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An RFID Directional Antenna for Location Positioning

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by

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ABSTRACT

This thesis presents a new antenna design for passive RFID tags operating at super high frequency band. The proposed antenna includes a cross-array of five elements supporting beam-scanning range over two perpendicular planes.

The beam-scanning capability allows the tag to communicate over longer distances without demanding extra power. A matching network between antenna elements and front-end circuitry has also been designed to eliminate phase shift. 3D full-wave electromagnetic simulation results using HFSS CAD tool indicate that the proposed antenna supports 10 dB gain and beam-scanning of more than 180^o over two planes which can be exploited to provide location positioning services.

DEDICATION

I dedicate this work to her, who always holds a beautiful smile when she sees me. To that lady that I will never be able to repay her for the gift she gave me, the gift of having her as my mother.

Thanks mom

ACKNOWLEDGEMENTS

I would like to extend my great thanks and appreciation to those people who have contributed to the completion of this research work and thesis.

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CHAPTER I

INTRODUCTION

Automatic identification procedures have become very popular in many service industries including purchasing and distribution logistics, manufacturing companies and material flow systems. Auto-ID can provide information regarding people, animals, goods and products in transit.

Barcode technology (Figure 1.1) as compared to Radio Frequency Identification (RFID) suffers from two main disadvantages: (a) it requires a direct line of sight for proper operation and (b) it strictly limits the amount of information that can be stored in a label. Although the cost of barcode system implementation is rather low compared to other available systems, due to the above disadvantages, it is expected to be fully replaced by RFID technology in the future.

Figure 1.1 An example of a barcode

This thesis discusses the transformation of a simple RFID patch antenna into a multidimensional radiation array which can be used in location positioning applications. The proposed antenna scheme has a thinner, more directive radiation pattern, with the capability to scan continuously on two planes. This also includes the size reduction of a single patch antenna before the creation of an array, deployment of matching techniques to improve the antenna efficiency, finding the optimized distance between array elements, and the design of an optimized feed line network to connect the array.

The thesis consists of six chapters, chapter two starts with an introduction of RFID systems, applications, tags, operating frequency, and the types of coupling. This chapter aims at describing the tag and its categories, also demonstrates the coupling mechanisms between the tag and the reader in RFID systems.

Chapter three demonstrates different type of antennas and their gain, with the essential antenna performance specifications and RFID antenna requirements for location positioning. A rectangular patch antenna is discussed with more details in chapter 4. The employed design technique, size reduction and matching methods have been covered in this chapter. It also presents the array design requirements to implement a directional antenna. Chapter five demonstrate the simulation results for the designed antenna element and the subsequent array antenna. A comparison between the proposed antenna and other types of beam scanning antennas are summarized in this chapter. Chapter six summarizes the conclusion and presents future works.

CHAPTER II

RFID SYSTEM AND LOCATION POSITIONING

RFID systems have the advantage of storing product information on an electronic chip within a tag which has the ability to uniquely define the identity of an object. RFID technology has already gained a considerable market share and currently it is widely deployed for contactless credit cards, commonly referred to as “PayPass”.

2.1 RFID System Components

A typical RFID system consists of three elements as shown (Figure 2.1):

1. Tag: This is a small antenna attached to a microchip to communicate with readers through radio waves.
2. Reader: A hardware device to interrogate RFID tags and send the results to a computer system through encoded radio signals.
3. Middleware: This is a software program used by reader to transmit its observations to a computer system.

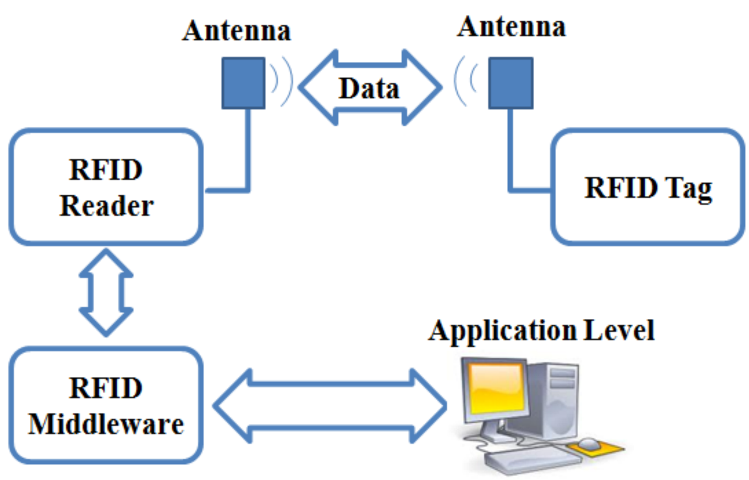


Figure 2.1 RFID system components

A reader generally contains a radio frequency module known as transceiver, a control component, and a coupling element to communicate with RFID tags and the middleware. In addition, many types of readers have various optional interfaces (RS 232, RS 485, etc.) which allow them to forward the received data to another system (PC, robot control system, etc.). An RFID tag includes two main components of (a) coupling element or antenna and (b) electronic circuits (Figure 2.2).

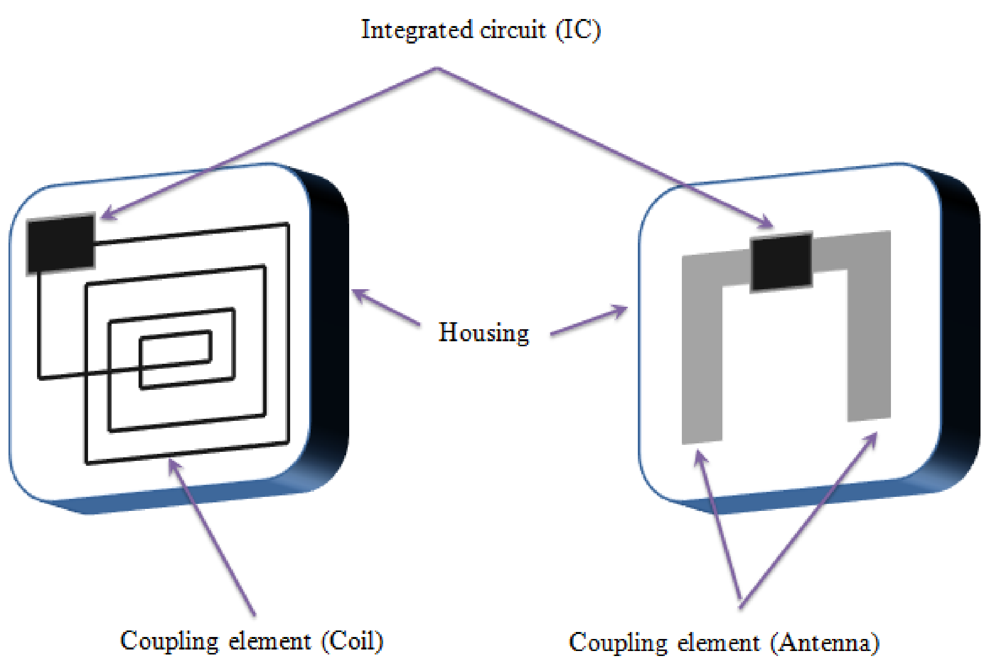


Figure 2.2 main components of an RFID tag or transponder

2.2 RFID Applications

Radio frequency identification is used in various applications due to the versatility that it provides for the industry. Industry has begun to rely on RFID systems in many applications as shown in Figure 2.3. Identification through radio frequency is widely used for:

- Access Control

  The access control application uses the RFID system to selectively grant access to a certain region. For example, RFID tags may be fastened to a vehicle, a hand-held card, a key chain, or a wristband which allows access to a road, a building, or a secure area.

- Tag and Ship

  Tag and ship applications allow a user to associate an RFID tag with an item, apply the physical tag to the item, and then verify that the tag operates properly while attached to the item.

- Pallet and Carton Tracking

  One of the most commonly used applications of RFID systems is pallet and carton tracking. This application puts a virtual "license plate" on a shipping unit made up of one or more items.

- Track and Trace

  One of the earliest applications of RFID was in the tracking procedure of dairy cattle. This has been further developed for other animals and pets. To trace animals, an RFID tags is inserted into glass capsules and then injected or worn as ear tags. These tags are used to identify lost animals and to sort, care for, and track the history of livestock. In recent years, RFID systems have also been increasingly used to track pharmaceutical products. Information collected from tracking livestock or pharmaceutical products can be critical in the event of a public health threat.

- Smart Shelf

  Smart Shelf is yet another interesting and useful application of radio frequency identification. In this scheme shelves or other containers are continuously tracked and their available items are identified. If an item is removed or added, the shelf immediately updates the inventory. For example, the RFID system can identify expired items within a given shelf if their expiry information is written on their corresponding Radio Frequency Identification tag.

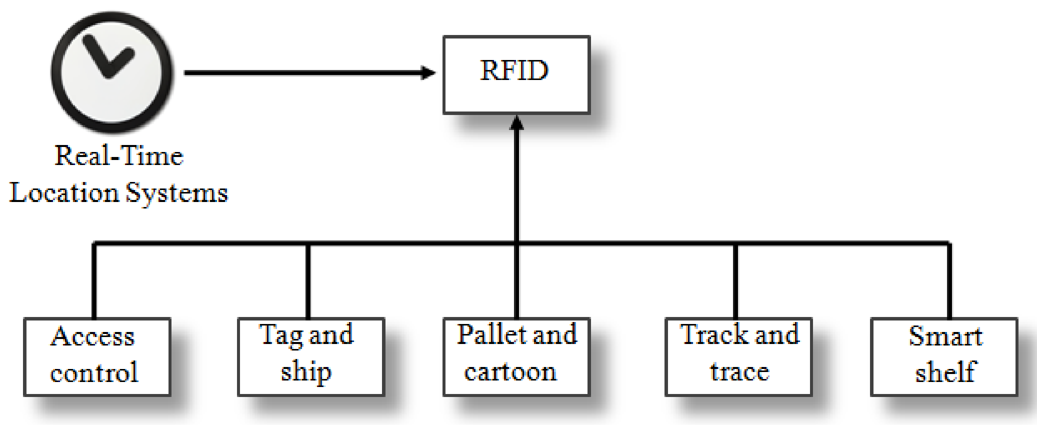


Figure 2.3 RFID applications

2.3 RFID Tags

In order for a tag to properly operate, it should have the following two basic functionalities:

- Tag Adherability:

  Any RFID tag must be able to be adhered to any object to which one might want to label. It may be injected into the object or tagged or glued to the surface of objects.

- Tag Readability:

  Any RFID tag must be able to communicate information over a given range of radio frequencies to enable the transfer of information from the tag to the reader.

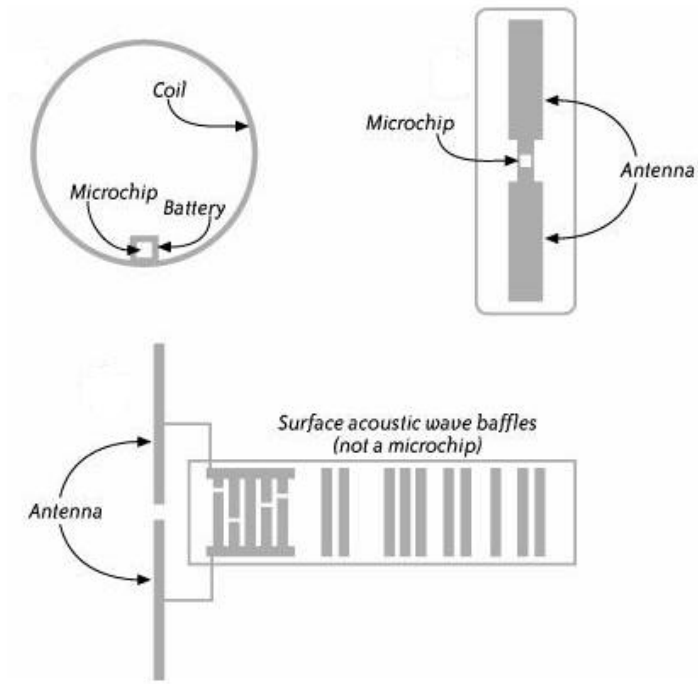


Figure 2.4 Typical RFID tags

Different types of tags offer one or more of the various features and capabilities listed below:

- Kill/Disable

  Some tags allow a reader to send a command to permanently disable the tag.

- Write Once

  The information stored in these tags cannot be changed after they are programmed by a manufacturer or a customer.

- Write Many

  These tags can be rewritten multiple times with new data.

- Anti-Collision

  The anti-collision mechanism gives the tag the ability to respond to the reader in correct time slots, preventing a failed communication. To minimize the instances of collision, a tag does not respond to the reader in the time slots assigned to other tags. This protocol allows the reader to know when a particular tag's response ends and when the next one starts to communicate.

- Security and Encryption

  These tags are able to participate in encrypted communications, accomplished by responding only to readers that can provide a secret password.

- Standards Compliance

  A tag may comply with one or more standards, enabling it to talk to readers that also comply with those standards.

2.4 RFID Tag Power Source

Generally, RFID tags may be divided in to three categories based on their main source of energy:

i) Passive Tags:

   Passive RFID tags do not have internal power supply. Instead, they are powered by energy induced in the antenna by RF signals.

ii) Active Tags:

   Active tags have an internal power source which makes them more reliable and provides a wider range of operation.

iii) Semi-Passive Tags:

These tags use battery to power microchips within the tags although, they also utilize RF signals to communicate with the readers. Semi-passive tags are able to initiate communications with other tags without the aid of a reader.

2.4.1 Frequency Ranges and License

RFID systems are classified as radio systems due to the electromagnetic waves radiated by these systems, therefore, it must be guaranteed that the operations or functions of the RFID systems will not disrupt or impair other radio services. To meet this requirement, RFID systems use frequency bands that have been reserved exclusively for industrial, scientific or medical applications. These frequency bands are classified worldwide as ISM frequency bands (Industrial–Scientific–Medical) as shown in table (2.1).

2.4.2 RFID Tag Coupling

Coupling is a method in which an RFID tag interacts with a reader to send or receive information. The type of coupling directly affects the read range between the tag and reader. The types of coupling are:

- Backscatter Coupling:

  Backscatter Coupling provides an elegant solution to the problem of how to make an RFID tag without a battery. The name itself, "backscatter," describes the method in which the RF waves transmitted by the reader are scattered back by the tag.

Table 2.1 RFID operating frequencies and associated characteristics

Band	LF Low frequency	HF High frequency	UHF Ultra high frequency	Microwave
Frequency	30–300kHz	3–30MHz	300 MHz–3GHz	2–30 GHz
Typical RFID Frequencies	125–134 kHz	13.56 MHz	433 MHz or 865 – 956MHz 2.45 GHz	2.45, 5.8 GHz
Approximate read range	less than 0.5 meter	Up to 1.5 meters	433 MHz = up to 100 meters 865-956 MHz = 0.5 to 5 meters	Up to 10 meters
Typical data transfer rate	less than 1 kbps	Approximately 25 kbps	433–956 = 30 kbps 2.45 =100 kbps	Up to 100 kbps
Characteristics	Short-range, low data transfer rate, penetrates water but not metal	Higher ranges, reasonable data rate (similar to GSM phone), penetrates water but not metal	Long ranges, high data transfer rate, concurrent read of <100 items, cannot penetrate water or metals	Long range, high data transfer rate, cannot penetrate water or metal
Typical use	Animal ID Car immobilizer	Smart Labels Contact-less travel cards Access & Security	Specialist animal tracking Logistics	Moving vehicle toll

In other words, backscattering is characterized by the reflection of the transmitted wave back to the source. The following step illustrates how a reader powers up the IC in a tag to communicate the information. First, the reader transmits a signal with a certain frequency. The tag which encloses an antenna, which resonates at the same frequency, captures the transmitted signal and then after collecting enough power activates the IC. Then, the chip starts to read the data sent by the reader and responds accordingly.

- Inductive Coupling:

  Inductive coupling is a widely used coupling mechanism for various RFID applications. An example of this coupling scheme is the vicinity-coupled smart card which follows the ISO 15693 standard. These tags are powered by the current which is generated by induction due to the magnetic field that passes through the coil antenna of the tag.

- Magnetic Coupling:

  Magnetic coupling is similar to inductive coupling. It is a close coupling scheme in which a pair of transformer coils is created between the reader and the tag. The main difference between these two techniques is in the shape of the core. Whereas in the inductive coupling the coils are placed in-line and parallel, in a magnetic coupling arrangement the reader coil is rounded or in a u-shape ferrite core with windings. Limitation with this design is in the distance between reader and the tag. The tag must be placed over the air gap in the core and at a distance of no more than 1cm.

- Capacitive Coupling:

  Capacitive coupling is another class of close coupling. The efficiency of this model is optimal when the tag is inserted into the reader. The major difference in this architecture is the use of electrodes instead of antennas. Both the reader and the tag contain conductive patches which must be held parallel in close proximity without touching, which results in the formation of a capacitor. This type of coupling is commonly used in smart cards (defined under ISO 10536).

2.5 RFID Location Positioning

In most RFID applications, location positioning is used only to detect the availability of a tag, while its location is unknown. There are a number of methods applied to RFID systems used to add the capability of location positioning. An example of such a scheme is the Received Single Strength Indicator (RSSI) (Figure 2.5); it uses passive tags as reference points placed on the ceiling, where the readers raise power levels until the desired tag responds.

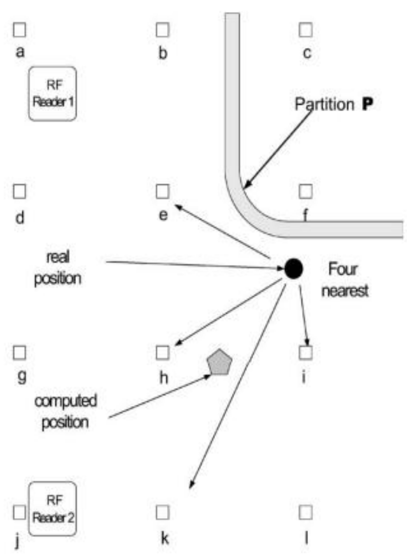


Figure 2.5 RSSI location positioning method

A narrow beam generated by a tag with scanning capability in multiple directions can significantly facilitate the development of a location positioning system.

CHAPTER III

ANTENNAS

An antenna serves as a converter which either converts current into radio waves or conversely captures radio waves with a given frequency band from air and converts them into current. Once a radio wave has been converted by the antenna into a corresponding current, this signal is later extracted by the circuitry attached to the antenna. Although this is the main function of the antenna, converting is not its only task. An antenna also acts as an advanced wireless system that is required to optimize or accentuate the radiated energy waves in some directions and repress it in certain directions. Here, the antenna acts as a radio wave directing device. RFID Antennas have different shapes and configurations depending on the particular application and its requirements. These structures could be as simple as two conducting wires or more complicated such as dish or horn antenna, where it might be a single element or an array of elements assembled in a given configuration.

The appropriate design of the antenna will reduce the design of extra components in the system, and thus improve the overall system performance. Major advances in the telecommunication industry occurred due to the enhancement of the antenna design; however, there are still many challenges to face due to address the challenges of designing high efficiency RFID antennas.

3.1 Types of Antenna

Antenna types may differ in physical shape, dimension, method of feeding, gain, bandwidth, impedance and other factors. A number of commonly used antenna types are explained, focusing on the gain and the directivity provided by them.

3.1.1 Dipole Antenna

Dipole antennas are one of the simplest and cheapest antenna types. A dipole antenna is a radio antenna that can be made of a simple wire with a center-fed driven element. It consists of two metal conductor wires oriented in parallel and collinear with each other, with a small space between them (Figure 3.1).

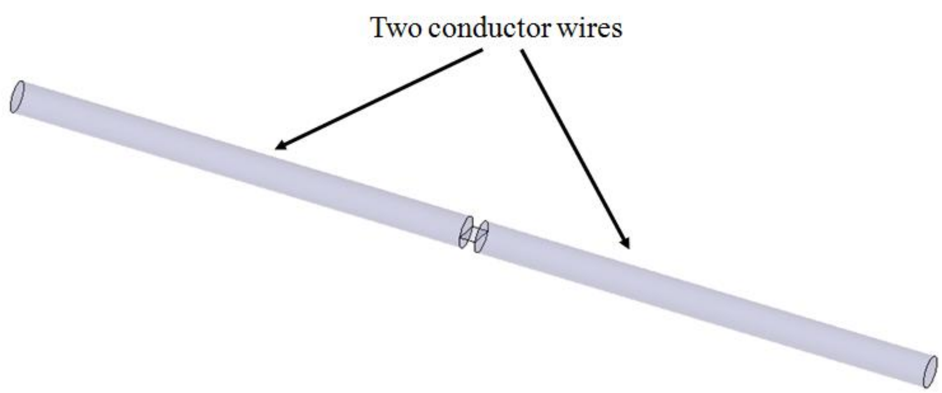


Figure 3.1 Dipole antenna structure

The radio frequency signal is applied to the antenna at the center, between the two conductors. There are various types of dipole antennas, each provides a given gain; in general a dipole antenna provides an antenna gain that runs between 1.5 and 2.15 dBi with a typical pattern shown in (Figure 3.2).

3.1.2 Patch (Microstrip) Antenna

When designing an antenna for an application where size, weight, cost, performance and ease of installation is a factor microstrip antenna is the perfect choice. These antennas are low profile, conformable to planar and non-planar surfaces, simple and economical to manufacture using modern printed-circuit technology. They are mechanically robust when mounted on rigid surfaces, compatible with MMIC designs and when the particular

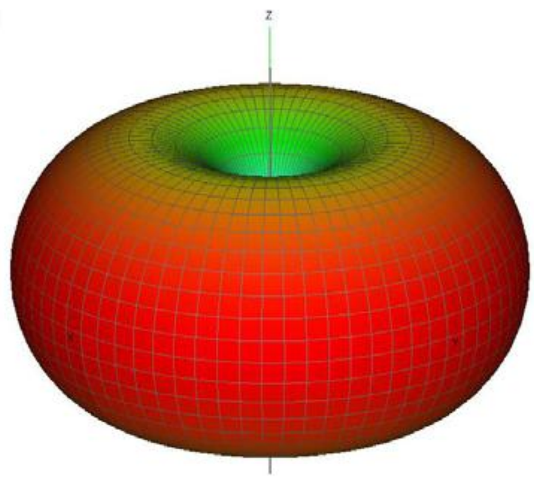


Figure 3.2 3D pattern of the dipole antenna radiation pattern

patch shape and mode are selected, they are very versatile in terms of resonant frequency, polarization, pattern, and impedance. Patch antennas have a high quality factor Q, which gives them a narrow bandwidth profile, thus it is desirable in narrow band applications.

Patch antennas, consist of a thin layer of a metallic strip (patch) mounted above a dialectic material, also known as the substrate, which separates the patch from the ground plane. There are different shapes of patch antennas, depending on the required properties and feed method, as seen in (Figure 3.3).

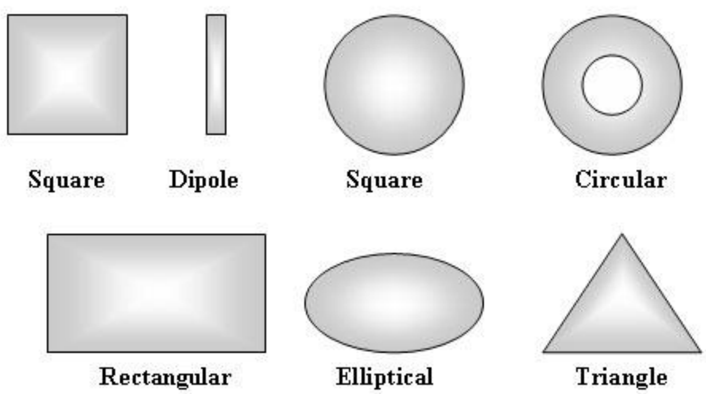


Figure 3.3 Different shapes of patch antennas

The most commonly used patch antenna is the rectangular patch antenna which is designed mainly by controlling two parameters length (*L*) and width (*W*). The parameter (*L*) controls the resonance frequency and (*W*) has a large impact on the input impedance (Figure 3.4).

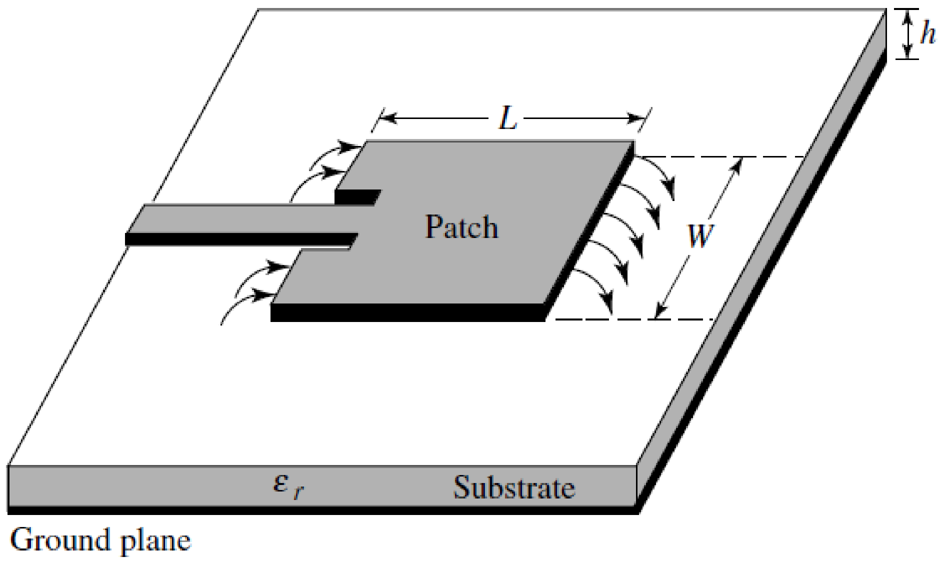


Figure 3.4 Microstrip rectangular patch antenna with design parameters

A rectangular patch antenna provides high gain which generally reaches 5dBi to7dBi, while maintaining a pattern that is more directed in one direction, normal to the patch surface, as shown in (Figure 3.5).

3.1.3 Horn Antenna

A Horn Antenna is an antenna that consists of a flaring metal waveguide shaped like a horn. This protrusion is useful in directing the radio waves in a beam formation (Figure 3.6).

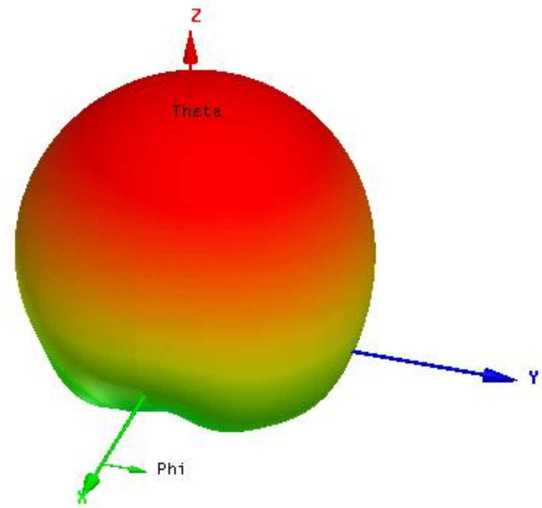


Figure 3.5 3D radiation patter of a patch (microstrip) antenna

Horn Antennas are widely used as antennas at UHF and microwave frequencies, above 300 MHz. They are used as feeders for larger antenna structures such as parabolic antennas, standard calibration antennas to measure the gain of other antennas, and as directive antennas for such devices as radar guns or microwave radiometers. Their advantages are moderate directivity (gain), broad bandwidth, as well as simple construction and adjustment.

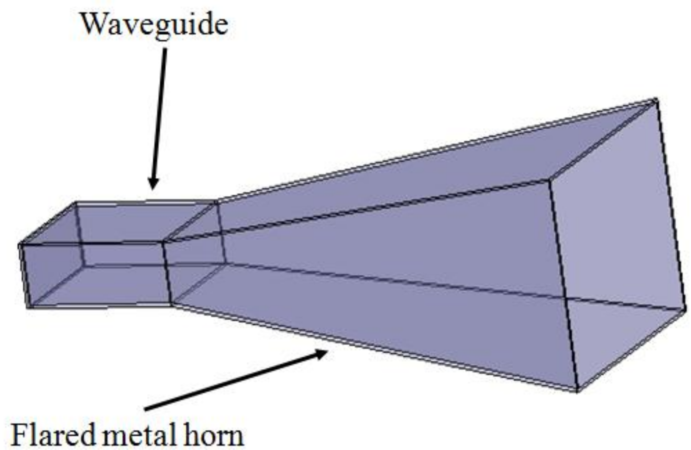


Figure 3.6 The horn antenna basic structure

The horn is mostly used as a feed element for large radio astronomy, satellite tracking, and communication dishes installed throughout the world. It is a common element of phased arrays and serves as a universal standard for calibration and gain measurements of other high gain antennas. The horn antenna's widespread applicability comes from its simplicity in construction, ease of excitation, versatility, large gain, and preferred overall performance. An electromagnetic horn can take many different shapes as shown in Figure 3.7. The horn is nothing more than a hollow pipe of different cross sections, which has been tapered to a larger opening. The type, direction, and amount of taper can have a profound effect on the overall performance of the element as a radiator.

This type of antenna represents a more complex design and larger size than the previously mentioned dipole and patch antennas; however, it provides higher gain, ranging from 10dBi to 20dBi. In addition, it has a radiation pattern similar to the patch antenna, in the manner that it projects the radiation mainly in one direction as shown in (Figure 3.8).

Many other antennas are used in everyday life applications, which can be found in literature, although this thesis has introduced just three. These three afore mentioned antenna types have been used to present a basic understand of various antenna structures and radiation behaviours.

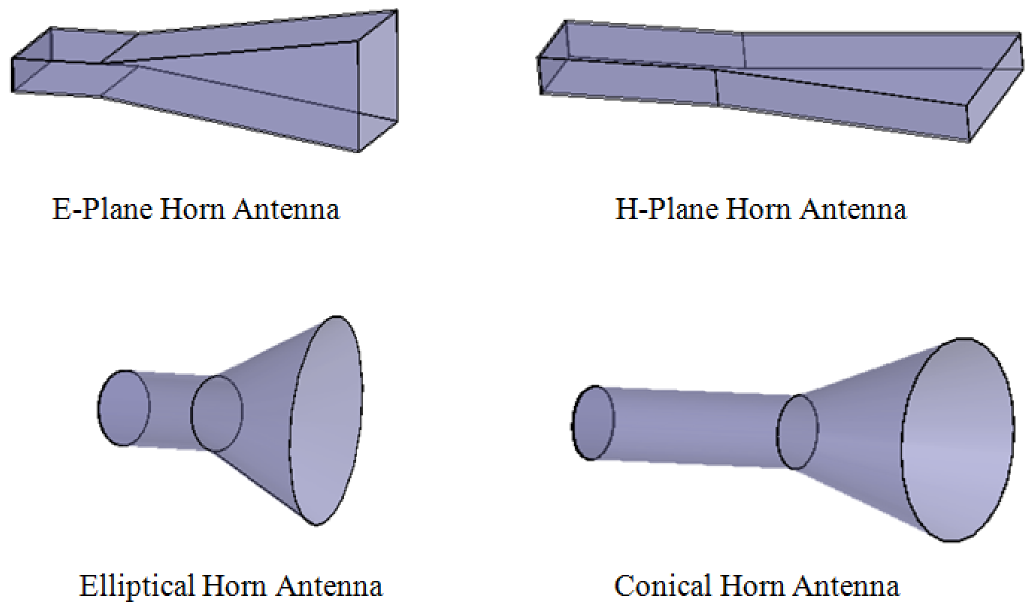


Figure 3.7 Different configurations of horn antenna

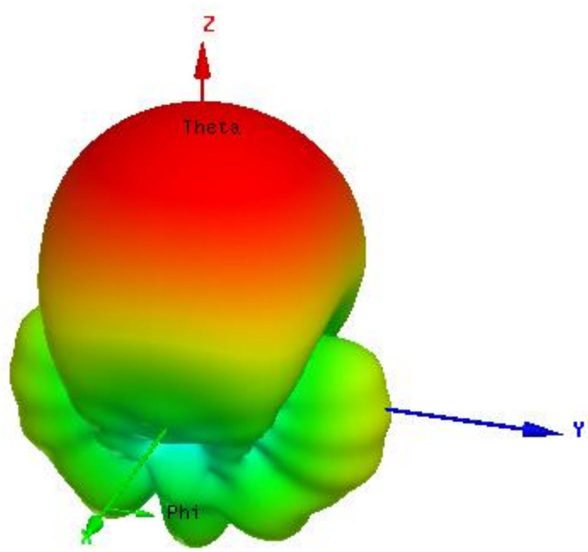


Figure 3.8 3D radiation pattern of horn antenna

3.2 Essential Antenna Performance Specifications

In this section, some of the major and most common antenna parameters will be discussed, explaining each of them and their effect on the overall performance.

3.2.1 Directivity

The Directivity of an antenna is defined as "the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. The average radiation intensity is equal to the total power radiated by the antenna divided by 4π. If the direction is not specified, the direction of maximum radiation intensity is implied." [7], the directivity of a non-isotropic source is equal to the ratio of its radiation intensity in a given direction over that of an isotropic source. Expressing it in a mathematical form, we must start with defining the radiation intensity (U) of an antenna, and the radiation intensity of an isotropic antenna (U_o) as in equation (3-1) and (3-2). Equation (3-3) expresses the directivity if the direction is specified while equation (3-4) expresses the maximum directivity if the direction is not specified.

$$U = r^2 W_{rad} \tag{3-1}$$

$$U_o = \frac{P_{rad}}{4\pi} \tag{3-2}$$

U = radiation intensity

r = distance

W_{rad} = radiation density

U_o = radiation intensity of an isotropic source

P_{rad} = total radiated power

$$D = \frac{U}{U_o} = \frac{4\pi U}{P_{rad}} \tag{3-3}$$

$$D_{\max} = D_o = \frac{U|_{\max}}{U_o} = \frac{4\pi U_{\max}}{P_{rad}} \tag{3-4}$$

D = directivity

D_o = maximum directivity

3.2.2 Antenna Efficiency

The overall efficiency of an antenna consists of a number of sub-efficiencies which are shown in figure 3.9 below. The total antenna efficiency e_0 is used to take into account

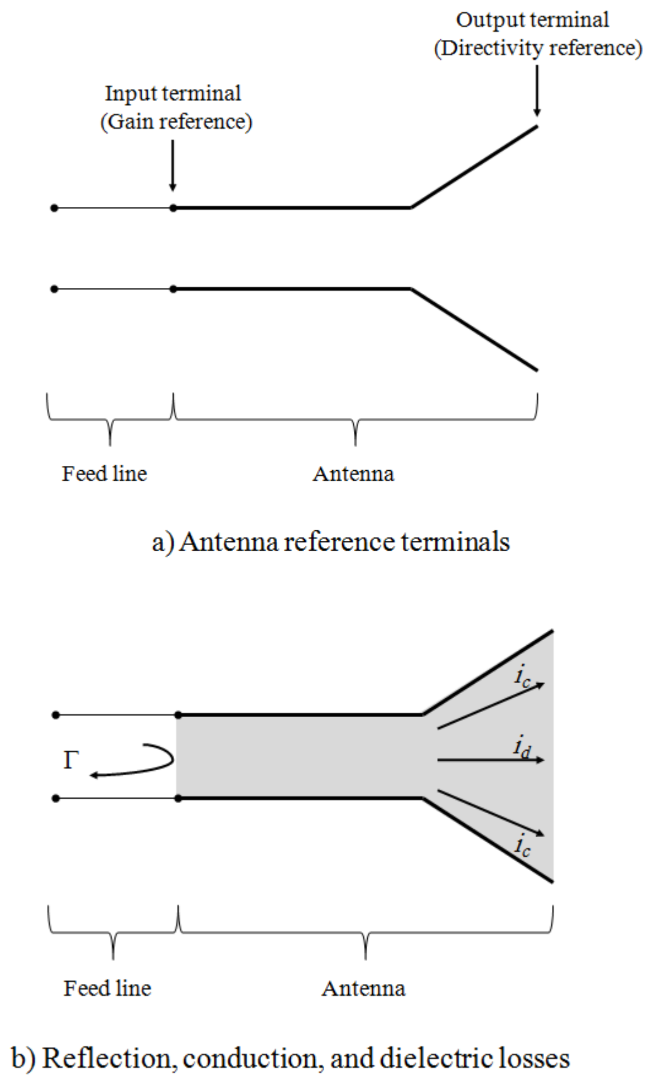


Figure 3.9 Reference terminals and losses of an antenna

losses at the input terminals and within the structure of the antenna. Such losses may be due to reflections caused by the mismatch between the feed line and the antenna, or losses caused by the conductor or the dielectric material of the antenna. The overall efficiency, or total efficiency, can be written as in (3-5).

$$e_0 = e_r e_c e_d \tag{3-5}$$

where

e_0 = total efficiency (dimensionless)

e_r = reflection(mismatch) efficiency = $(1 - |\Gamma|^2)$ (dimensionless)

e_c = conduction efficiency (dimensionless)

e_d = dielectric efficiency (dimensionless)

Generally, e_c and e_d are very difficult to compute, although they can be determined experimentally. The total efficiency can also be rewritten as (3-6)

$$e_0 = e_r e_{cd} \tag{3-6}$$

where e_{cd} = $e_c e_d$ = antenna radiation efficiency, which is used to relate the gain and directivity.

3.2.3 Gain

Antenna Gain is used to characterize the performance of an antenna. Although the gain of antenna is closely related to the directivity, it is a measure that takes into account the efficiency of the antenna as well as its directional capabilities, while the directivity is a parameter that describes only the directional properties of the antenna, and is therefore controlled only by the pattern.

The gain of an antenna in a given direction is defined as "the ratio of the intensity, in the given direction to the radiation intensity that would be obtained if the power were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power captured by the antenna divided by *4π*.” [7]. This can be expressed in equation (3-7)

$$Gain = \frac{4\pi U}{P_{in}} \tag{3-7}$$

U = radiation intensity

P_{in}= total input power to the antenna

By checking figure 3.9 (a) we can find out a relation between the input power (P_{in}) and the radiated power (P_{rad}) which is defined as in (3-8)

$$P_{rad} = e_{cd} P_{in} \tag{3-8}$$

Equations (3-7) and (3-8) can assist in providing a relationship between the directivity of an antenna and its gain, as the directivity is related to the radiated power and the gain is related to the input power to the antenna. Equation (3-9) explains this relation more clearly.

$$Gain = e_{cd} D \tag{3-9}$$

where

D = directivity of the antenna

e_{cd} = antenna radiation efficiency

3.2.4 Bandwidth

The Bandwidth of an antenna is defined as “the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard.” The bandwidth can be considered as the range of frequencies, on both sides of a center frequency, where the antenna characteristics (such as input impedance, pattern, beam width, polarization, side lobe level, gain, beam direction, and radiation efficiency) are within an acceptable deviation of those at the center frequency. For broadband antennas, the bandwidth is usually expressed as the ratio of the upper-to-lower frequencies of acceptable operation. For example, a 10:1 bandwidth indicates that the upper frequency is 10 times greater than the lower. For narrowband antennas, the bandwidth is expressed as a percentage of the frequency difference (upper minus lower) over the center frequency of the bandwidth. Since the characteristics (input impedance, pattern, gain, polarization, etc.) of an antenna do not necessarily always vary in the same manner, or become critically affected by the frequency, there is no unique characterization of the bandwidth. The specifications are set in each case to meet the needs of the particular application. Usually there is a distinction made between pattern and input impedance variations. Accordingly, pattern bandwidth and impedance bandwidth are used to emphasize this distinction. Associated with pattern bandwidth are gain, side lobe level, beamwidth, polarization, and beam direction, while input impedance and radiation efficiency are related to impedance bandwidth.

3.2.5 Input Impedance

Input Impedance is defined as "the impedance presented by an antenna at its terminals or the ratio of the voltage to current at a pair of terminals or the ratio of the appropriate components of the electric to magnetic fields at a point." This can be measured by finding the relation between the voltage and the current at the input terminal of the antenna. The ratio of the voltage to current at these terminals, with no load attached, defines the impedance of the antenna as

$$Z_A = R_A + X_A \tag{3-10}$$

where

Z_A = antenna impedance at the antenna input terminals

R_A = antenna resistance at the antenna input terminals

X_A = antenna reactance at the antenna input terminals

The antenna impedance will further be discussed in the next chapter and the method to control antenna impedance will be covered.

CHAPTER IV

RECTANGULAR PATCH ANTENNA

A patch antenna was chosen as a building block to implement the directional RFID antenna due to its comparatively simple design geometries, as well as the high gain that it provides. Patch antenna is widely used for applications operating at microwave and higher frequency bands, where weight, size, performance and ease of installation are constraints. The antenna consists of a metal patch mounted on top of a grounded dielectric substrate (Figure 4.1).

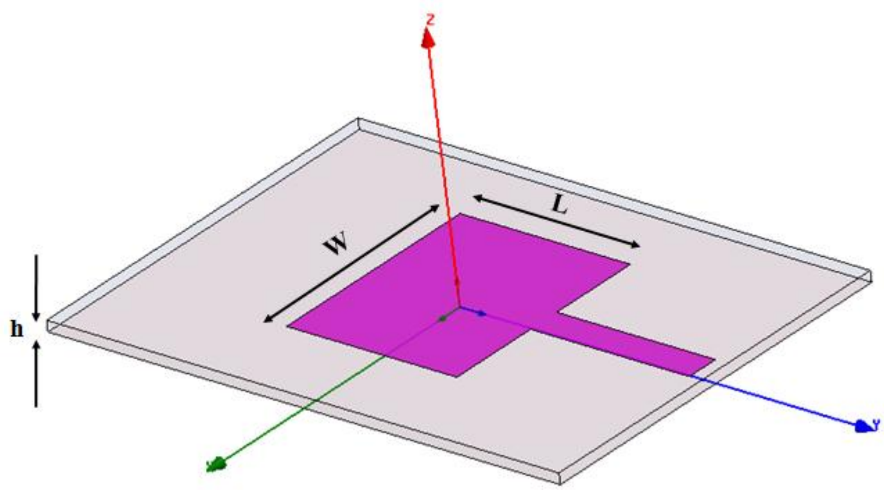


Figure 4.1 Basic patch antenna structure

In this chapter, various methods of modeling and designing a single patch (microstrip) antenna are demonstrated. The transmission line modeling method which is chosen for the analysis and design of the antenna will be described. In order to reduce the reflection of the signal through the feed line due to the difference between the characteristic impedance of the feed line and the antenna, a matching network has been implemented. Moreover, the method used to reduce the size of the single element, and thus the overall size of the proposed directional antenna, will be described. The technique used to create an optimized directional array patch antenna will also be covered. Finally, the design method to implement the connection network and the employed optimization technique will be discussed. These techniques reduce the coupling effect and reduce the phase shift between the microstrip lines.

4.1 Modelling a Microstrip Patch Antenna

A Microstrip antenna can be modelled or analysed using various methods and techniques, the most popular and well known techniques are the transmission line, cavity, and full wave models.

The transmission line model is used in this work and the design steps for a rectangular patch antenna which it is widely used have been discussed.

4.2 Transmission line model

This model treats the antenna as if it is a microstrip transmission line, then it proceeds to represent it as two parallel radiating narrow slots, which has a width of *W* and height of *h*, separated by length of *L* (Figure 4.2).

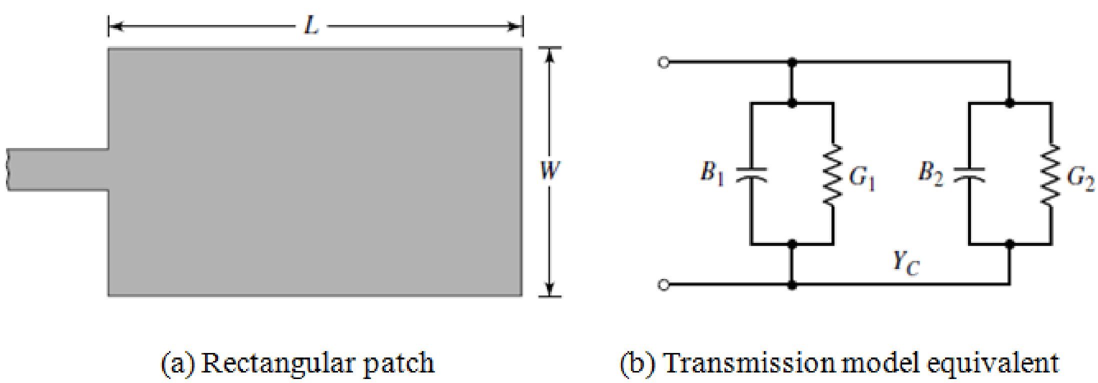


Figure 4.2 Rectangular patch antenna and its equivalent transmission line model

When designing the antenna, there are several effects and factors that should be taken into account.

4.2.1 Fringing Effect

This effect arises due to the patch having finite dimensions (*W* and *L*). As illustrated along the length in Figure 4.3 (a) and (b) for both radiating slots of the antenna, the electric field fringes outward from the edges causing the length and the width to seem electrically longer than what it is. Fringing has a higher impact on the length (*L*) as this dimension controls the frequency at which the antenna resonates. The amount of fringing is a function of the ratio between the length of the antenna (*L*) and the height of the substrate (*h*) which is (*L/h*), and as well as the substrate material.

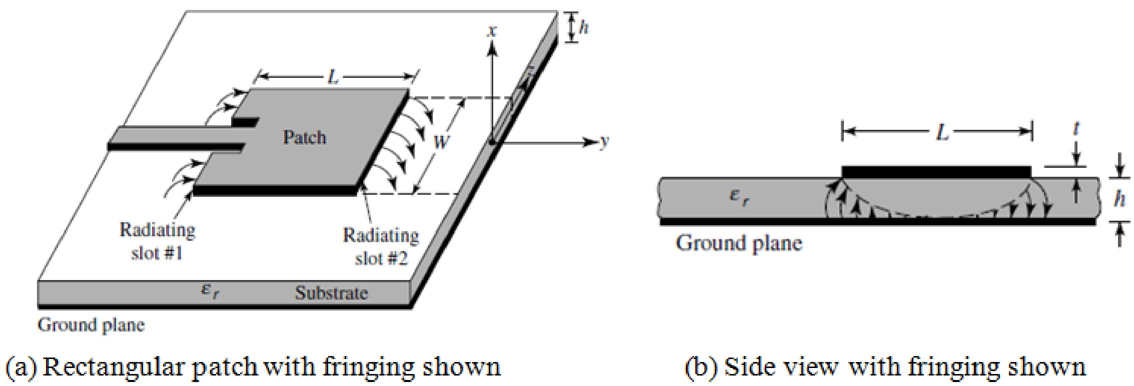


Figure 4.3 The patch antenna with side view showing fringing [7]

The second factor effecting fringing is the substrate material. Because the antenna is treated as a microstrip line, it is surrounded by two different dielectric constants, air and the substrate. This means that the electric field will pass through two materials; however, as shown in Figure 4.4, it will mostly be in the substrate. Regardless, the air dielectric constant should be taken into consideration to properly estimate the amount of fringing.

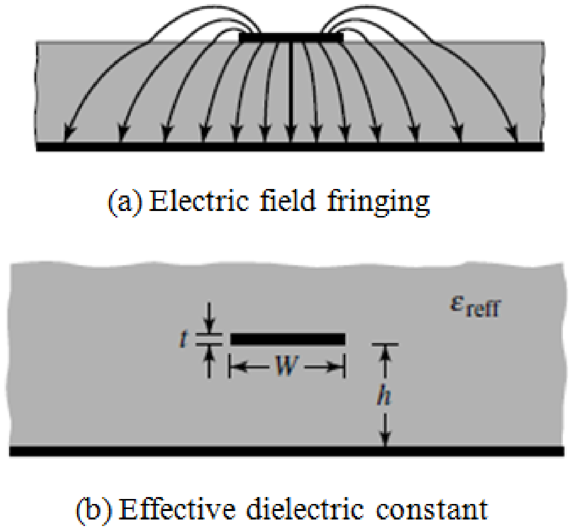
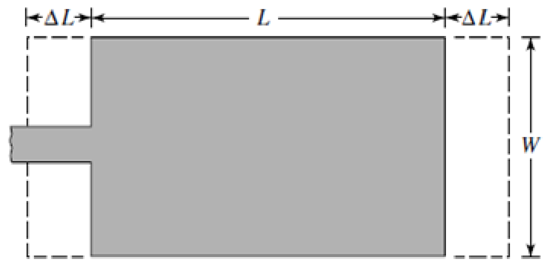


Figure 4.4 The electrical field and the effective dielectric constant

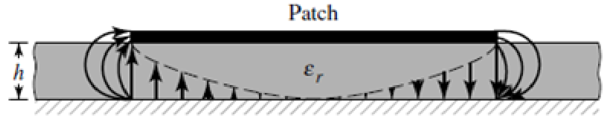
To accomplish this, an effective dielectric constant is introduced (ε_{reff}). Since the microstrip patch resides between air and the substrate, the values of (ε_{reff}) should be between 1 and ϵ_r. Equation (4-1) shows how to calculate the effective dielectric constant.

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-0.5} \tag{4-1}$$

As mentioned above, the fringing effect will cause the size of the antenna to appear larger than its actual length (Figure 4.5). Due to this effect, the length used to determine the resonant frequency must be re-calculated. The effective resonant frequency is thus controlled by varying the length of the antenna L. The new extension to the antenna length ΔL can be calculated and then used later in the design of the antenna to find out the effective length L_{eff} that the antenna will have due to the fringing. The extension of the length is a function of the ratio between the width of the patch antenna (W) and the height (h) of the antenna as expressed by equation (4-2).



(a) Top view of the patch antenna



(b) Side view of the patch antenna

Figure 4.5 Demonstration of the fringing effect on the electrical length

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} \tag{4-2}$$

Thus, the effective antenna length can be described by

$$L_{eff} = L + \Delta L \tag{4-3}$$

4.2.2 Design Requirements

To design the antenna, a number of input variables are needed, which can be chosen depending on the design requirements. The inputs are:

a) Substrate material (ε_r):

There are many types of substrate materials that can be used to design a microstrip patch antenna. The dielectric constant for those materials is in the range of 2.2 to 12. The dielectric constants that are highly desirable for good antenna performance are in the lower end of the range because they provide better efficiency, larger bandwidth and loosely bound fields but at the cost of larger patch element size.

b) Substrate height (*h*):

Substrate height is normally much less than the free space wavelength (λ_0), and it varies between $0.003\lambda_0 < h < 0.05\lambda_0$. The thicker this layer, the better loosely bound fields for radiation into space. When a thinner layer is chosen, the antenna efficient decreases.

c) Resonance frequency (f_r):

This is the frequency on which the antenna is required to operate and is set to meet the standards that the RFID system works on.

4.2.3 Designing Procedure

From the given inputs (h, ε_r, and fr), the following steps are taken to find the width of the required patch antenna width (W) and length (L):

1- The width of the antenna is calculated using equation (4-4).

$$W = \frac{c}{2.f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{4-4}$$

where (c), is the speed of light in free space.

2- The length of the patch antenna is determined using (4-1), (4-2), and the following equation (4-5).

$$L = \frac{c}{2.f_r.\sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{4-5}$$

4.3 Patch Antenna Feeding Methods

There are different types of feeding for microstip patch antennas. The most common ones are:

1- Microstrip line:

Similar to the microstrip patch, the microstrip feeding line is a conducting strip, which is usually smaller in width than the patch antenna. The microstrip feed line has a number of properties that makes it a desirable feeding method. Among the advantages, a microstrip feed line is relatively simple to fabricate, easy to be matched to the antenna, and straightforward to model. Figure 4.6 shows the microstrip feed line equivalent circuit model which consists of a capacitor, inductor, and a resistor in parallel, connected to another inductor in series.

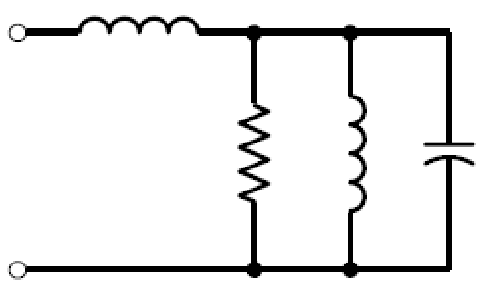


Figure 4.6 Equivalent circuit of the microstrip feed line

2- Coaxial probe:

As opposed to the microstrip feed line where the signal is fed in parallel to the patch antenna, the signal in the Coaxial probe is fed from beneath the patch antenna. Here, the inner conductor of the coaxial is connected to the radiating patch and the outer conductor of the coaxial is connected to the ground patch of the antenna. This feeding method shown in Figure 4.7 is also easy to fabricate. The equivalent circuit model is the same model used for the previously mentioned microstrip feed line.

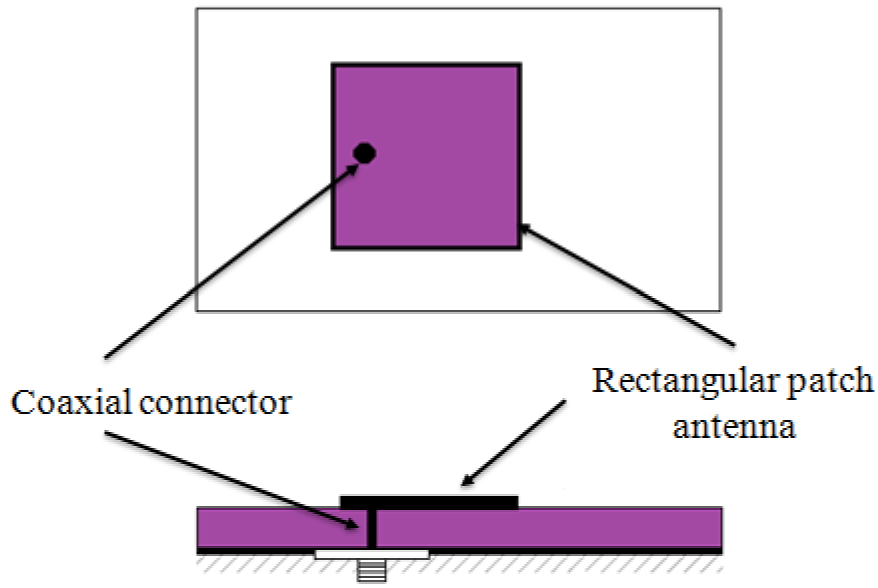
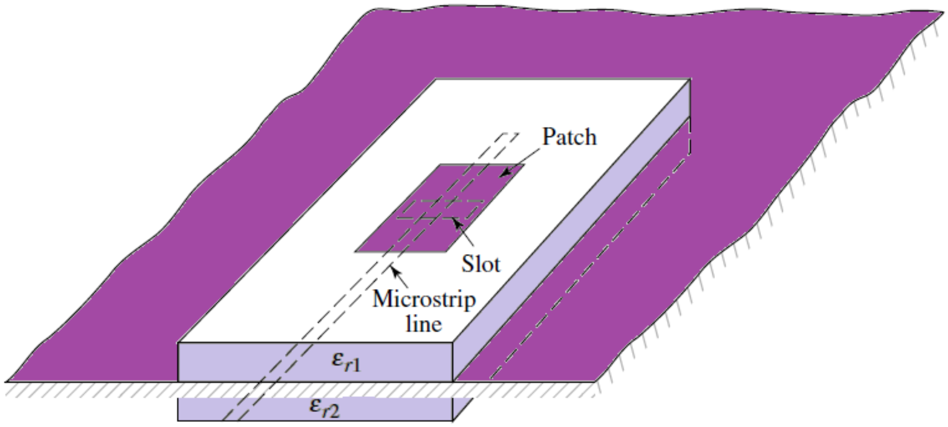


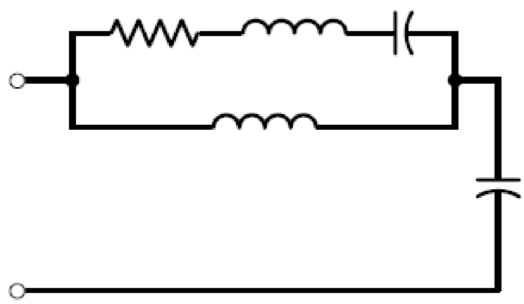
Figure 4.7 The feed line method

3- Aperture Coupling:

The geometry of the Aperture Coupled patch antenna is shown in Figure 4.8(a). The radiating microstrip patch element is etched on the top of the antenna substrate, and the microstrip feed line is etched on the bottom of the feed substrate. The thickness and dielectric constants of these two substrates may thus be chosen independently to optimize the distinct electrical functions of radiation and circuitry. This type of feed overcomes some problems that conducting feeds have, but is also the most difficult in fabrication. Figure 4.8(b) shows the equivalent circuit.



(a) Aperture Coupling

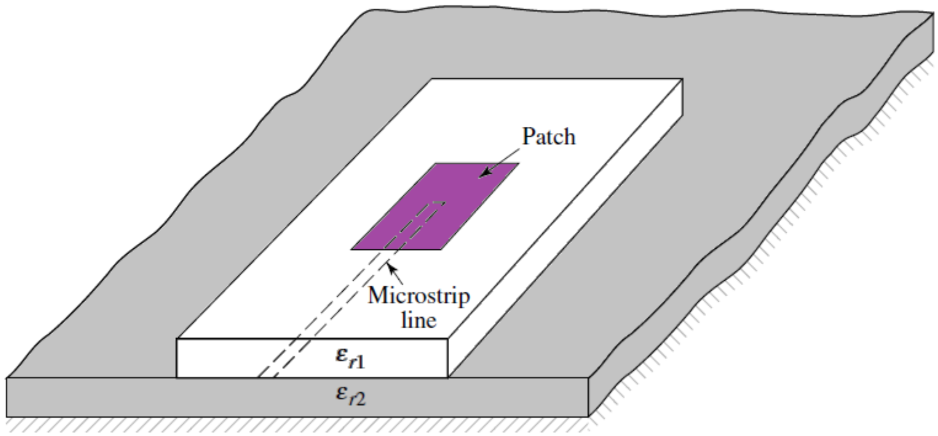


(b) Equivalent circuit

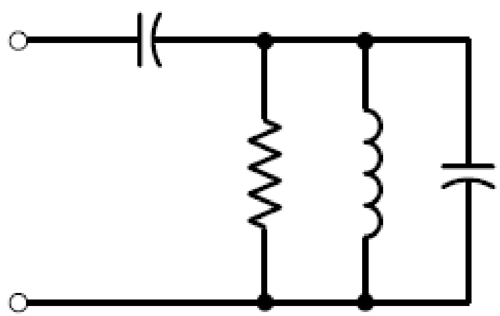
Figure 4.8 The Aperture Coupling and its equivalent circuit model

4- Proximity Coupling:

Proximity coupling is a feed method where a coupling mechanism is used to feed an antenna (Figure 4.9(a)), although, this feeding method has a wider bandwidth in comparison to the other methods that are introduced. Proximity Coupling is simple to model, however, in fabrication this design has an increased complexity. Shown in Figure 4.9(b), the equivalent circuit of the line.



(a) Proximity coupling



(b) Equivalent circuit

Figure 4.9 The proximity coupling and its equivalent circuit model

The microstrip line proves to have the properties that are required for the desired patch antenna design.

4.4 Matching The Feed Line to The Antenna

There is a difference in width size between the feed line and the antenna that is connected to it, this results in a difference in input impedance. Due to this variation in impedances, a mismatch will occur, causing a higher percentage of the signal fed to be reflected back. This will negatively impact the antenna efficiency and gain. The inset feed line method

(Figure 4.10) is commonly used with microstrip feed lines to enable better matching with microstrip antenna, solving this problem.

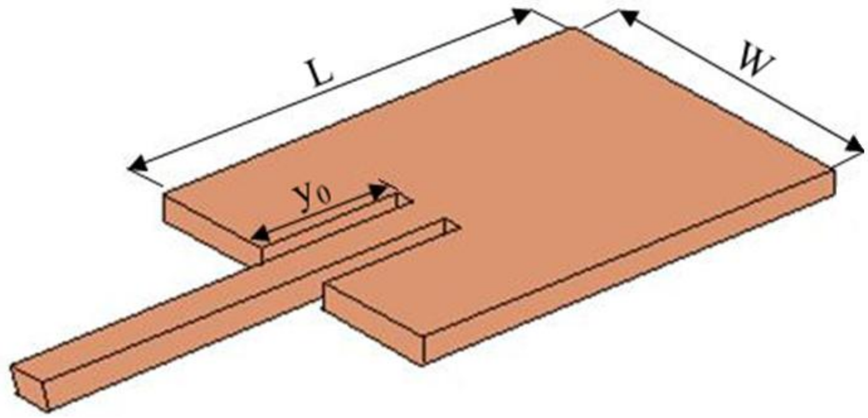


Figure 4.10 A rectangular patch antenna with an inset feed (y_0)

The theory of the Inset feed line method is based upon the voltage current variation within the patch antenna. The current within the patch is at its minimum on the edges of the patch and reaches maximum magnitude near the middle of the patch antenna. From ohms law, it can be concluded that it is possible to control the antenna input impedance that the feed line sees by modifying the location that it is being fed in the antenna. This gives the required input impedance. Figure (4.11) shows that relation, which can be calculated in equation (4-6).

$$R_{in}(y = y_0) = R_{in}(y = 0)\cos^2(\pi y_0 / L) \tag{4-6}$$

The inset feed line method is one of the commonly used methods that are efficient, easy to implement, and will be implemented during this design.

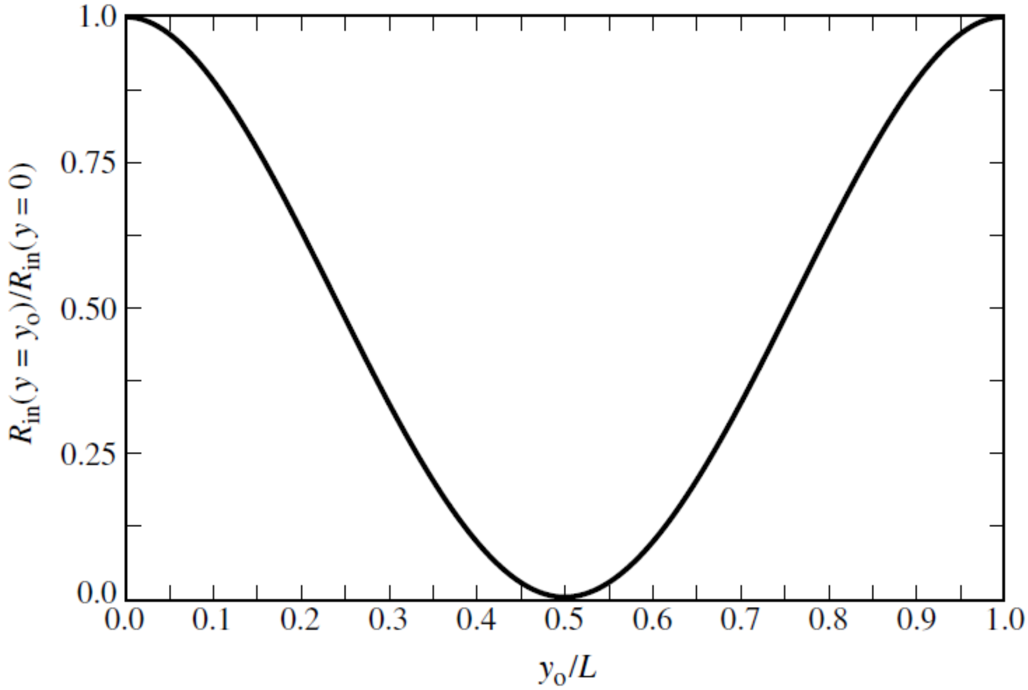


Figure 4.11 Inset microstrip-line feed and variation of normalized input resistance

4.5 Patch Antenna Size Reduction

The Defected Microstrip Structure (DMS) technique has been utilized to reduce the size of the patch element used as a building block. This method uses the Slow-Wave Factor (SWF) in microstip lines to optimize the dimensions of rectangular patch antennas. SWF specifies the relationship between the wave number in free space (k_0) and the propagation constant (β) of the transmission line. For lossless microstrip line, SWF is determined as:

$$SWF = \sqrt{\varepsilon_{reff}} \quad (4\text{-}7)$$

where (ε_e), is the effective permittivity of the material. The propagation constant is determined by (4-8) where (k0), is the wave number in free space.

$$\beta = \sqrt{\varepsilon_{reff}}\, k_0 \quad (4\text{-}8)$$

The SWF of a microstrip line rises when a discontinuity is introduced in the path of the electromagnetic wave which increases the characteristic impedance of the line.

4.6 Array Design

As demonstrated in the previous chapter, various types of antennas have different directivity. For a typical antenna, the radiation pattern has a wide beam width; this implies a lower directivity and thus less gain. In many applications, it is required to have an antenna with a very directive characteristic (high gain) to reach increased distance requirements. This can be achieved by enlarging the electrical size of the antenna. Occasionally, increasing the size of a single element may lead to more directivity, however, to have better directivity without largely increasing the area of the antenna, an assembly of a number of single elements can be set in a certain configuration or structure. This structure is known as an array.

The total field of the array is determined by the vector addition of the fields radiated by the individual elements. This assumes that the current in each element is the same as that of the isolated element without taking into account the coupling effect between elements within the array. This coupling effect can be reduced by controlling the distance between the antenna elements in the array. To increase the directivity, it is necessary for the radiation field of the array elements to align in a one direction and cancel in all other directions.

For an array of identical elements, the shape of the overall radiation patter can be controlled by the total size of the array, the distance between elements, the excitation amplitude of each element, the phase input to each element, or the pattern of each single element.

4.7 Linear Array

A Linear Array is achieved by placing the antenna elements along a single line (Figure 4.12).

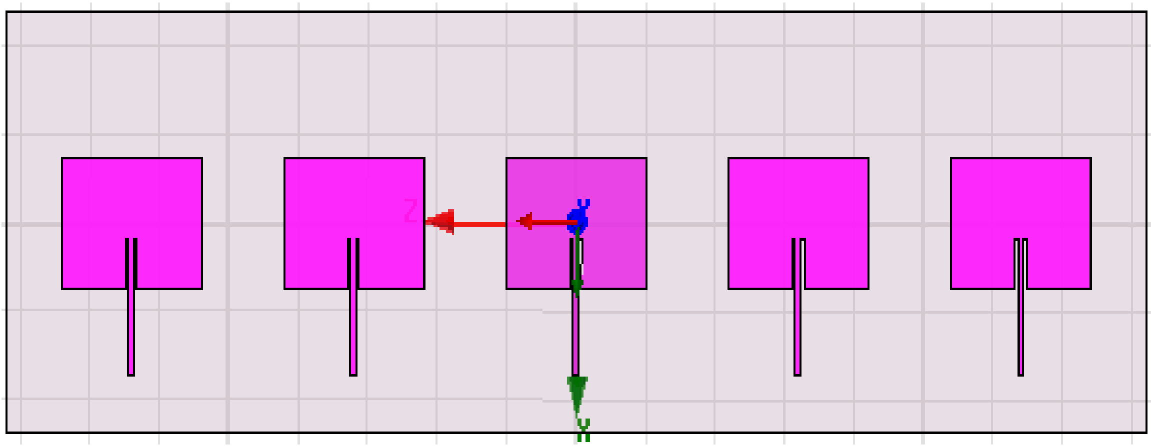


Figure 4.12 Example of a rectangular five patch antenna linear array

The distance between the elements may be uniform or non-uniform, this depends on the radiation pattern requirements. Generally, patch antennas are designed based on configurations consisting of elements of uniform separation. The focus will be directed towards two different types of linear arrays, the uniform amplitude and the non-uniform amplitude arrays. Both cases have uniform spacing between the array elements.

4.7.1 Uniform Amplitude Array Antenna

A uniform array is an array which consists of elements that are identical in the magnitude and have a progressive phase (β) between them (Figure 4.13). A progressive phase (β) represents the phase by which the current in each element leads the current of the preceeding element.

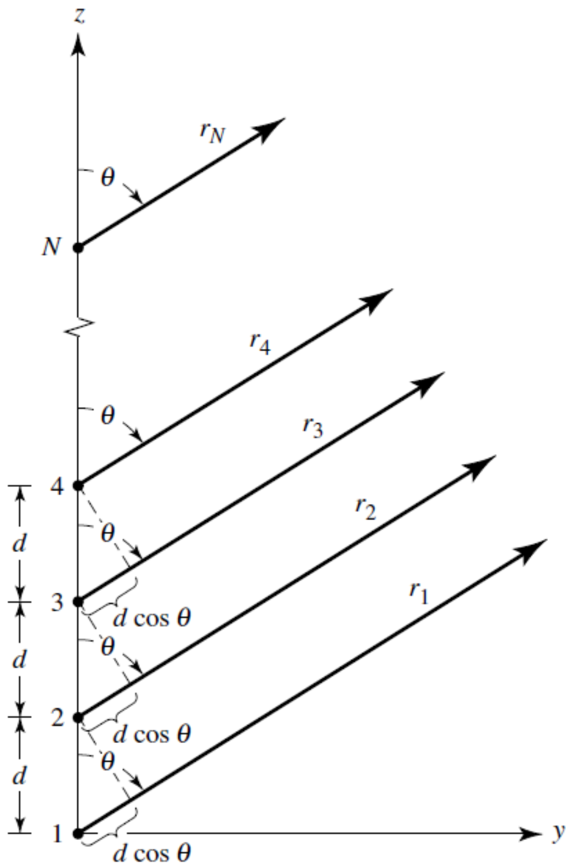


Figure 4.13 Uniform linear array

For non isotropic elements, the total radiating field can be formed by multiplying the field of one element by the array factor (*AF*). The array factor (*AF*) is a function of the geometry of the array and the excitation phase. For a uniform array, *AF* is defined by equation (4-9). This is the pattern multiplication rule and it applies only for arrays of identical elements.

$$AF = \sum_{n=1}^{N} e^{j(n-1)\alpha} \tag{4-9}$$

where

$$\alpha = kd\cos\theta + \beta \tag{4-10}$$

k = wave constant which is $2\pi/\lambda$

d = distance between array elements

θ = the angle of radiation

β = progressive phase between array elements

If the reference point of the array calculation is the physical center of the array, the array factor of (4-9) can be reduced as shown in equation (4-10):

$$AF = \left[\frac{\sin(\frac{N}{2}\alpha)}{\sin(\frac{1}{2}\alpha)} \right] \qquad (4\text{-}10)$$

For example, Figure 4.14 demonstrates how to get the antenna array radiation pattern by multiplying the radiation pattern of a single element of the array to the array factor (*AF*).

4.7.2 Non-Uniform Amplitude Array Antenna

In this section, the radiation pattern is calculated for array antennas with Non-Uniform Amplitudes. The array factor for a non-uniform array differs from that of a uniform array. There are two different array factors (AF) in a non-uniform array, depending on whether it is an odd or even array (Figure 4.16).

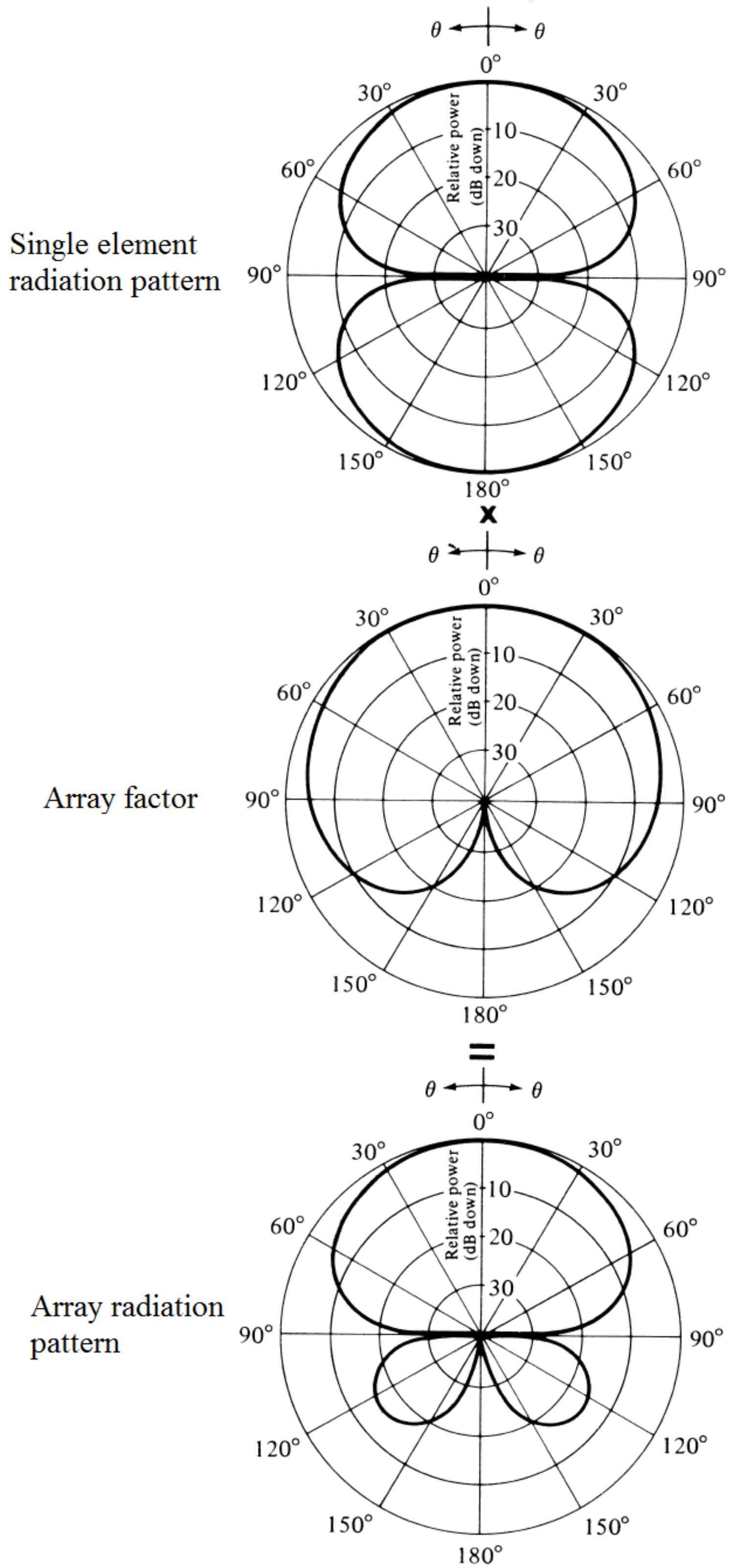
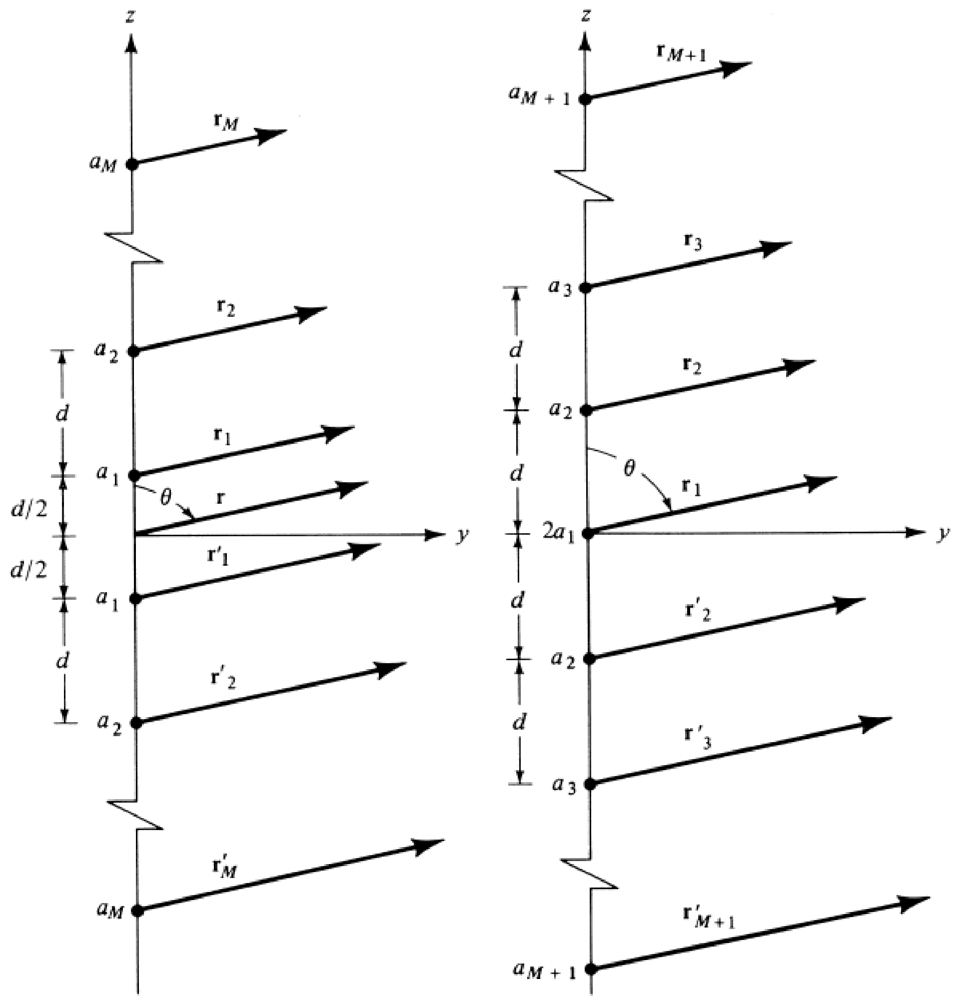


Figure 4.15 Radiation field multiplications, and the resulted array pattern.



(a) Even array (b) Odd array

Figure 4.16 Non-uniform amplitude arrays of even and odd number of elements.

The array factor for a linear non-uniform even array, assuming that the amplitude excitation is symmetrical about the origin, is calculated as:

$$(AF)_{2M}(even) = \sum_{n=1}^{M} a_n \cos[(2n-1)t] \tag{4-11}$$

where

$$t = \frac{\pi d}{\lambda}\cos\theta \tag{4-12}$$

In addition, for a given odd array with a number of elements (*M+1*), the array factor is calculated from (4-13). To simplify the calculation, it is assumed that the excitation of the centre element is doubled as shown in Figure (4.15).

$$(AF)_{2M+1} = \sum_{n=1}^{M+1} a_n \cos[2(n-1)t] \qquad (4\text{-}13)$$

In this research crossed linear arrays with non-uniformed amplitudes has been chosen for the array antenna implementation. This will create a one surface multidimensional scanning array which will be explained and demonstrated in the next chapter.

4.8 Scanning

To have the maximum scanning angle for the array, the distance between the elements needs to be calculated accurately and optimized. Equation (4-14) shows the maximum scanning angle.

$$\frac{d}{\lambda} = \frac{1}{\left|1+\sin\theta_{\max}\right|} \qquad (4\text{-}14)$$

Where λ is the wave length, θ_{max} is the maximum angle of scanning. The maximum radiation of the array can be controlled by varying the phase difference of the input used to feed the array elements. Thus, the radiating beam can be focused in different directions to cover a wider area and ensure a longer range of communication as compared to conventional patch antennas.

4.9 Matching Network

For the array antenna to radiate efficiently, the antenna elements have to be fed separately through inputs with different phase shifts. The inputs are commonly supplied by an integrated circuit. A matching network is required to connect the antenna elements to the inputs to ensure proper operation of the antenna. A poor implementation of this network may introduce an extra phase shift due to extended microstrip lines or cause mutual coupling reducing the antenna gain. The lengths of interconnects between the patches and the inputs are calculated using (4-15), (4-16), and (4-17) to minimize undesired phase shift caused by unmatched interconnects.

$$\Delta\phi = \beta\Delta\ell \tag{4-15}$$

$$\beta = \frac{\omega}{V_P} \tag{4-16}$$

$$V_P = \frac{1}{\sqrt{\varepsilon_{reff}}} \tag{4-17}$$

Where $\Delta\phi$ is the phase difference, $\Delta\ell$ is the length change, and ε_{eff} is the effective dielectric constant of the substrate.

CHAPTER V

CALCULATIONS AND RESULTS

A rectangular patch was chosen as a building block to design the proposed directional array antenna due to its relatively higher gain and ease of implementation. In this chapter the design steps to implement the rectangular patch, improve its performance and reduce the size have been presented. The employed feeding method which enables the array element to steer the beam in two perpendicular pales has been covered and the design details of the connection network have been presented. Simulation results using Ansoft's HFSS CAD tool for 3D full wave analysis have also included followed by a comparison table indicating the advantages of the proposed array antenna.

5.1 Single Element

The antenna is required to resonate at 5.8 GHz, which is the SHF or microwave ISM band reserved for the RFID system. The height of the substrate was chosen 1.00 mm and FR4 epoxy was selected as a substrate. FR4 epoxy is proven to perform well in high frequency applications, mostly in printed circuit boards (*PCB*).

Table 5.1

Antenna type	**Typical**
Substrate	FR4
W (mm)	15.74
L (mm)	12.05
h (mm)	1
Copper height (mm)	0.01

These three requirements are used as inputs to equations (4-1) to (4-5). The output of the single element design is summarized as in table 5.1. The designed patch antenna is shown (Figure 5.1).

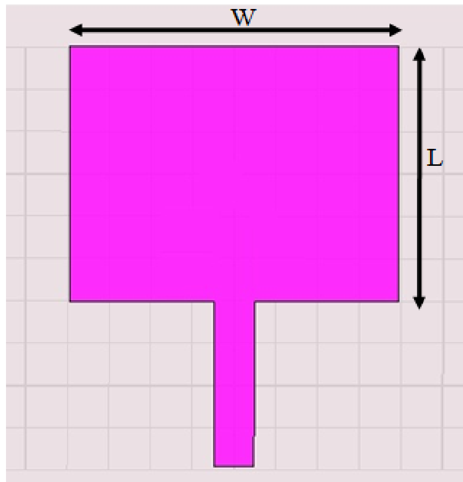


Figure 5.1 The designed patch antenna

5.2 Inset Feed

For the purpose of matching the feed line to the antenna, which is a wider strip line with higher input impedance, the inset method described in section 4.4 was applied and used

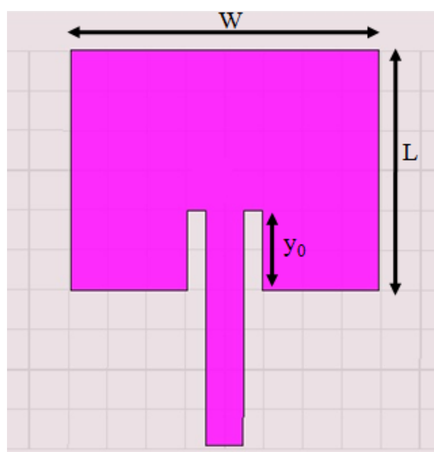


Figure 5.2 The inset feed introduction to the antenna design

to match the microstrip feed line to the microstrip antenna, as shown (Figure 5.2), with a value of (y_0) which is 3.99 mm.

5.3 Patch Antenna Size Reduction

As discussed in section 4.5, the defect microstrip structure (DMS), has been utilized to reduce the size of the patch antenna. The final design is demonstrated in Figure 5.3.

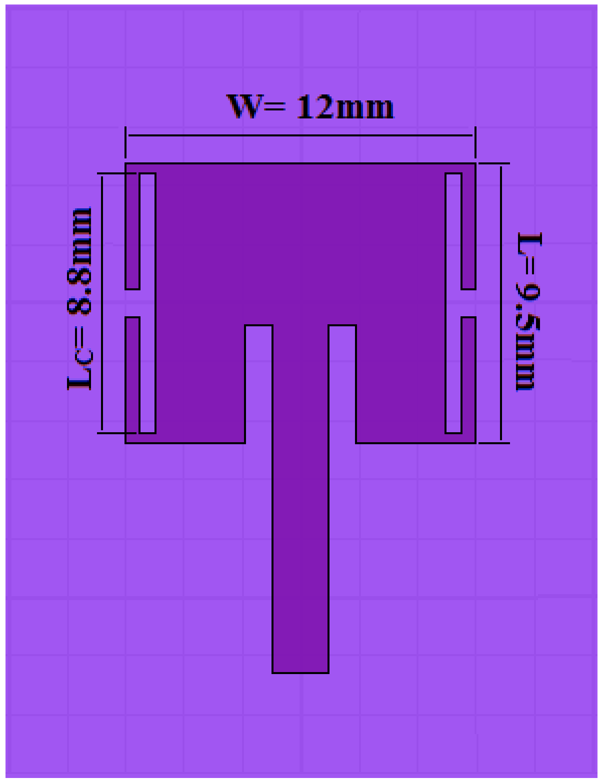


Figure 5.3 The reduced patch antenna

The DMS method was used and optimized to get the best results, where (L_C) represents the length of the microstrip defect that is being introduced to the antenna. Table 5.2 shows a comparison between the typical and the compact single element patch antenna. This table shows the width of the antenna (W) being reduced from 15.74 mm to 12 mm, and the reduction of the antenna length (L) from 12.05 mm to 9.5 mm.

Table 5.2

Antenna type	Typical	Compact
Substrate	FR4	FR4
W (mm)	15.74	12
L (mm)	12.05	9.5
h (mm)	1	
Copper height (mm)	0.01	

The overall area of the patch was reduced from 189.667 mm^2 to 114 mm^2, which is 40% reduction from the original size of the antenna. Figure 5.4 shows the return loss of the antenna, where it resonates around the required frequency (5.8 GHz), with a return loss of -14 dB.

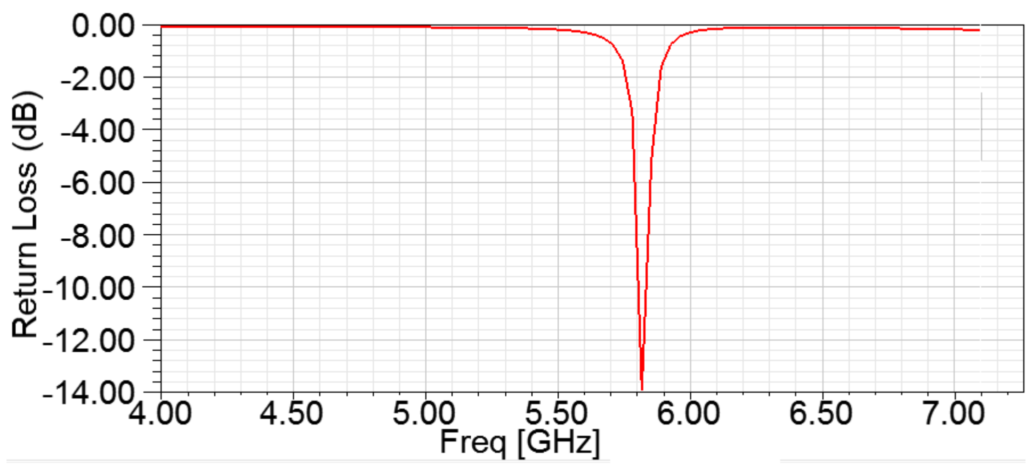


Figure 5.4 The return loss of the designed antenna

The single compact antenna's radiation pattern is shown in Figure 5.5 with a gain of 6.66 dB. This antenna is used as the building block in creating the novel cross five multidimensional scanning patch array antenna.

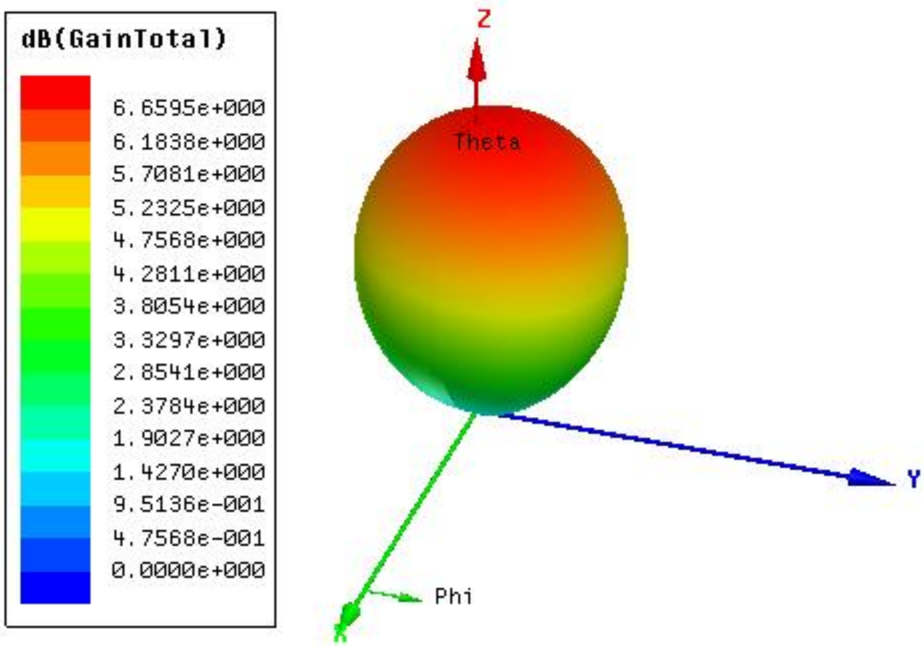


Figure 5.5 The radiation pattern of the compact multidimensional array antenna

5.4 Array Design

The design of the array antenna includes the positioning of the antennas as well as the distance between each element. This cross shape design gives the antenna the ability to radiate symmetrically in both directions. The method in which the array antenna is constructed will allow a microstrip feed line to pass through the array to the integrated circuit (*IC*). The design is shown in Figure 5.6. The distances between elements were calculated to get the maximum angle of radiation with minimum mutual coupling between antennas.

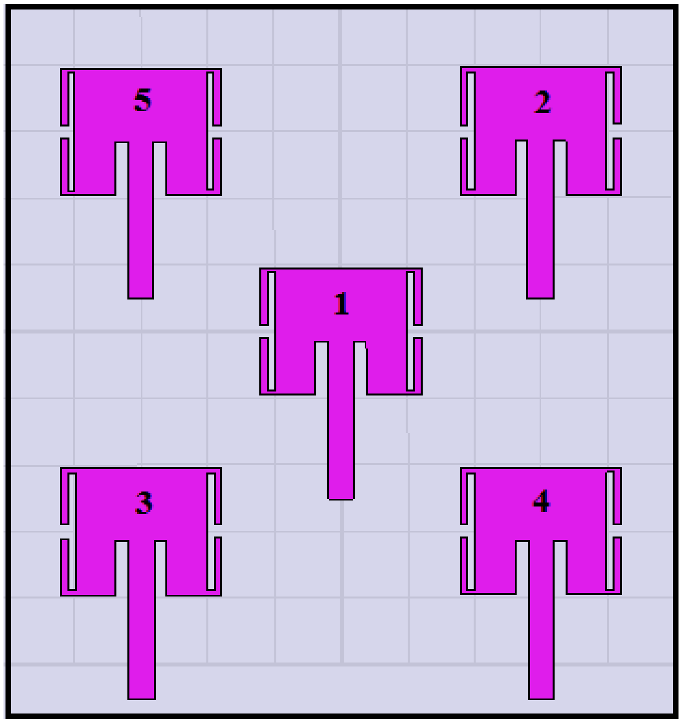


Figure 5.6 The implemented cross array patch antenna

5.5 Matching Network

The width of the lines has been calculated to match the characteristic impedance of 50 ohm. The length of the interconnections was set to eliminate phase shift between the signals applied to the matching network and signals delivered to the antenna elements. The final layout of the array antenna is shown in Figure 5.7.

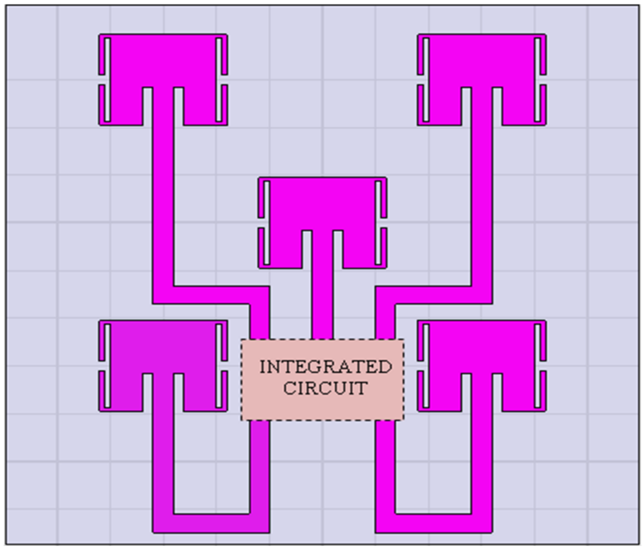


Figure 5.7 Total design of the reduced multidimensional scanning antenna

5.6 Simulation and Results

The proposed cross-shape antenna was implemented and simulated using Ansoft's 3D full-wave electromagnetic field software HFSS. The radiation pattern for the antenna is shown in Figure 5.8. When all antenna elements are fed with in-phase inputs, the main lobe yields a gain of 9.55 dB.

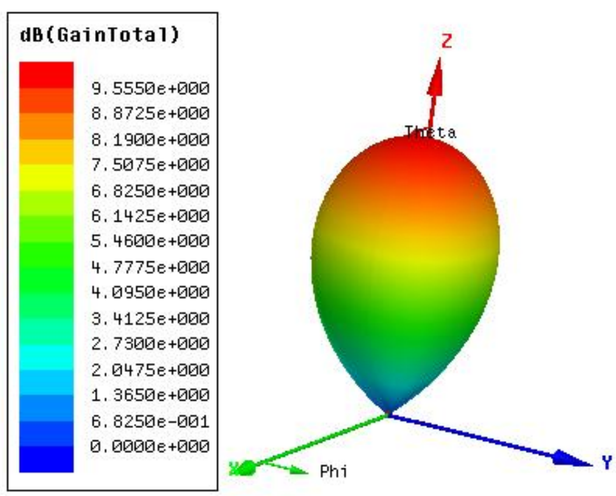


Figure 5.8 Radiation pattern of the compact multidimensional array antenna while all elements are in phase

The antenna is designed to work in two modes, (a) when patch-1, 2 and 3 form an element, or (b) when patch-1, 4 and 5 are fed as an element with an in-phase input as shown in Figure 5.9.

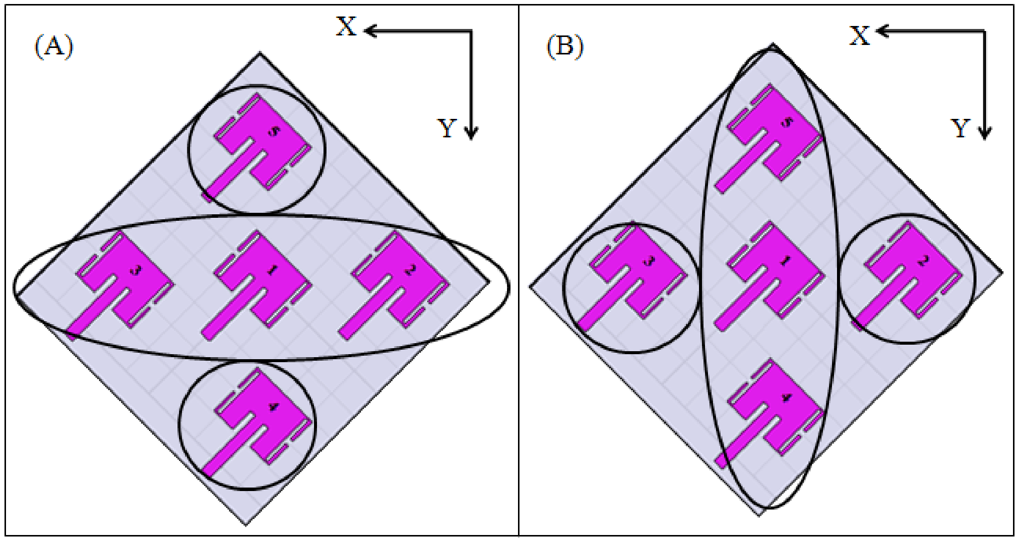


Figure 5.9 (a) shows antenna elements 1, 2, and 3 grouped together and fed with in-phase inputs to scan (YZ) plane. Figure 5.9 (b) shows antenna elements 1, 4, and 5 grouped together and fed with in-phase inputs to scan (XZ) Plane

Although the space between the antenna elements is equal, their gains are different. For instance, in Figure 5.9 (a) one element includes three patches of 1,2 and 3 while each of the other two elements include just one patch. The beam scanning is solely controlled by shifting the phase between the inputs. The beam-scanning took place within two planes of YZ and XZ as follows:

A. Scanning Along YZ Plane (Φ=90°)

   This was accomplished by feeding patche-4, array element (patch-1, 2, 3) and patch-5 aligned along the Y axis with input signals having a constant phase difference. It has to be noted that the three patches in the array element are fed with in-phase inputs. Figure 5.10 shows the scanning over both negative and positive angles for 90^{o} constant phase difference between the inputs.

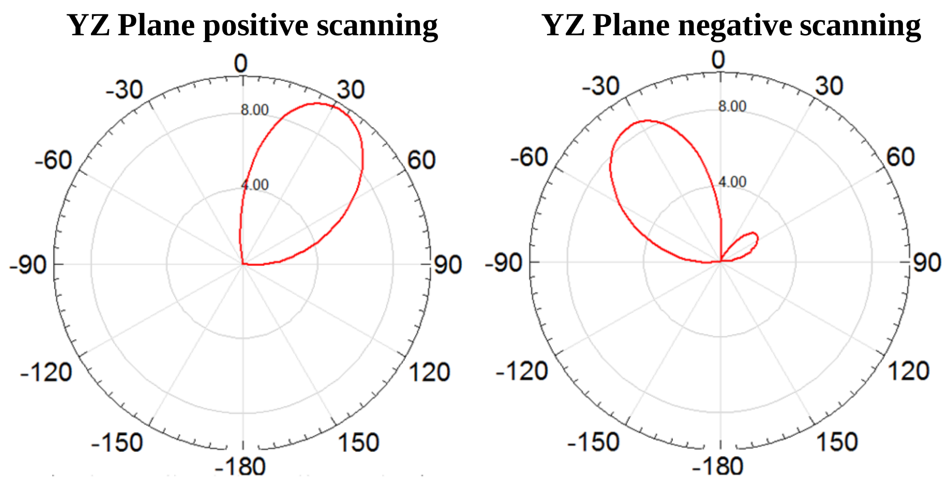


Figure 5.10 Radiation pattern at $\Phi=90^{o}$ (YZ) plane

B. Scanning Along XZ Plane (Φ=0°)

Similar to the scanning along YZ plane, the scanning over XZ plane was realized by providing a constant phase difference signals to feed patch-3, array element (patch-1, 4, 5), and patch-2 which were aligned along the X axis. For a phase difference of 90^{o}, Figure 5.11 shows the scanning in different directions.

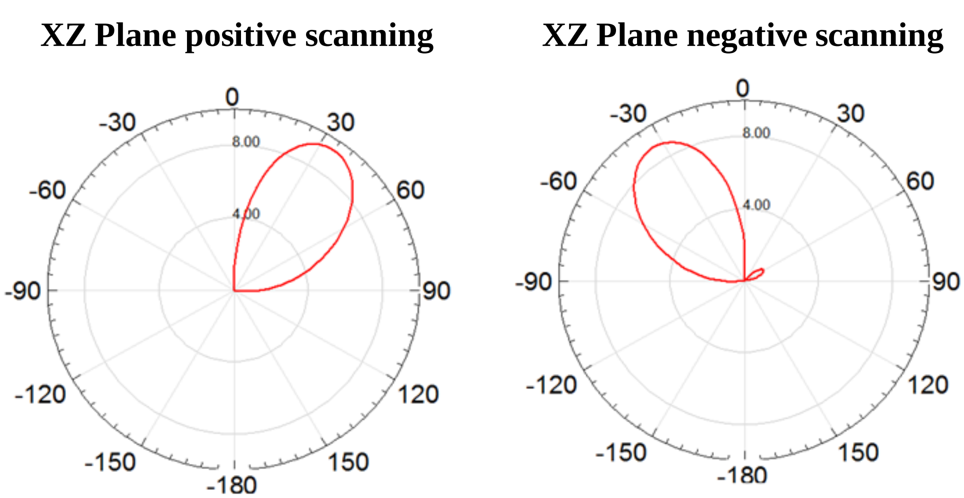


Figure 5.11 Radiation pattern at $\Phi=0^{o}$ (XZ) plane

To compare the performance of the array antennas with the design presented in the literature, the following Figure of merit has been calculated.

$$figure\ of\ \ merit = \frac{Gain \times Total\ angle\ of\ \ scanning}{Total\ number\ of\ \ elements}$$

Table 5.3 shows the results. It can be seen that the proposed scheme outperforms the current solution by a considerable margin. The proposed antenna supports a good gain and a wide scanning range with just a few antenna elements.

Table 5.3 Different phased array antenna

	No. of elements	**Gain (dBi)**	**Total angle of scanning**	**Figure of merit**
Proposed	5	10	180	360
Kalis [15]	4	4.3	91	61.2
Kronberger [16]	3	6.7	90	140.3
Bai [17]	8	13	120	299.25
Eldek [18]	32	19	60	149
Xianzhong [19]	160	27	35	110

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

A new multidimensional wide scanning array antenna for RFID systems is presented in this paper. A size reduction technique has been employed to reduce the overall area occupied by antenna by 40%. While commonly used array antennas support scanning over just one plane, the implemented antenna can steer the radiation beam over two perpendicular planes reducing the blind spots considerably. A matching network between the array elements and the transceiver has also been designed to eliminate the effects of phase shift and optimize the antenna performance.

A new grouping technique for antenna elements has been employed to optimize the antenna performance and maximize the gain during the beam scanning. The implemented antenna supports a wide angle of scanning along both planes with a scanning angle of 180^o over two planes. The antenna occupies a total area of 4.5cm×4.5cm which makes it desirable for RFID applications.

Future research would include changing and exploring different type of substrate materials. Aperture Coupling can be used as a method of feed. Different configurations can be explored to radiate in planes other than only the XZ and YZ planes. Fabrication and measurement results should be considered in the future works as well.

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