaps.

Unintentional EMIs may reduce the performance of the victim system, but they are not able to damage its electronic parts.

3.3.1 Direct Radiation

Direct radiation is one of the most common EMI and it occurs in an environment where a piece of devices or a system radiates electromagnetic energy at a frequency which is being used by a receiver system, so the victim receiver system will directly receive the interfering signal. In addition to this, if an interferer signal is not at the center frequency, but within bandwidth (BW) of the victim receiver antenna, so interferer signal will also be coupled into the system with low power.

Direct radiation or coupling can be originated from wireless devices, such communication systems like radars, satellites, or any other transmitter of a system using the same BW with the victim system.

Direct radiating interference can be modeled as shown in Fig 3.2. The interfering signals couple into the system passing through receiver (Rx) antenna.

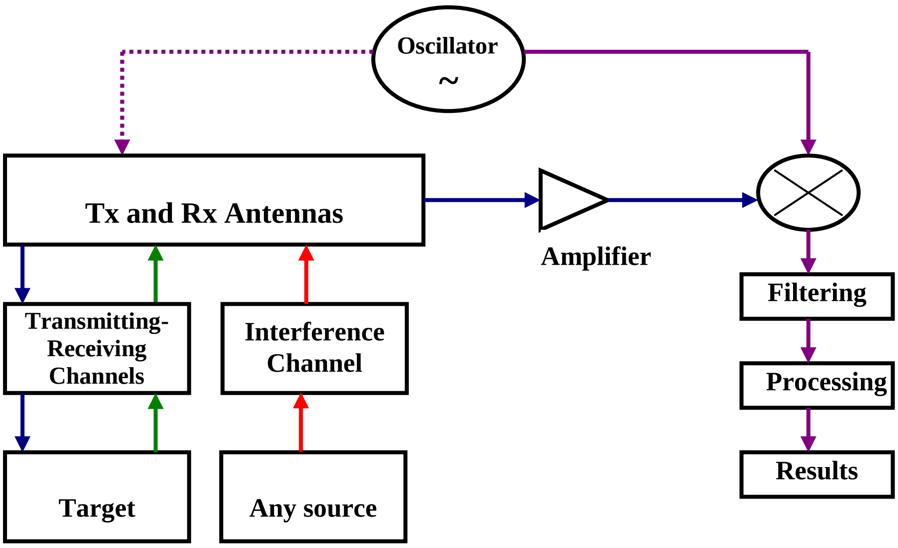

Figure 3.2. EMI Coupling into a receiver’s front-end circuitry.

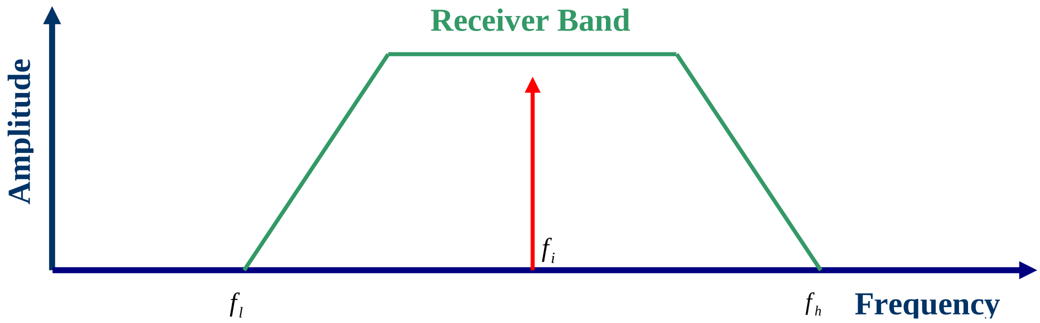

Figure 3.3 Frequency of an interfering signal

In Fig. 3.3, the interfering signal used in this model is shown,

$$BW = f_h - f_l \tag{13}$$

where BW being the bandwidth of the antenna, f_h is the highest detectable frequency of antenna, f_l is the lowest detectable frequency of antenna, f_i is the frequency of interferer signal, and $f_l \le f_i \le f_h$.

3.4 EMI Analysis Between Antennas

In this section, three cases for the analysis of EMI between antennas will be considered. One of them is the case of transmitter with a dipole antenna against a receiver with micro-strip patch antenna. The second one is the case of transmitter with circular loop antenna against receiver with micro-strip patch antenna. Finally, simultaneous EMI of the dipole and circular loop antennas over a microstrip patch antenna will be discussed.

3.4.1. EMI Between a Dipole Transmitter and a Microstrip Patch Receiver

This is the first case, in this study, that will be investigated about electromagnetic interference (EMI) between two different types of antennas. In this case, we assume there is a dipole antenna with the length of *2h*, which is located along the z-axis on the origin centered shown in the Fig. 3.4 below.

We will consider this dipole antenna as an interference source over a microstrip antenna located at the point *P*. Therefore, on this scenario, the dipole antenna is assumed to be a transmitter and micro-strip antenna is assumed to be a victim receiver.

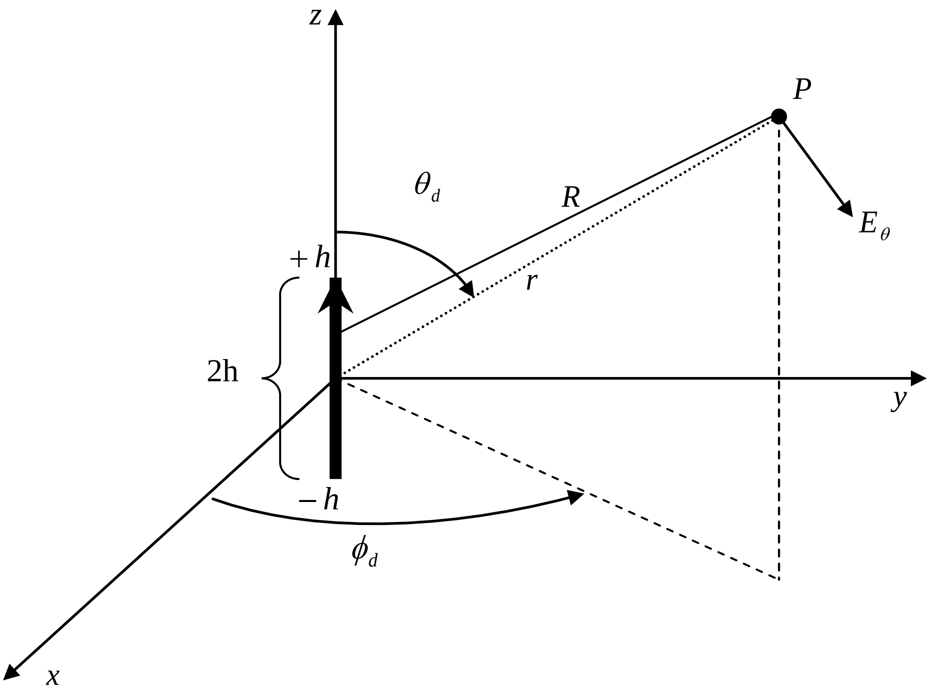

Figure 3.4. Dipole Antenna with Spherical Coordinates

The vector potential of this dipole, $\vec{A}_{rd}$, at point P is

$$\vec{A}_{rd} = \frac{\mu_0}{4\pi} I_0 \int_{-h}^{+h} \frac{e^{-jkR}}{R} dz' \, \vec{e}_z \qquad (14)$$

where z' is any point on the antenna, R is the distance from any point on the antenna to the point P, $\vec{e}_z$ is the unit vector on the z-axis.

So, we can convert the integration in (14) as

$$\vec{A}_{rd} = \frac{\mu_0}{4\pi} I_0 \frac{e^{-jkr}}{r} \int_{-h}^{+h} e^{jkz' \cos\theta_d} \, dz' \, \vec{e}_z \tag{15}$$

where I_0 is the dipole current flowing only on the z-axis. If we evaluate the integral in (15), we get

$$\vec{A}_{rd} = \frac{\mu_0}{4\pi} I_0 \frac{e^{-jkr}}{r} \frac{e^{jkz' \cos\theta_d}}{jk\cos\theta_d} \Big|_{-h}^{+h} \vec{e}_z \tag{16}$$

by putting the values +h and –h into (16) gives

$$\vec{A}_{rd} = \frac{\mu_0}{4\pi} I_0 \frac{e^{-jkr}}{r} \left(\frac{e^{jkh\cos\theta_d} - e^{-jkh\cos\theta_d}}{jk\cos\theta_d} \right) \vec{e}_z \tag{17}$$

If we apply the Euler's formula for sine function, so we get

$$e^{jkh\cos\theta_d} - e^{-jkh\cos\theta_d} = 2j\sin(kh\cos\theta_d) \tag{18}$$

and then putting it into the equation (17) above, so it gives

$$\vec{A}_{rd} = \frac{\mu_0 I_0 h}{4\pi} \frac{e^{-jkr}}{r} \left\{ \frac{2\not{j}\sin(kh\cos\theta_d)}{\not{j}kh\cos\theta_d} \right\} \vec{e}_z \tag{19}$$

If we abbreviate (19), then we get

$$\vec{A}_{rd} = \frac{\mu_0 I_0 h}{2\pi} \frac{e^{-jkr}}{r} \left\{ \frac{\sin(kh\cos\theta_d)}{kh\cos\theta_d} \right\} \vec{e}_z \tag{20}$$

From the vector potential equation of a dipole antenna, we can easily derive its electric field, E_{ffd} at a distance d in the far field as

$$\vec{E}_{ffd} = -\frac{j\omega\mu_0 I_0 h}{2\pi} \left\{ \frac{\sin(kh\cos\theta_d)}{kh\cos\theta_d} \right\} \frac{e^{-jkr}}{r} \vec{e}_{\theta_d} \tag{21}$$

where *r* is the distance between the interferer antenna and the victim antenna. The subscript *ffd* stands for "far field of a dipole".

At this point, from this equation we can define $f(\theta_d)$ which is called as pattern function of dipole with the dependence of the spherical angle θ and derived as

$$\mathrm{f}(\theta_d) = \frac{\sin(kh\cos\theta_d)}{kh\cos\theta_d}\,. \tag{22}$$

where the term e^{-jkr} is the description of phase-variation of the wave versus distance, and $k = \frac{2\pi}{\lambda}$ is the wave number.

We now need to evaluate the effects of the radiation from the interferer with a dipole antenna mentioned above over a victim receiver with a micro-strip antenna.

For a rectangular micro-strip patch antenna, we next evaluate the E_θ and E_φ components of far fields from Carver and Mink [3] as

$$\left|E_{\theta_m}\right| = \left| \left[\cos(ks\cos\theta_m)\right] \left[\frac{\sin(\frac{ka}{2}\sin\theta_m \sin\phi_m)}{\frac{ka}{2}\sin\theta_m \sin\phi_m} \right] \left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m) \right] \cos\phi_m \right| \tag{23}$$

and,

$$\left|E_{\phi_m}\right| = \left| \left[\cos(ks\cos\theta_m)\right] \left[\frac{\sin(\frac{ka}{2}\sin\theta_m \sin\phi_m)}{\frac{ka}{2}\sin\theta_m \sin\phi_m} \right] \left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m) \right] \cos\theta_m \sin\phi_m \right| \tag{24}$$

where a is the width of the microstrip patch, b is the length of the microstrip patch, s is the thickness of the dielectric substrate as modeled in Fig. 3.5.

The total electric field vector is then described as

$$\vec{E}_{ffm} = E_{\theta_m}.\vec{e}_{\theta_m} + E_{\phi_m}.\vec{e}_{\phi_m} \tag{25}$$

where the subscript *ffm* stands for “far field of a microstrip patch antenna”.

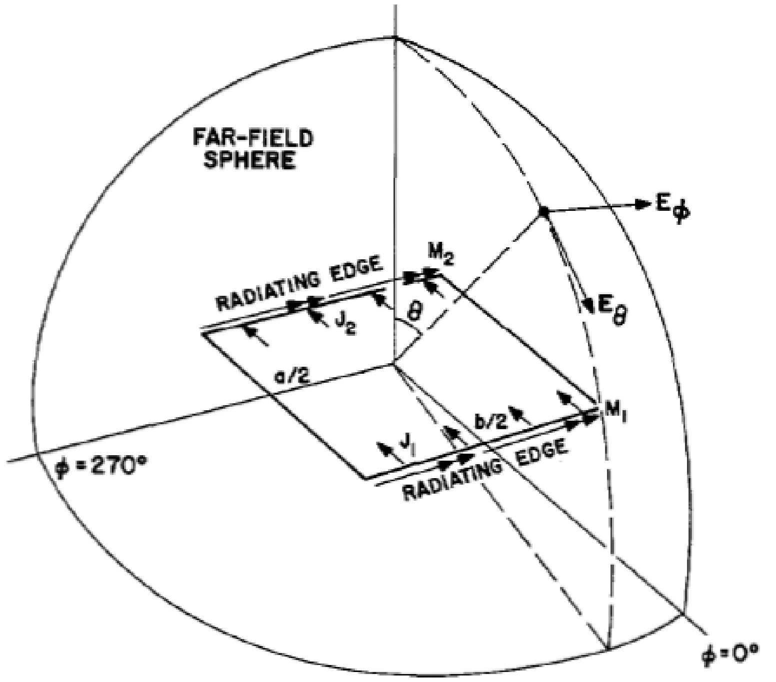

Figure 3.5. Spherical geometry of rectangular microstrip patch antenna [3].

Now, we are able to derive the total electric field, E_{rm} received by microstrip patch antenna by putting (21) and (25) together.

$$E_{rm} = \sqrt{\left(f(\theta_d) g_1(\theta_m, \phi_m) \frac{e^{-jkr}}{r} (\vec{e}_d . \vec{e}_{\theta_m}) \right)^2 + \left(f(\theta_d) g_2(\theta_m, \phi_m) \frac{e^{-jkr}}{r} (\vec{e}_{\theta_d} . \vec{e}_{\phi_m}) \right)^2} \quad (26)$$

where $g_1(\theta_m, \phi_m)$ is the pattern function of E_θ component of microstrip patch defined in (23), and $g_2(\theta_m, \phi_m)$ is the pattern function of E_ϕ component of microstrip patch defined (24).

If we put (22), (23) and (24) into (26), then it gives

$$E_{rm} = \left\{ -\frac{j\omega\mu I_0 h}{2\pi} \frac{\sin\left(kh\cos\theta_d\right)}{kh\cos\theta_d} \frac{e^{-jkr}}{r} \right\}$$

$$\times \left(\left[\left[\cos(ks\cos\theta_m)\right] \left[\frac{\sin(\frac{ka}{2}\sin\theta_m \sin\phi_m)}{\frac{ka}{2}\sin\theta_m \sin\phi_m} \right] \left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m) \right] \cos\phi_m (\vec{e}_{\theta_d} . \vec{e}_{\theta_m}) \right]^2 \right.$$

$$\left. + \left[\left[\cos(ks\cos\theta_m)\right] \left[\frac{\sin(\frac{ka}{2}\sin\theta_m \sin\phi_m)}{\frac{ka}{2}\sin\theta_m \sin\phi_m} \right] \left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m) \right] \cos\theta_m \sin\phi_m (\vec{e}_{\theta_d} . \vec{e}_{\phi_m}) \right]^2 \right)^{1/2} \quad (27)$$

Equation (27) is a general form for the total electric field received by the microstrip patch antenna.

In this electromagnetic interference phenomenon, both the dipole interferer antenna and the microstrip patch antenna as a victim have different coordinate systems.

Now, we will show the dependency of the angles θ_d, θ_m and ϕ_m with each other. In Fig. 3-6, a dipole and a micro-strip antenna are shown in the different coordinates systems. Dipole antenna is located in the origin of (x, y, z) coordinate system while micro-strip antenna is located in the origin of (x_1, y_1, z_1) coordinate system. The distance between antennas is d. In this figure, r and r_1 are virtual distances.

In Cartesian coordinates $x = x_1 + x_0$, $y = y_1 + y_0$, and $z = z_1 + z_0$. From this, we can define the distance, d, between antennas as

$$d = \sqrt{x_0^{\ 2} + y_0^{\ 2} + z_0^{\ 2}}\ . \quad (28)$$

where x_0, y_0 and z_0 are the coordinates in the xyz coordinate system shown in the Fig. 3.6. If we use the spherical coordinates, we have

$$r\sin\theta\cos\phi = r_1 \sin\theta_1 \cos\theta_1 + x_0\,. \quad (29)$$

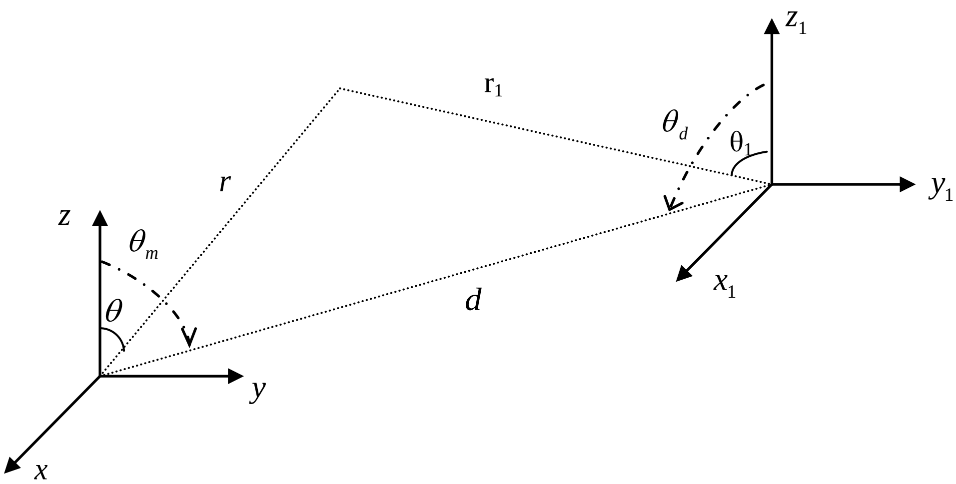

Figure 3.6. 3D-Coordinates of interfering dipole and microstrip patch antennas

We can also define it for y_0 as

$$r\sin\theta\sin\phi = r_1\sin\theta_1\sin\theta_1 + y_0 \tag{30}$$

and for z_0 as

$$r\cos\theta = r_1\cos\theta_1 + z_0\,. \tag{31}$$

If the angle θ_1 approaches to θ_d, and the angle θ approaches to θ_m, so it gives $x_0 = d\sin\theta_m\cos\phi_m$, $y_0 = d\sin\theta_m\sin\phi_m$ and $z_0 = d\cos\theta_m$. Hence, we get

$$r\cos\theta_m = r_1\cos\theta_1 + d\cos\theta_m\,. \tag{32}$$

If we put the equation $r = d - r_1$ into (32), so it gives

$$\cos(\pi - \theta_m) = \cos\theta_d \tag{33}$$

So, we will use equation (33) as $\theta_d = \pi - \theta_m$ in (27).

3.4.1.1 Derivation of the Unit Vectors

The unit vector $\vec{e}_{\theta_1}$ is defined as

$$\vec{e}_{\theta_1} = \cos\theta_1\cos\phi_1\vec{e}_{x_1} + \cos\theta_1\sin\phi_1\vec{e}_{y_1} - \sin\theta_1\vec{e}_{z_1} \tag{34}$$

Because of the fact that the axis directions are same on both coordinate systems in Fig. 9 , so we have $\vec{e}_x = \vec{e}_{x_1}$, $\vec{e}_y = \vec{e}_{y_1}$, and $\vec{e}_z = \vec{e}_{z_1}$. So, it gives

$$\vec{e}_{\theta_1} = \cos\theta_1 \cos\phi_1 \vec{e}_x + \cos\theta_1 \sin\phi_1 \vec{e}_y - \sin\theta_1 \vec{e}_z \tag{35}$$

If $\theta_1 \to \theta_d$, and $\theta \to \theta_m$, we have

$$\vec{e}_{\theta_d} = \cos\theta_d \cos\phi_d \vec{e}_x + \cos\theta_d \sin\phi_d \vec{e}_y - \sin\theta_d \vec{e}_z \tag{36}$$

and,

$$\vec{e}_{\theta_m} = \cos\theta_m \cos\phi_m \vec{e}_x + \cos\theta_m \sin\phi_m \vec{e}_y - \sin\theta_m \vec{e}_z \tag{37}$$

We now need to find the azimuth angle (ϕ_d) of the dipole antenna. If we look into xy plane along z-axis, we see a shape like in Fig. 3.7.

According to the geometry of Fig. 3.9, we have

$$\phi_d = \pi - \phi_m . \tag{38}$$

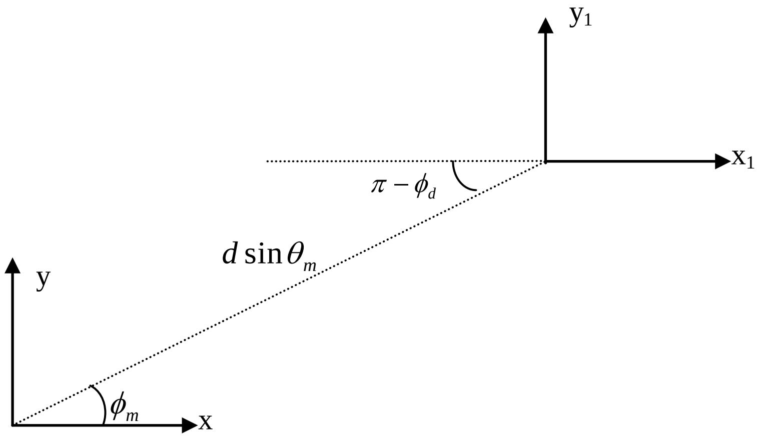

Figure 3.7. Azimuthal angles on the x-y plane

If we rewrite (36) by using (33) and (38), we get

$$\vec{e}_{\theta_d} = \cos(\pi - \theta_m)\cos(\pi - \phi_m)\vec{e}_x + \cos(\pi - \theta_m)\sin(\pi - \phi_m)\vec{e}_y - \sin(\pi - \theta_m)\vec{e}_z$$

$$= \cos\theta_m \cos\phi_m \, \vec{e}_x - \cos\theta_m \sin\phi_m \, \vec{e}_y - \sin\theta_m \, \vec{e}_z \tag{39}$$

Now, we can calculate the term $\vec{e}_d . \vec{e}_{\theta_m}$, which is the scalar multiplication of the unit vectors, as

$$\vec{e}_d . \vec{e}_{\theta_m} = (\cos\theta_m \cos\phi_m)^2 - (\cos\theta_m \sin\phi_m)^2 + \sin^2\theta_m \tag{40}$$

The unit vector $\vec{e}_{\phi_m}$ is defined as

$$\vec{e}_{\phi_m} = -\sin\phi_m \vec{e}_x + \cos\phi_m \vec{e}_y \tag{41}$$

So we can find the scalar multiplication of the vectors $\vec{e}_d . \vec{e}_{\phi_m}$ by using (39) and (41) as

$$\vec{e}_d . \vec{e}_{\phi_m} = -2\cos\theta_m \cos\phi_m \sin\phi_m . \tag{42}$$

3.4.1.2 Total Received Power

We are trying to find the *total received power* by the microstrip victim antenna. For that purpose, we should use equation (11). So,

$$P_{rm} = \frac{E_{rm} E_{rm}^*}{2Z_0} \tag{43}$$

where P_{rm} is the power intensity in the receiver that is a microstrip patch antenna. If we put (27), (40) and (42) into (43), so we get

$$P_{rm} = \frac{1}{2Z_0} \left\{ \frac{\omega\mu I_0 h}{2\pi} \frac{\sin(kh\cos(\theta_m))}{kh\cos\theta_m} \frac{1}{r} \right\}^2$$

$$\left(\left[[\cos(ks\cos\theta_m)] \left[\frac{\sin(\frac{ka}{2}\sin\theta_m \sin\phi_m)}{\frac{ka}{2}\sin\theta_m \sin\phi_m} \right] \left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m) \right] \cos\phi_m (\vec{e}_{\theta_d} . \vec{e}_{\theta_m}) \right]^2 \right.$$

$$\left. + \left[[\cos(ks\cos\theta_m)] \left[\frac{\sin(\frac{ka}{2}\sin\theta_m \sin\phi_m)}{\frac{ka}{2}\sin\theta_m \sin\phi_m} \right] \left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m) \right] \cos\theta_m \sin\phi_m (\vec{e}_{\theta_d} . \vec{e}_{\phi_m}) \right]^2 \right) \tag{44}$$

By using (13), we can find the total received power on the victim system that is in the microstrip patch antenna, P_{trm}, as

$$P_{trm} = \frac{A_e}{2Z_0}\left\{\frac{\omega\mu I_0 h}{2\pi}\frac{\sin\left(kh\cos(\theta_m)\right)}{kh\cos\theta_m}\frac{1}{r}\right\}^2$$

$$\left(\left[\left[\cos(ks\cos\theta_m)\right]\left[\frac{\sin(\frac{ka}{2}\sin\theta_m\sin\phi_m)}{\frac{ka}{2}\sin\theta_m\sin\phi_m}\right]\left[\cos(\frac{kb}{2}\sin\theta_m\cos\phi_m)\right]\cos\phi_m(\vec{e}_{\theta_d}.\vec{e}_{\theta_m})\right]^2\right.$$

$$\left.+\left[\left[\cos(ks\cos\theta_m)\right]\left[\frac{\sin(\frac{ka}{2}\sin\theta_m\sin\phi_m)}{\frac{ka}{2}\sin\theta_m\sin\phi_m}\right]\left[\cos(\frac{kb}{2}\sin\theta_m\cos\phi_m)\right]\cos\theta_m\sin\phi_m(\vec{e}_{\theta_d}.\vec{e}_{\phi_m})\right]^2\right) \quad (45)$$

where, A_e is the effective area of the microstrip patch antenna.

3.4.2. EMI between a Circular Loop Transmitter and a Microstrip Patch Receiver

This is the second type of EMI which is studied in this thesis between two different antennas. In this case, we assume there is a loop antenna with the radius of a_1, and it is located in the origin centered shown in Fig. 3.8.

We will take this loop antenna into account as an interference source over a microstrip patch antenna at the point *P*. Therefore, on this scenario, the loop antenna is assumed to be a transmitter and the microstrip antenna is assumed again to be a victim receiver.

Electric field vector of the circular loop antenna at the point *P* can be defined as

$$\vec{E} = \vec{e}_{\phi_l}\frac{j\omega\mu_0 I_0 a_1}{4\pi}\int_0^{2\pi}\frac{e^{-jkR}}{R}d\phi' \quad (46)$$

where I_0 is the current flowing on the circular loop antenna is R is the distance from the antenna to the point P. We can define the distance R as

$$R = \sqrt{r^2 + a_1^2 - 2ra_1 \sin\theta_l \cos(\phi_l - \phi')} \,. \tag{47}$$

In the far field, the distance R can be approximately defined as

$$R \approx r - a_1 \sin\theta_l \cos(\phi_l - \phi') \tag{48}$$

where r is the distance from the origin of the coordinate system to the point *P*. Hence, equation (46) can be converted as

$$\vec{E}_{ffl} \approx \vec{e}_{\phi_l} \frac{j\omega\mu_0 I_0 a_1}{4\pi} \frac{e^{-jkr}}{r} \int_0^{2\pi} e^{jka\sin\theta_l \cos(\phi - \phi')} d\phi' \tag{49}$$

where the subscript *ffl* stands for "far field of the circular loop antenna".

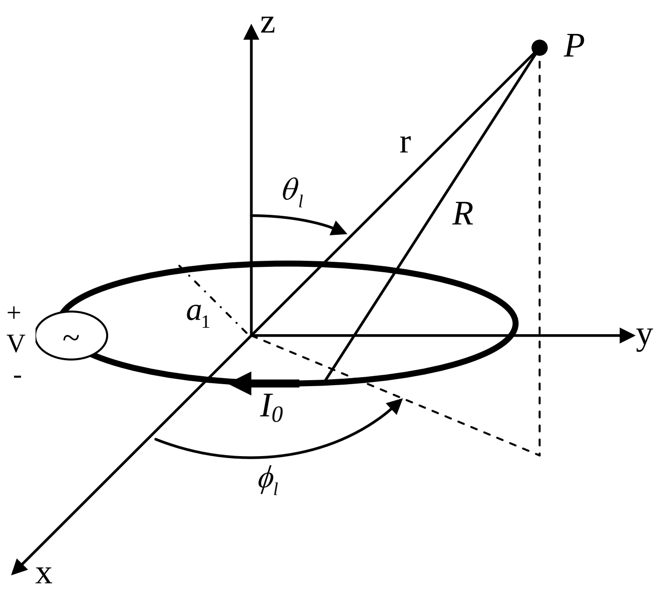

Figure 3.8. Spherical coordinates of the circular loop antenna

Equation (49) can also be written in terms of Bessel functions as

$$\vec{E}_{ffl} \approx \vec{e}_{\phi_l} \frac{j\omega\mu_0 I_0 a_1}{4\pi} \frac{e^{-jkr}}{r} \sum_{n=-\infty}^{\infty} J_n(ka_1 \sin\theta_l) \exp\left[jn\left(\frac{\pi}{2} - \phi\right)\right] \int_0^{2\pi} e^{jka_1 \sin\theta_l \cos(\phi-\phi')} d\phi' .$$

(50)

So, from (50), we find it as

$$\vec{E}_{ffl} = \vec{e}_{\phi_l} \frac{j\omega\mu_0 I_0 a_1}{2} \frac{e^{-jkr}}{r} J_0(ka_1 \sin\theta_l) \quad (51)$$

where J_0 is the Bessel function of the first kind.

We need to find the received wave, E_{rm}, on the microstrip patch antenna to be able to evaluate the power intensity. By using equation (26), we get

$$E_{rm} = \frac{j\omega\mu_0 I_0 a_1}{2} \frac{e^{-jkr}}{r} J_0(ka_1 \sin\theta_l)$$

$$\times \left(\left[[\cos(ks\cos\theta_m)] \left[\frac{\sin(\frac{ka_2}{2}\sin\theta_m \sin\phi_m)}{\frac{ka_2}{2}\sin\theta_m \sin\phi_m} \right] \left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m) \right] \cos\phi_m (\vec{e}_{\phi_l} . \vec{e}_{\theta_m}) \right]^2 \right.$$

$$\left. + \left[[\cos(ks\cos\theta_m)] \left[\frac{\sin(\frac{ka_2}{2}\sin\theta_m \sin\phi_m)}{\frac{ka_2}{2}\sin\theta_m \sin\phi_m} \right] \left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m) \right] \cos\theta_m \sin\phi_m (\vec{e}_{\phi_l} . \vec{e}_{\phi_m}) \right]^2 \right)^{1/2}$$

(52)

where a_1 represents the diameter of the radiating circular loop antenna, and a_2 represents the width of the receiving microstrip patch antenna.

3.4.2.1 Total Received Power

The power intensity received by microstrip patch antenna is again calculated like in equation (44), so we get

$$P_{rm} = \frac{1}{2Z_0}\left(\frac{\omega\mu_0 I_0 a_1}{2}\frac{1}{r}J_0(ka_1 \sin\theta_l)\right)^2$$

$$\times\left(\left[\left[\cos(ks\cos\theta_m)\right]\left[\frac{\sin(\frac{ka_2}{2}\sin\theta_m \sin\phi_m)}{\frac{ka_2}{2}\sin\theta_m \sin\phi_m}\right]\left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m)\right]\cos\phi_m(\vec{e}_{\phi_l}.\vec{e}_{\theta_m})\right]^2\right.$$

$$\left.+\left[\left[\cos(ks\cos\theta_m)\right]\left[\frac{\sin(\frac{ka_2}{2}\sin\theta_m \sin\phi_m)}{\frac{ka_2}{2}\sin\theta_m \sin\phi_m}\right]\left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m)\right]\cos\theta_m \sin\phi_m(\vec{e}_{\phi_l}.\vec{e}_{\phi_m})\right]^2\right)$$

(53)

where, P_{rm} is the power intensity on the microstrip patch antenna caused by the circular loop interferer.

By using (13), we can again find the total received power on the victim system which is a microstrip patch antenna, P_{trm} as

$$P_{trm} = \frac{A_e}{2Z_0}\left(\frac{\omega\mu_0 I_0 a_1}{2}\frac{1}{r}J_0(ka_1 \sin\theta_l)\right)^2$$

$$\times\left(\left[\left[\cos(ks\cos\theta_m)\right]\left[\frac{\sin(\frac{ka_2}{2}\sin\theta_m \sin\phi_m)}{\frac{ka_2}{2}\sin\theta_m \sin\phi_m}\right]\left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m)\right]\cos\phi_m(\vec{e}_{\phi_l}.\vec{e}_{\theta_m})\right]^2\right.$$

$$\left.+\left[\left[\cos(ks\cos\theta_m)\right]\left[\frac{\sin(\frac{ka_2}{2}\sin\theta_m \sin\phi_m)}{\frac{ka_2}{2}\sin\theta_m \sin\phi_m}\right]\left[\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m)\right]\cos\theta_m \sin\phi_m(\vec{e}_{\phi_l}.\vec{e}_{\phi_m})\right]^2\right)$$

(54)

where, A_e is the effective area of the microstrip patch antenna.

3.4.2.2 Derivation of the Polarization Vectors

Similarly to equation (41), we can describe the azimuthal unit vector $\vec{e}_{\phi_l}$ as

$$\vec{e}_{\phi_l} = -\sin\phi_l \vec{e}_x + \cos\phi_l \vec{e}_y \tag{55}$$

From this, we can find $\vec{e}_{\phi_l} . \vec{e}_{\phi_m}$ by using equation (38) as

$$\vec{e}_{\phi_l} . \vec{e}_{\phi_m} = \left(\sin^2\phi_m + \cos^2\phi_m\right) = 1 \tag{56}$$

and,

$$\vec{e}_{\phi_l} . \vec{e}_{\theta_m} = -2\cos\theta_m \cos\phi_m \sin\phi_m \tag{57}$$

Hence, the equation (54) is transformed as

$$P_{trm} = \frac{A_e}{2Z_0}\left[\frac{\omega\mu_0 I_0 a_1}{2}\frac{1}{r}J_0(ka_1 \sin\theta_m)\right]^2$$

$$\left(\left[\cos(ks\cos\theta_m)\sin c\left(\frac{ka_2}{2}\sin\theta_m \sin\phi_m\right)\left\{\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m)\right\}\cos\phi_m\left(-2\cos\theta_m \cos\phi_m \sin\phi_m\right)\right]^2\right.$$

$$\left.+\left[\left\{\cos(ks\cos\theta_m)\right\}\sin c\left(\frac{ka_2}{2}\sin\theta_m \sin\phi_m\right)\times\cos(\frac{kb}{2}\sin\theta_m \cos\phi_m)\ \cos\theta_m \sin\phi_m\right]^2\right). \tag{58}$$

3.4.3. EMI Between Two Different Transmitters and a Microstrip Patch Receiver

In this section, we will discuss the EMI phenomenon by considering two different transmitters including a dipole antenna and a circular loop antenna over a micro strip patch antenna as a receiver. So, in this case, we assume two interference sources over a victim system.

Firstly, we need to find the total electric field of the incident waves received by the microstrip patch antenna. It is defined as

$$E_{rm} = f(\theta_m, \phi_m)\left(E_d \vec{e}_d + E_l \vec{e}_l\right)\vec{e}_m \tag{59}$$

where, E_{rm} is the total electric field generated by a dipole antenna and a circular loop antenna over a microstrip patch antenna, $f(\theta_m, \phi_m)$ is the pattern function of the microstrip patch antenna, $E_d .\vec{e}_d$ is the electric field vector of the dipole antenna, and $E_l .\vec{e}_l$ is the electric field vector of the circular loop antenna.

In (27) and (52), we have already derived the electric fields generated by a dipole antenna and a loop antenna over a microstrip patch antenna separately. If we combine those results in (59), we get two components of total electric field over the microstrip patch antenna. First one is

$$\begin{aligned} E_{rmd} = &\left(-\frac{j\omega\mu_0 I_{0d}\, h}{2\pi} \frac{\sin\left(kh\cos(\theta_{m1})\right)}{kh\cos\theta_{m1}} \frac{e^{-jkd_1}}{d_1} \right) \\ &\times \left(\left[\left[\cos(ks\cos\theta_{m1})\right] \left[\frac{\sin(\frac{ka}{2}\sin\theta_{m1}\sin\phi_{m1})}{\frac{ka}{2}\sin\theta_{m1}\sin\phi_{m1}} \right] \left[\cos(\frac{kb}{2}\sin\theta_{m1}\cos\phi_{m1})\right] \cos\phi_{m1}(\vec{e}_{\theta_d}.\vec{e}_{\theta_m}) \right]^2 \right. \\ &\left. + \left[\left[\cos(ks\cos\theta_{m1})\right] \left[\frac{\sin(\frac{ka}{2}\sin\theta_{m1}\sin\phi_{m1})}{\frac{ka}{2}\sin\theta_{m1}\sin\phi_{m1}} \right] \left[\cos(\frac{kb}{2}\sin\theta_{m1}\cos\phi_{m1})\right] \cos\theta_{m1}\sin\phi_{m1}(\vec{e}_{\theta_d}.\vec{e}_{\phi_m}) \right]^2 \right)^{1/2} \end{aligned} \tag{60}$$

where, E_{rmd} is the electric field received by the microstrip patch antenna generated by the dipole antenna, $\vec{e}_d .\vec{e}_{\theta_m} = \left(\cos\theta_{m1}\cos\phi_{m1}\right)^2 - \left(\cos\theta_{m1}\sin\phi_{m1}\right)^2 + \sin^2\theta_{m1}$, $\vec{e}_d .\vec{e}_{\phi_m} = -2\cos\theta_{m1}\cos\phi_{m1}\sin\phi_{m1}$, d_1 is the distance between the dipole antenna and the microstrip patch antenna, I_{0d} is the current flowing on the dipole antenna.

Second component of the total electric field over the microstrip patch antenna is defined as

$$E_{rml} = \frac{j\omega\mu_0 I_{0l} a_1}{2} \frac{e^{-jkd_2}}{d_2} J_0(ka_1 \sin\theta_{m2})$$
$$\times\left(\left[\cos(ks\cos\theta_{m2})\sin c\left(\frac{ka_2}{2}\sin\theta_{m2}\sin\phi_{m2}\right)\cos(\frac{kb}{2}\sin\theta_{m2}\cos\phi_{m2})\cos\phi_{m2}(\vec{e}_{\phi_l}.\vec{e}_{\theta_m})\right]^2\right.$$
$$\left.+\left[[\cos(ks\cos\theta_{m2})]\sin c\left(\frac{ka_2}{2}\sin\theta_{m2}\sin\phi_{m2}\right)\left[\cos(\frac{kb}{2}\sin\theta_{m2}\cos\phi_{m2})\right]\cos\theta_{m2}\sin\phi_{m2}(\vec{e}_{\phi_l}.\vec{e}_{\phi_m})\right]^2\right)^{1/2}$$

(61)

where E_{rml} is the electric field received by the microstrip patch antenna generated by the circular loop antenna, d_2 is the distance between the circular loop antenna and the microstrip patch antenna, I_{0l} is the current flowing on the circular loop antenna, a_1 is the radius of the circular loop antenna, and a_2 is the width of the microstrip patch antenna.

In Fig. 3.9, EMI mechanism which occurs simultaneously between two interferer including a dipole and a circular loop antenna over a microstrip patch antenna is shown, where d_1 , d_2 , d_3 are distances for dipole to microstrip, circular loop to microstrip and dipole to circular loop antennas, respectively. If we apply the cosine rule, we get

$$d_3^2 = d_1^2 + d_2^2 - 2d_1 d_2 \cos\theta_{m3} \qquad (62)$$

The angle θ_{m3} can be written as

$$\theta_{m3} = \pi - (\theta_{m1} + \theta_{m2}) \qquad (63)$$

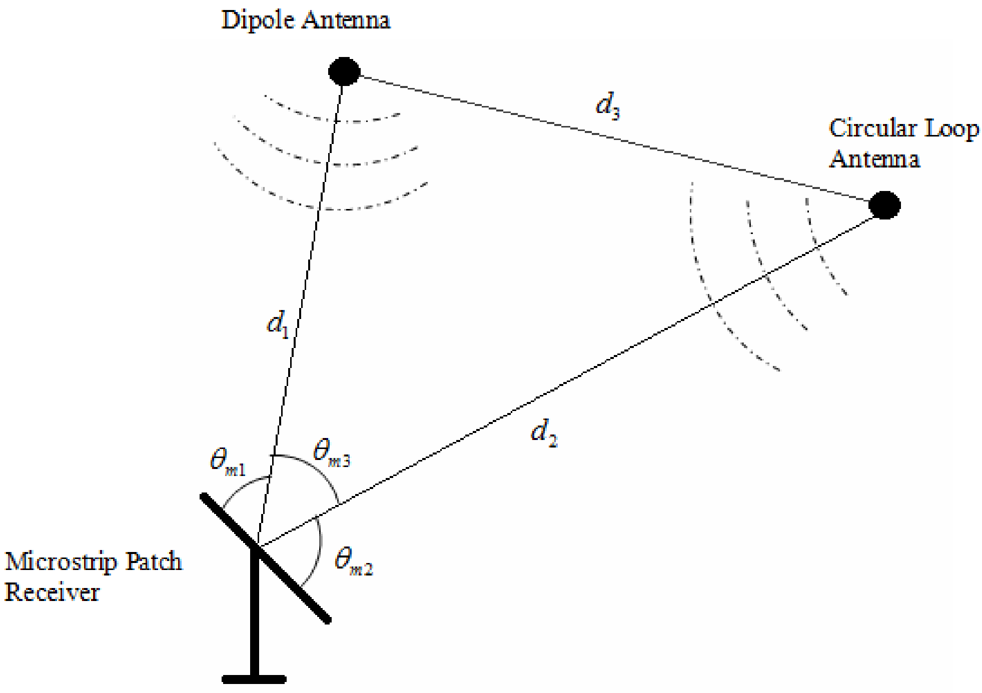

Figure 3.9. Simultaneous EMI of two interferer over a microstrip patch antenna.

Hence,

$$\cos(\theta_{m1} + \theta_{m2}) = \frac{d_3^2 - (d_1^2 + d_2^2)}{2d_1 d_2} \tag{64}$$

From (64), we can describe the angle θ_{m2} as

$$\theta_{m2} = \arccos\left\{\frac{d_3^2 - (d_1^2 + d_2^2)}{2d_1 d_2}\right\} - \theta_{m1} \tag{65}$$

Now, we are able to define the total electric field of the incident waves received by the microstrip patch antenna, E_{rm}, as

$$E_{rm} = E_{rmd} + E_{rml} \tag{66}$$

Hence, we can derive the total received power in the receiver as

$$P_{trm} = \frac{A_e\left(E_{rm}.E_{rm}^{*}\right)}{2Z_0} \tag{67}$$

where, A_e is the effective area of the microstrip patch antenna.

CHAPTER 4

SIMULATIONS

In this chapter, we will perform some simulations for the power equations derived in chapter 3 in order to predict the interference effects on a victim system with respect to its antenna angles. MATLAB simulation environment is used in the simulations.

This chapter is divided into three main parts which include simulations for dipole and circular loop antennas both separately and simultaneously over a microstrip patch antenna.

4.1 Simulations for EMI Power Generated by a Dipole Antenna Over a Microstrip Patch Antenna

We have derived an equation for total power received by a micro-strip patch antenna generated from a dipole antenna in (45). For numerical analysis, we will take the values as k=2π/λ, h=λ/2, a=λ/4, b= λ/4, s= λ/8, the amplitude $\frac{A_e}{2Z_0}\left(\frac{1}{d}\frac{\omega\mu I_0 h}{2\pi}\right)^2$ will be taken as 1 and the azimuth angle of micro-strip patch antenna ϕ_m will be taken as 0 (zero). With those assumptions, the equation (45) will be transformed as

$$P_{trm} = \left\{\frac{\sin(\pi\cos(\theta_m))}{\pi\cos\theta_m}\right\}^2$$

$$\times\left(\left[\left[\cos\left(\frac{\pi}{4}\cos\theta_m\right)\right](\sin c(0))\left[\cos\left(\frac{\pi}{4}\sin\theta_m\cos\phi_m\right)\right]\cos\phi_m(\vec{e}_{\theta_d}.\vec{e}_{\theta_m})\right]^2\right.$$

$$+\left[\left[\cos(\frac{\pi}{4}\cos\theta_m)\right][\sin c(0)]\left[\cos(\frac{\pi}{2}\sin\theta_m\cos\phi_m)\right]\cos\theta_m\sin\phi_m(\vec{e}_{\theta_d}.\vec{e}_{\phi_m})\right]^2\Bigg)$$

(68)

Because $\sin 0 = 0$, $\cos 0 = 1$, and $\sin c0 = 1$, so the scalar multiplication of the unit vectors derived in (40) and (42) will be transformed as

$$\vec{e}_d.\vec{e}_{\theta_m} = \cos^2\theta_m + \sin^2\theta_m = 1 \tag{69}$$

$$\vec{e}_d.\vec{e}_{\phi_m} = -2\cos\theta_m\cos\phi_m\sin\phi_m = 0 \tag{70}$$

Hence, the equation (68) will be transformed as

$$P_{trm} = \left\{\frac{\sin(\pi\cos(\theta_m))}{\pi\cos\theta_m}\right\}^2\left(\cos(\frac{\pi}{4}\cos\theta_m)\right)^2\left(\cos(\frac{\pi}{4}\sin\theta_m)\right)^2 . \tag{71}$$

4.1.1 Plotting in MatLab

The polar function has been used for simulating the equations derived in section 4.1. It accepts polar coordinates, plots them in a Cartesian plane, and draws the polar grid on the plane. The code written in MatLab R2009a is given in the following:

```
%Theta is the elevation angle of microstrip antenna.
%Phi is the azimuth angle of microstrip antenna.
%h is the length of the dipole antenna
%a is the width of the microstrip patch.
%b is the length of the microstrip patch.
%s is the thickness of the dielectric substrate.
%k is the wave number, lamda is the wavelength.
%k=2*pi/λ, h= λ/2, a= λ/4, b= λ/4, s= λ/8

teta = 0:.001:0.5*pi; phi = 0;
A = (sin(pi*cos(teta))./(pi*cos(teta)));
B = cos(0.25*pi*cos(teta));
C = sinc(0.5*pi*0.5*sin(teta)*sin(phi));
D = (cos(0.5*pi*0.5*sin(teta)*cos(phi)))*cos(phi);
E = (A.^2).*(B.^2).*(C.^2).*(D.^2);
polar(teta,E)
```

Polar representations of the received power on microstrip patch antenna with respect to the elevation angle θ_m, where $0 \le \theta_m \le \pi/2$ are given in figure 4-1a and 4-1b.

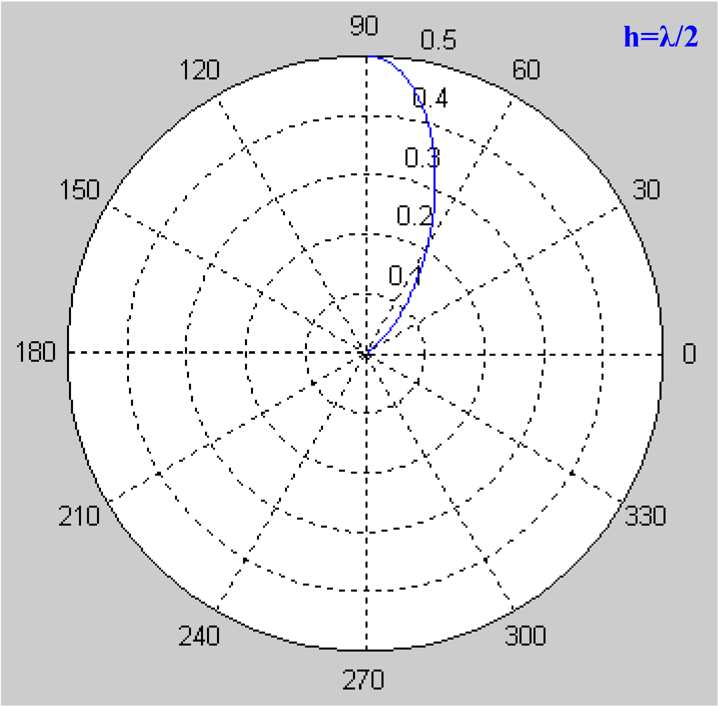

Figure 4.1a. Polar representation of EMI power generated by a dipole antenna over a microstrip patch antenna (for h=λ/2).

It is assumed in Fig. 4.1a that the microstrip patch antenna to be in the center of the coordinate plane. Because we found the relationship between the elevation angles of the microstrip patch antenna and the dipole antenna, which are θ_m and θ_d respectively in the equation (33), so it is illustrated with respect to the angle θ_m only.

When the angle θ_m goes to $\frac{\pi}{2}$, the power transmission from the dipole to the microstrip patch antenna gets its highest value. In this case, the elevation angle of the dipole is 0°. On the other hand, for the angle values of θ_m below $\frac{\pi}{6}$, the power transfer becomes zero. It gets the smallest value between the angles $\frac{\pi}{6}$ and $\frac{\pi}{3}$.

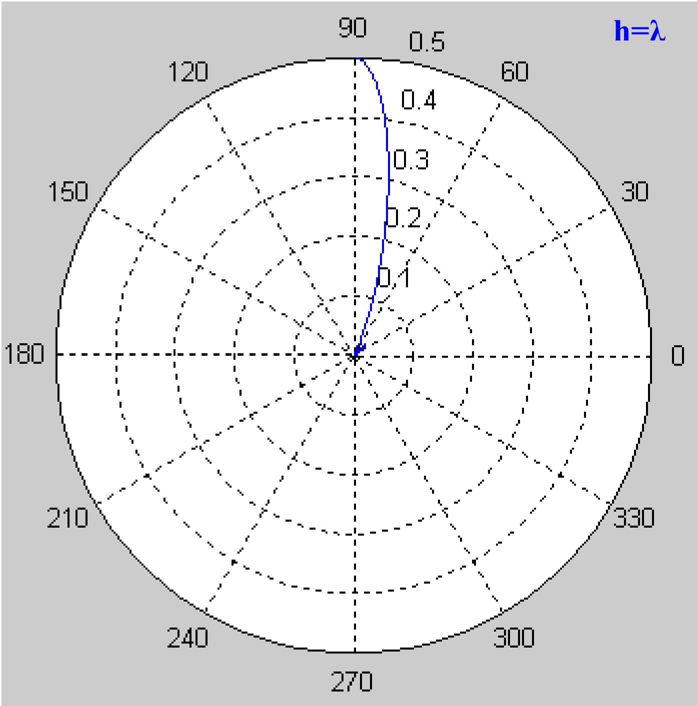

Figure 4.1b. Polar representation of EMI power generated by a dipole antenna over a microstrip patch antenna (for h=λ/2).

In Fig. 4.1b, it is seen a similar pattern with the plot in Fig. 4.1a because the only parameter changed is the length of dipole antenna at this case. If we increased the dipole's length from $\frac{\lambda}{2}$ to λ, the magnitude of the power transmission does not change, but its pattern becomes narrow. Both patterns in Fig. 4.1a and b have been plotted for $0 \le \theta_m \le \frac{\pi}{2}$ because the elevation angle of the microstrip patch antenna assumed for a victim system is considered to change from the ground (0°) level to its vertical (90°) level.

4.2 Simulations for EMI power generated by a Circular Loop Antenna over a Microstrip Patch Antenna

We have also derived an equation for total power received by a microstrip patch antenna generated from a circular loop antenna in (54). For numerical analysis, we will take the values as k=2π/λ, a_1=λ/4 (radius of the circular loop antenna), a_2=λ/4 (width of the micro-strip patch antenna), b= λ/4, s=λ/8, and the amplitude $\frac{A_e}{2Z_0}\left(\frac{\omega\mu_0 I_0 a_1}{2}\frac{1}{r}\right)^2$ will be taken as 1, and the azimuth angle of microstrip patch antenna ϕ_m will be taken as $\frac{\pi}{6}$. With those assumptions, the equation (58) is transformed as

$$P_{trm}=\left(J_0(\frac{\pi}{2}\sin\theta_m)\right)^2$$

$$\times\left\{\left[\left(\cos(\frac{\pi}{4}\cos\theta_m)\right)\times\sin c\left(\frac{\pi}{8}\sin\theta_m\right)\times\cos\left(\frac{\sqrt{3}\pi}{8}\sin\theta_m\right)\times\frac{-3}{4}\cos\theta_m\right]^2\right.$$

$$\left.+\left[\cos\left(\frac{\pi}{4}\cos\theta_m\right)\times\sin c\left(\frac{\pi}{8}\sin\theta_m\right)\times\cos\left(\frac{\sqrt{3}\pi}{8}\sin\theta_m\right)\times\cos\theta_m\times\frac{1}{2}\right]^2\right\} \quad (72)$$

where $\theta_l=\pi-\theta_m$.

4.2.1 Plotting in MatLab

The commands *polar* and *besselj* have been used for simulating the equations derived in the section 4.2. The code written in MatLab R2009a is the following:

```
%Teta is the elevation angle of microstrip antenna.
%Phi=pi/6 (the azimuth angle of microstrip antenna).
%a1 is the radius of the loop antenna
%a2 is the width of the microstrip patch.
%b is the length of the microstrip patch.
%s is the thickness of the dielectric substrate.
%k is the wavenumber, lambda is the wavelength.
%k=2*pi/lambda, a1= lambda/4, a2= lambda/4, b= lambda/4, s= lambda/8

teta = 0:.001:0.5*pi;
A = besselj(0,0.5*pi*sin(teta));
B = cos(0.25*pi*cos(teta)).*sinc(0.125*pi*sin(teta))
.*cos(0.866*pi*sin(teta)).*cos(teta).*(-0.75);
C =cos(0.25*pi*cos(teta)).*sinc(0.125*pi*sin(teta))
.*cos(0.2165*pi*sin(teta)).*cos(teta).*0.5;
D = -(A.^2).*((B.^2)+(C.^2));
polar(teta,D)
```

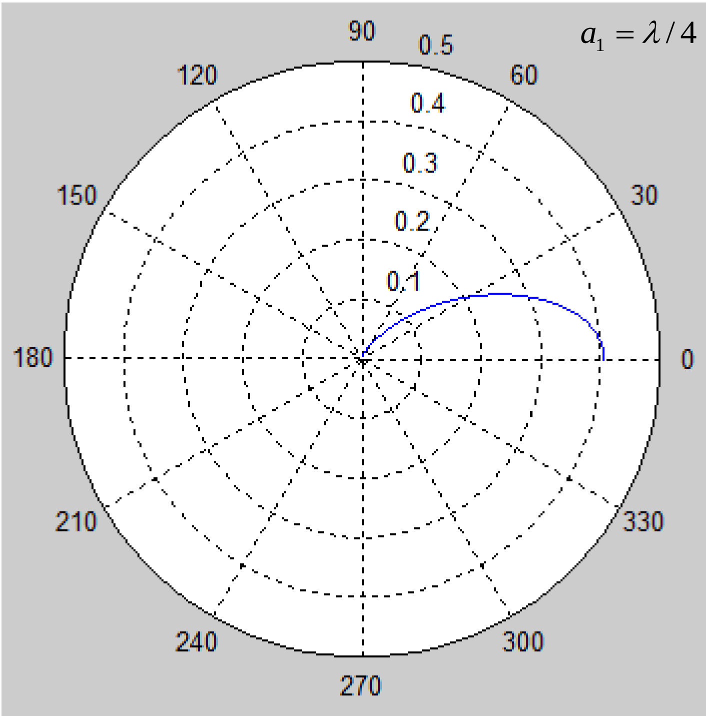

Figure 4.2a. Polar representation of EMI power generated by a circular loop over a microstrip patch antenna (for $a_1 = \lambda/4$)

When the elevation angle of the microstrip patch antenna is below $\frac{\pi}{6}$, electromagnetic power transmission from the circular loop antenna to the microstrip antenna gets its maximum value. In Fig. 4.2a, microstrip patch antenna as a receiver is located on the center, and receives maximum power with zero elevation angle.

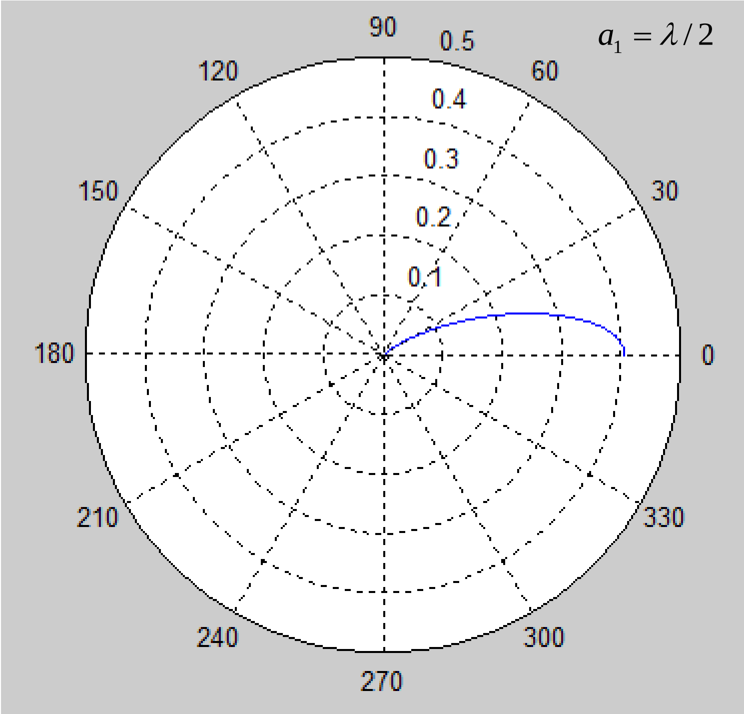

Figure 4-2b. Polar representation of EMI power generated by a circular loop antenna over a microstrip patch antenna (for $a_1 = \lambda / 2$)

The similar graphical shape of the power transmission with a narrower lobe can be seen in Fig. 4.2b, if the radius is multiplied by two.

4.3 Simulations for EMI Power Generated by a Dipole and a Circular Loop Antennas Over a Microstrip Patch Antenna

In (62), we derived the equation for total power received by a microstrip patch antenna generated by a dipole antenna and a circular loop antenna simultaneously. In simulations, for calculating E_{rmd} we will take the values for the dipole and microstrip antennas as k=2π/λ, h=λ/2, a=λ/4, b= λ/4, s= λ/8, the amplitude component $\frac{\omega \mu I_{0d} h}{2\pi}$ will be taken as 1 and the azimuth angle of micro-strip patch antenna ϕ_{m1} will be taken as 0 (zero). Therefore, we can convert E_{rmd} as

$$E_{rmd} = -j \frac{e^{-jkd_1}}{d_1} \sin c\,(\pi \cos\theta_{m1}) \cos(\frac{\pi}{4} \cos\theta_{m1}) \cos\left(\frac{\pi}{4} \sin\theta_{m1}\right) . \tag{73}$$

For numerical calculation in terms of E_{rml}, we will take the values for circular loop and microstrip antennas as k=2π/λ, a_1=λ/2, a_2=λ/4, b= λ/4, s= λ/8. The amplitude component $\frac{\omega\mu_0 I_0 a_1}{2}$ will be taken as 1, and the azimuthal angle ϕ_{m2} will be taken as $\pi/6$. So, we can convert E_{rml} as

$$E_{rml} = j \frac{e^{-jkd_2}}{d_2} \left(J_0 (\frac{\pi}{2} \sin\theta_{m2}) \right)$$

$$\times \left\{ \left[\left(\cos(\frac{\pi}{4} \cos\theta_{m2}) \right) \times \sin c\left(\frac{\pi}{8} \sin\theta_{m2} \right) \times \cos\left(\frac{\sqrt{3}\pi}{8} \sin\theta_{m2} \right) \times \frac{-3}{4} \cos\theta_{m2} \right]^2 \right.$$

$$\left. + \left[\cos\left(\frac{\pi}{4} \cos\theta_{m2} \right) \times \sin c\left(\frac{\pi}{8} \sin\theta_{m2} \right) \times \cos\left(\frac{\sqrt{3}\pi}{8} \sin\theta_{m2} \right) \times \cos\theta_{m2} \times \frac{1}{2} \right]^2 \right\}^{1/2} . \tag{74}$$

We will use the expression derived in (65) instead of θ_{m2}, so the equation will depend on the angle θ_{m1} only.

4.3.1 Plotting in MatLab

Similar MatLab commands have been used for simulations in the followings:

```
tm1 = 0:.001:0.5*pi;
d1 = 5; d2 = 12; d3 = 13;
ED = -i.*(exp(i*2*pi*d1)./d1).*sinc(pi*cos(tm1))
.*cos(0.25*pi*cos(tm1)).*cos(0.25*sin(tm1));
tm2 = acos((d1.^2+d2.^2-d3.^2)./(2*d1*d2))-tm1;
A = besselj(0,0.5*pi*sin(tm2));
B = cos(0.25*pi*cos(tm2)).*sinc(0.125*pi*sin(tm2))
.*cos(0.2165*pi*sin(tm2)).*cos(tm2).*(-0.75);
C = cos(0.25*pi*cos(tm2)).*sinc(0.125*pi*sin(tm2))
.*cos(0.2165*pi*sin(tm2)).*cos(tm2).*0.5;
EL = i.*exp(-i*2*pi*d2)./d2.*A.*(((B.^2)+(C.^2)).^0.5);
E = ED + EL;
P = E.*conj(E);
polar(tm1,P)
```

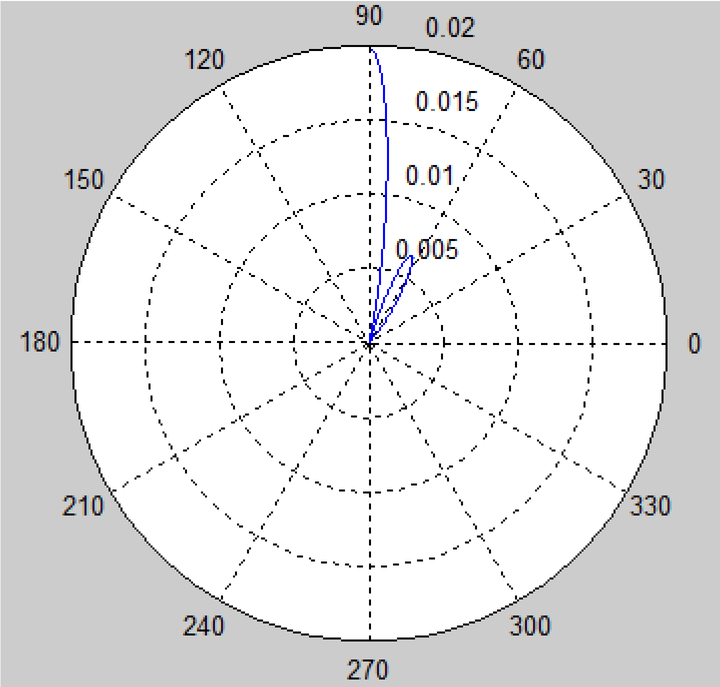

Figure 4.3a. Polar representation of EMI power generated by a dipole antenna together with a circular loop antenna over a microstrip patch antenna (for $a_1 = \lambda/4$ and $h = \lambda/2, d_1 = 5, d_2 = 12, d_3 = 13$).

The effects of electromagnetic interference can be seen clearly in the Fig. 4.3a. This plot shows two lobes which are generated by the dipole and circular loop antennas over a microstrip patch antenna. In this simulation, θ_{m1} which is elevation angle of the microstrip patch antenna is plotted from 0° to $\pi/2^\circ$. The other elevation angle

θ_{m2} is found in terms of θ_{m1} in (65). The distances between antennas d_1, d_2 and d_3 are selected as 5 m, 12 m, and 13 m respectively.

The lobe in the right hand side of the plot can be thought as a destructive interference if we consider the lobe in the left hand side as a wanted power or wave.

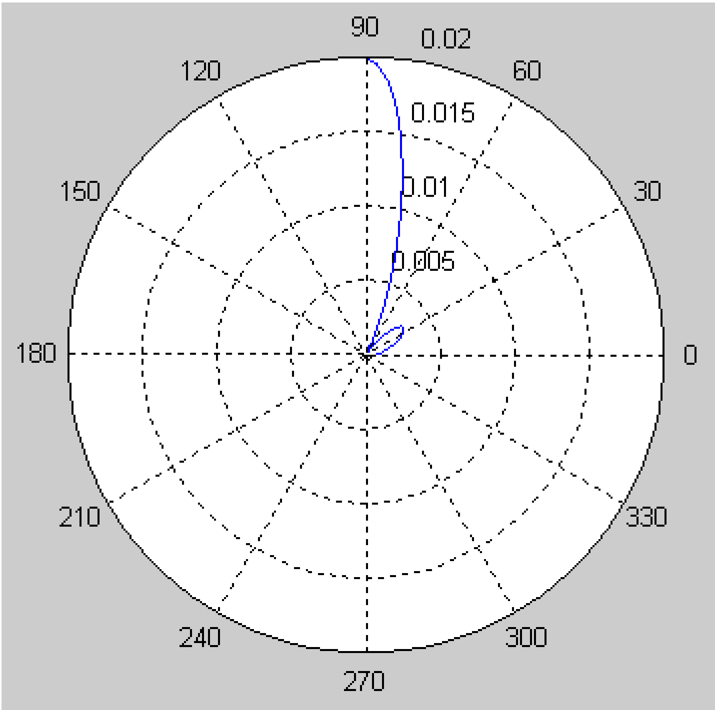

Figure 4.3b. Polar representation of EMI power generated by a dipole antenna together with a circular loop antenna over a microstrip patch antenna (for $a_1 = \lambda/8, h = \lambda/4, d_1 = 5, d_2 = 12, d_3 = 13$).

In Fig. 4.3b, it can be seen that the destructive effect of EMI is less than that of Fig. 4.3a. In this simulation, the distances are selected the same with the simulation above, but the length of the dipole and the radius of the circular loop antenna are reduced by half.

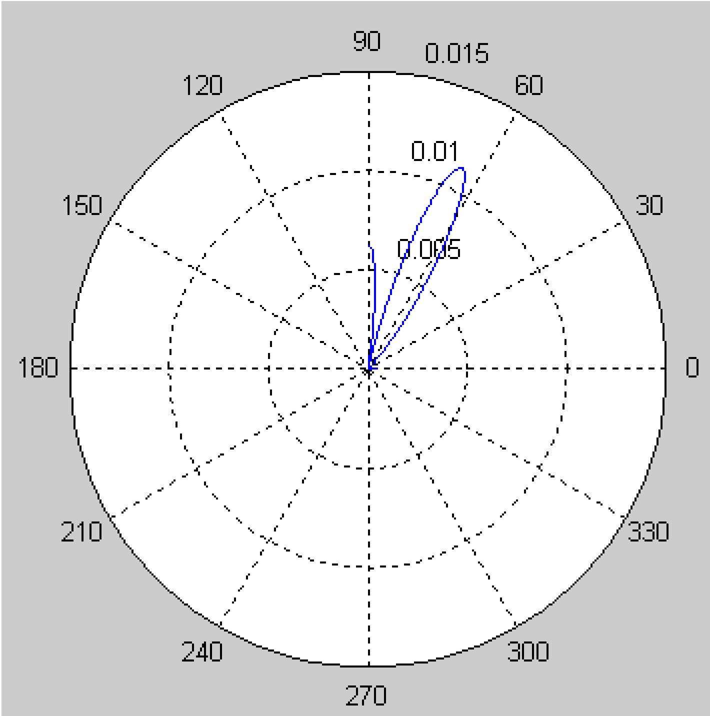

Figure 4.3c. Polar representation of EMI power generated by a dipole antenna together with a circular loop antenna over a microstrip patch antenna for $a_1 = \lambda/8$, $h = \lambda/2$, $d_1 = 5, d_2 = 5, d_3 = 8$.

If we bring the circular loop antenna closer to the microstrip antenna while the distance between the dipole and microstrip antennas are constant, the effect of circular loop antenna in the total EMI improves excessively. This phenomenon can be seen in Fig. 4.3c above easily. The lobe in the right hand side has a more magnitude if compared with that of Figures 4.3a and 4.3b.

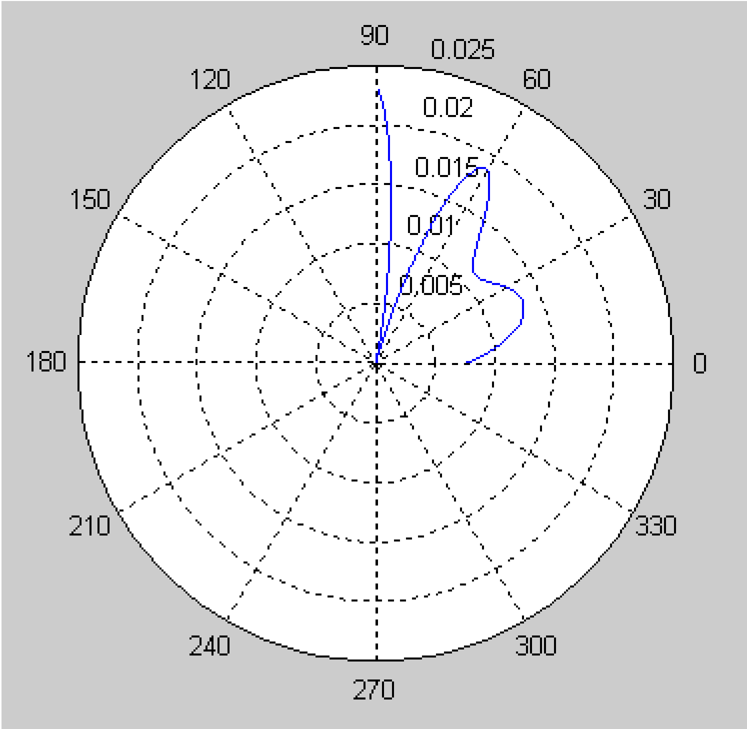

Figure 4.3d. Polar representation of EMI power generated by a dipole antenna together with a circular loop antenna over a microstrip patch antenna for $a_1 = \lambda / 8$, $h = \lambda$, $d_1 = 5, d_2 = 5, d_3 = 3$.

The similar interference effect which is also shown in Fig. 4.3c can be seen in Fig. 4.3d and 4.3 e. In those simulations, lobes with different magnitudes occurre if the distances between the antennas are changed.

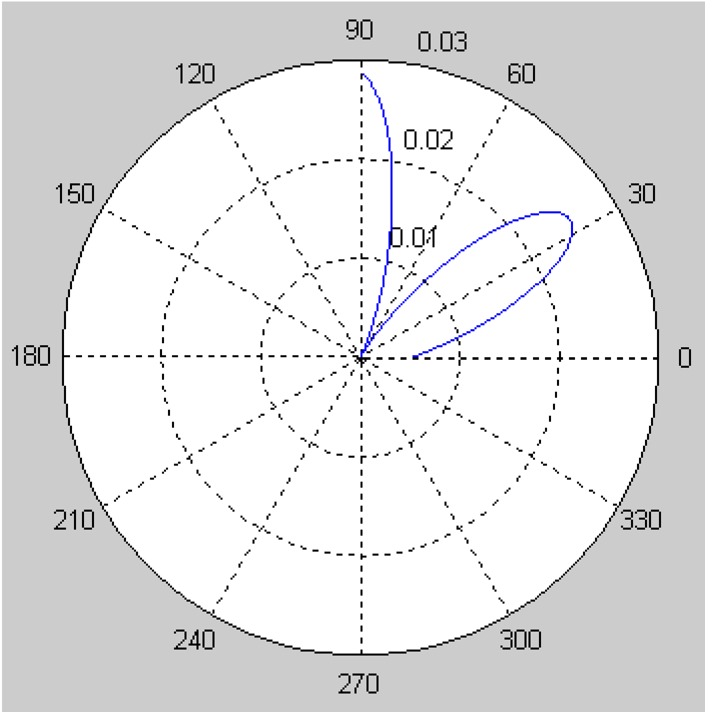

Figure 4.3e. Polar representation of EMI power generated by a dipole antenna together with a circular loop antenna over a microstrip patch antenna for $a_1 = \lambda/4, h = \lambda/4, d_1 = 5, d_2 = 5, d_3 = 3$.

CHAPTER 5

CONCLUSION

The aim of this thesis is to give a mathematical analysis method for electromagnetic interference phenomenon between such kind of antennas like a dipole antenna, a circular loop antenna and a microstrip patch antenna.

In Chapter 1, a historical introduction to the antennas and EMC (Electromagnetic Compatibility) is given.

In Chapter 2, fundamental properties of the antennas are discussed. Radiation pattern, gain, directivity and polarization are some of the most important antenna parameters. Later in this chapter, radiation characteristics of these antennas in terms of power transmission from one to another are studied. The electric field vectors of the antennas in the far field are used for the derivation of power transmission formula. The total power which is received by a receiver antenna is dependant on the amplitude of the transmitter antenna, radiation patterns of the receiver and transmitter antennas, and polarization vectors of the receiver and transmitter antennas. The gain effects of the antennas are included with the radiation patterns.

In Chapter 3, electromagnetic interference (EMI) phenomenon between antennas is defined first. Three EMI cases are discussed. Firstly, EMI between a dipole antenna and a microstrip patch antenna is studied. Secondly, EMI between a circular loop antenna and a microstrip patch antenna is studied. Lastly, EMI between a dipole antenna together with a circular loop antenna as a transmitter and a microstrip patch antenna as a receiver is studied. Mathematical formulations are derived in terms of power transmission by using the radiation patterns and polarization vectors of the antennas.

In Chapter 4, simulation results for the derivations which are done in Chapter 3 are presented. All the plots are carried out in MatLab. To be able to simulate the power transmission between antennas, the amplitude effect of the transmitter is ignored by selecting it as 1 in all the simulations. Because the geometrical relationship between the elevation angles of the interfering antennas are found in chapter 3, all the simulations are done with respect to the elevation angle of the receiver antenna that is microstrip patch antenna. The azimuthal angle of the antennas is selected as zero degree for simplicity.

To sum up, in this thesis study electromagnetic interference is considered as a power transmission from an antenna or system to another one. The well-known Friis power transmission equation is modified in equation (9). Hence, the polarization and phase effects are included in the new transmission equation.

Finally for the future work, this thesis study can be extended to cover other types of antennas like aperture, reflector and antenna arrays. Additionally, some experiments by using the antennas which are studied in this thesis can be performed to compare with the simulation results.

REFERENCES

1**. Sarkar, T.K., Salazar-Palma M., Sengupta D.L.** (2010), *James Clerk Maxwell: The Founder of Electrical Engineering*, IEEE.

2. **Balanis, C.A.** (1992), *Antenna Theory: A Review*, Proceedings of the IEEE, Vol. 80, No. 1.

3. **Carver, K.R., Mink, J.W.** (1981), *Microstrip Antenna Technology*, IEEE Transactions on Antennas and Propagation, Vol. AP-29, No. 1.

4. **Wrede, R., Spiegel, M.R.** (2002)**,** *Schaum's Outline of Theory and Problems of Advanced Calculus 2nd Edition*, McGraw-Hill, USA.

5. **Balanis, C.A.** (2008), *Modern Antenna Handbook*, John Wiley & Sons, Inc., USA.

6. **Rahmat-Samii, Y., Williams, L.I., Yaccarino, R.G.** (1995), *The UCLA Bi-polar Planar-Near-Field Antenna-Measurement and Diagnostics Range*, IEEE Antennas and Propagation Magazine, Vol. 37, No. 6.

7. http://en.wikipedia.org/wiki/Radiation_pattern, visited on December 2011.

8. **Clayton, R.P.** (2006), *Introduction to Electromagnetic Compatibility,* John Wiley & Sons, Inc., New Jersey.

9. **Skolnik, M.** (1980), *Introduction to Radar Systems 2nd Edition*, McGraw-Hill, Singapore.

10. **Radasky W.A., Baum C. E., Wik M.W**. (2004) *Introduction to the Special Issue on High-Power Electromagnetics (HPEM) and Intentional Electromagnetic Interference (IEMI)*, IEEE Transactions on Electromagnetic Compatibility, Vol. 46, NO. 3.

APPENDIX

CIRRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: Durukan, Sami

Nationality: Turkish (TC)

Date and Place of Birth: 22 January 1983, Kırşehir

Marital Status: Married

Phone: +90 530 236 68 30

mail: durukansan@gmail.com

EDUCATION

Degree	Institution	Year of Graduation
MSc.	Çankaya Univ. Electronics and Communication Engineering	2012
BSc.	Istanbul Technical Univ. Electronics and Communication Engineering	2005
High School	Kırşehir High School	2000

WORK EXPERIENCE

Year	Place	Enrollment
2009-Present	Roketsan	Senior Test Engineer
2008-2009	MAN	Senior Quality Eng.
2007-2008	Ford OTOSAN	Test Engineer

FOREIGN LANGUAGES

Advanced English