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MUTUAL COUPLING IN MIMO SYSTEMS

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ABSTRACT

The drive towards greater efficiency in communications systems has led to the birth of many new technologies and considerable improvements in existing systems over the last 20 years. These developments have been underpinned by increasing demands for higher data speeds, capacity and reliability by end users on a global level. Wireless communications systems have witnessed rapid transformations with this regard. Numerous enhancements in data capacities have been the hallmark of these systems. One of the principal components in achieving improved performance in wireless systems is the antenna system. Single Input Single Output (SISO) antenna topologies have traditionally been employed in wireless links. As the demand for higher data rates have persisted various limitations have arisen. Multiple Input Multiple Output (MIMO) antenna topologies have provided promise of the desired system capacity and reliability. Since MIMO systems employ two or more antenna pairs simultaneously, the effects of mutual coupling become a significant consideration in the quest to achieve high system performance. Therefore a clear understanding of mutual coupling effects with varying conditions in necessary for practical purposes. A lot of work has already been done on this subject. This thesis shall seek to substantiate some fundamental evidence on the relationship between mutual coupling effects and antenna element separation. The procedure shall involve the use of proven computer aided design software to achieve this purpose. Microstrip antennas (used interchangeably with patch antennas), widely known for their efficacy in wireless communications applications will be used for the tests. Specifically the more common linearly polarized rectangular microstrip antenna shall be utilised.

DEDICATION

This thesis is dedicated to the Alpha and Omega, who helped me and saw me through this work with favour and success.

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I wish to specially thank my first supervisor, Dr. Kevin Paulson for his much needed guidance and constructive criticisms. His patience and flexibility enabled me to finally find the right focus.

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CHAPTER 1
INTRODUCTION

1.0 Introduction

Over the last 30 years the demand for greater data capacity in wireless communications systems by end users has increased immensely. This has been witnessed for instance in the case of mobile cellular technology history in Farley (2006), where the first generation (1G) systems were launched commercially in 1983. These were analogue systems and had provision for voice only. By 1991 the second generation systems (GSM) were developed which were digital and had data capacities of 9.6 kbps up to 14.4 kbps. Data rates in the 2G systems evolved in 2000 from 117 kbps in the General Packet Radio Service (GPRS) to 384 kbps provided by the Enhanced Data Rates for GSM Evolution (EDGE). The third generation 3G systems were introduced soon after with maximum data capacity of 2 Mbps in stationary environments. The 3G systems were then enhanced to the High Speed Packet Access (HSPA) with capacities of 14.4 Mbps in the downlink. Presently, fourth generation systems are being tested and prepared for commercial use with expected data rates of 1Gbps in stationary environments and 100Mbps in fast moving vehicles. This data capacity revolution has also been witnessed in various other forms of wireless communications systems and despite all these advancements, there still remains more demand for greater capacity. Therefore, presently, new technologies and innovations are being developed.

1.1 Antenna Systems

The antenna is “that part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves” (IEEE 145-1993). The antenna is also normally required to focus radiation energy in select directions and inhibit same in other directions (Balanis, 2007). It serves as the connection between free space and a guiding system. The antenna is therefore an integral part of a wireless system and the system capacity is heavily dependent on the antenna system. The two broad categories of antenna systems include the longstanding Single Input Single Output (SISO) systems and more recent Multiple Input Multiple Output (MIMO) systems.

1.1.1 SISO Systems

Traditional wireless links have employed the use of Single Input Single Output (SISO) systems which comprise single transmit and receive antennas. The capacity, C or maximum error-free transmission rate for a unit bandwidth (Hz) of a wireless SISO link is given by Shannon's Law (Stallings, 2007):

$$C = log_2(1 + SNR) \text{ bits/s/Hz} \qquad 1.1$$

Where SNR= Signal to Noise ratio

The quest for more data capacity has led to the maximum exploitation of the Shannon theorem in order to derive as much capacity as possible. However, as demand for yet more data has increased, it has become impractical to yield more capacity from SISO systems as described by 1.1. This is because such a process would require an increase in bandwidth in order to increase the bits per second (bps). Alternatively, increasing the transmit power would permit a higher modulation scheme to be applied to a given bit error rate (BER) which increases the bps for a given bandwidth. However, these two methods are undesirable firstly because spectrum (bandwidth) is a finite and valuable resource and is thus strongly regulated with limits to its availability. Secondly, transmitted power of communications systems is also well regulated with the primary aim of preventing interference and negative impacts on other systems operating in similar or close spectral channels. In a bid to resolve these challenges there have also emerged antenna upgrades which include the Multiple Input Single Output (MISO) system and the Single Input Multiple Output (SIMO) system. The MISO system essentially improves the transmitted data capacity by employing multiple transmit antennas with a single receive antenna element. The SIMO system on the other hand is aimed at improving reception reliability by consisting of multiple receive antenna elements with a single transmit antenna.

1.1.2 MIMO Systems

Multiple Input Multiple Output (MIMO) systems have been proposed over the last several years as a more viable solution to capacity demands without increasing bandwidth and transmitted power. The MIMO system utilises multiple transmitting and receiving antennas at the same time (Pahlavan, Levesque, 2005) and offers an increase in spectral efficiency (Hotler). MIMO systems make use of the transceiver techniques of beamforming, spatial diversity and spatial multiplexing. Beamforming and spatial diversity are used in MISO and SIMO systems but spatial multiplexing is used only in MIMO systems. It involves the transmission of multiple data streams in parallel across the radio channel. This increases the data rate over a given signal bandwidth (Suvikunnas, Salo et al, 2008). The high spectral efficiencies provide by a MIMO system are made possible by rich scattering environments which enable signals from each transmitter to be conveyed distinctly through uncorrelated channels to the receiver which is hence able to separate the signals from each transmit antenna at the same frequency (Hotler, 2001). These techniques deliver a linear increase in spectral efficiency as against logarithmic increase in the traditional systems outlined in the previous section.

1.2 Mutual Coupling

The major elements to achieving MIMO capacity realization are signal processing and coding, the propagation channel and antenna design (Jensen, Wallace, 2004). MIMO antenna design is primarily aimed at reducing signal correlation between the antenna elements. Correlation is known to have negative effects on MIMO system capacity (Svantesson, Ranheim, 2001)(Jungnickel et al, 2003). Mutual coupling is known to cause subchannel correlation (Shiu et al, 2000)(Balanis, 1997). Mutual coupling can be described as the interactions between the electromagnetic fields of antenna elements in an array (Ow, 2005). These interactions may also occur between two or more antenna elements from different communications systems that are placed in close proximity. Principally, the energy transmitted from one element is received by any adjacent elements (Parthasarathy, 2006). This produces several undesired effects. They include distortions in current distribution (Zhang, Wang et al, 2008) and impedance mismatches (Lee, 1970) which results in degradation of radiation patterns of individual elements (Zhang, Wang et al, 2008).

Various studies have shown that mutual coupling is a strong factor in determining MIMO channel capacity (Svantesson, Ranheim, 2001)(Janaswamy, 2002)(Wallace, Jensen, 2004)(Waldschmidt, Schulteis, Wiesbeck, 2004). The effects of mutual coupling from most studies on the subject reveal three major results. Firstly, Therefore it has been shown to reduce capacity and degrade MIMO system performance (Chae, Oh, Park, 2006)(Shiu, Foschini, Kahn, 2000)(Ozdemir, Arvas, Aslan, 2004)(Janaswamy, 2002). Secondly, mutual coupling has been shown to improve capacity (Svantesson, Ranheim, 2001)(Jungnickel et al, 2003)(Chiurtu, 2002)(Clerckx et al, 2003). Finally, it has also been shown that mutual coupling is beneficial to capacity in certain conditions (Clerckx et al, 2003)(Wallace, Jensen, 2002).

1.3 Microstrip Antennas

The microstrip or patch antenna was invented over fifty years ago and its applications have increased considerably in the last two decades (Deschamps, 1953)(Gutton, Baissinot, 1955). This is due its low profile structure and other special properties which make it a simple, affordable and flexible means for antenna implementation. Therefore microstrip antennas have become widely preferable for applications in wireless communication systems such as military systems, mobile satellite systems, cellular systems, global positioning systems (GPS), remote sensing and direct broadcast satellite (DBS) systems.

1.4 Aims and Objectives

It has been shown that decreased antenna element separation produces an increase in signal correlation (Mbonjo Mbonjo et al, 2004). There mutual coupling becomes an indispensable consideration when implementing MIMO systems. The practical implications are quite significant in the cases of wireless applications such as mobile phones and other handheld or portable devices. The terminals of these systems have small dimensions which limit the antenna element separations to very low orders of wavelength. Therefore a thorough understanding of mutual coupling effects, particularly with element separation is required for effective antenna array design.

Consequently, the aims of this work shall be to investigate the effects of mutual coupling with variations in element separation (or spacing) and the relative positions of the elements. The work in Parthasarathy (2006) concludes that the mutual coupling effects between two linearly polarized rectangular patch antennas vary distinctly with element separation up to one wavelength of the operation frequency after which no significant variations occur. It also adds that position also has an influence on the mutual coupling effects. This study shall seek to confirm the aforementioned conclusions. Hence the specific objectives of this study shall be:

- To design a linearly polarized rectangular microstrip (patch) antenna theoretically and with computer simulation. The results shall be compared.
- To determine the mutual coupling effects with variations in element separation and position between two linearly polarized rectangular microstrip (patch) antennas.

This shall be achieved principally by computer simulation. The Zeland Corporation's IE3D Full-wave Method of Moments electromagnetic solver software shall be used throughout this study.

1.5 Chapter Summary

Chapter two provides a background to MIMO systems with emphasis on the general system model and the primary signalling schemes of spatial multiplexing and space-time coding. A brief literature review on MIMO antenna design is also included. The review is focused on the aspects of orientation, printed antennas, mutual coupling and diversity in antenna systems. The third chapter comprises two major sections. The first section gives a brief discussion on a number of general and specific antenna performance properties associated with MIMO systems. These include radiation pattern, directivity, gain, polarization and input impedance. The second section includes an overview of antenna diversity featuring diversity combining techniques and antenna diversity techniques. Microstrip antenna theory aspects are discussed in chapter four. The aspects covered are broadly divided into two. Firstly, the general technical aspects are presented covering the general features, advantages and disadvantages, feed techniques and methods of analysis. Secondly, the design aspects are considered which include the design parameters and rectangular microstrip antenna design. Chapter five presents the design simulation results and discussion. A single rectangular patch design procedure and results are given for the theoretical and computer simulation methods. Secondly the various simulation results and mutual coupling analysis for two rectangular patches are provided along with a discussion of the outcomes. Finally, the sixth chapter gives a brief summary of the conclusions of the thesis and an outline of areas for further study and improvement.

CHAPTER 2
BACKGROUND AND LITERATURE REVIEW

2.0 Introduction

In this chapter an overview of MIMO systems is provided and a literature review. The first section introduces the MIMO system model, capacity and major signalling schemes. The second section includes the literature review which is focused on antenna design.

2.1 MIMO System Model

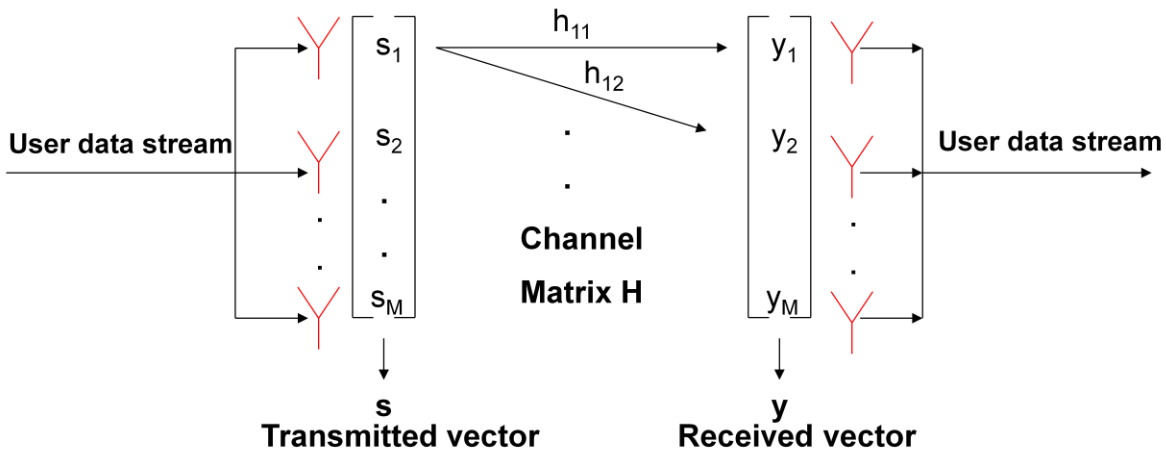


Figure 2.1 MIMO System Model (CommsDesign.com)

The general MIMO system channel model is represented in Figure 2.1. A brief introduction of MIMO systems was presented in chapter one. The system model in Figure 2.1 contains the MIMO channel only. The radio frequency (RF) and signal processing and coding components of the MIMO communications system are excluded. The system is described from Jensen and Wallace (2004). The set of transmitted user data streams, which may given by any symbol vector, are encoded and transformed at the M-element number antenna transmitter M_T to produce the $s(\omega)$ transmitted input waveforms (ω $is\ frequency$). These waveforms are processed by the channel matrix H(ω) to produce the $y(\omega)$ received output waveforms at the M-element number antenna receiver M_R. The waveforms are then filtered decoded to give the received user data stream. This process can be represented mathematically for linear channel elements by equation 2.1:

$$y(\omega)= H(\omega)\, s(\omega) + n(\omega) \qquad 2.1$$

Where $n(\omega)$ is the additive noise comprising channel interference and RF noise.

The channel matrix $H(\omega)$ consists of elements H_{ij} which represent the transfer functions of the jth transmit and ith receive antennas respectively. The matrix $H(\omega)$ is given as:

$$H(\omega) = \begin{bmatrix} h_{11}(\omega) & h_{12}(\omega) & h_{1M_T(\omega)} \\ h_{21}(\omega) & h_{22}(\omega) & h_{2M_T(\omega)} \\ h_{M_R1}(\omega) & h_{M_R2}(\omega) & h_{M_{R}M_T}(\omega) \end{bmatrix} \quad 2.2$$

From equation 2.1 it can be seen that the transmit vector $s(\omega)$ is factored with the channel matrix $H(\omega)$ therefore the number of input data streams must not exceed the rank of $H(\omega)$. Henceforth the channel element will be considered without the frequency factor ω for the purpose of simplicity. The narrowband channel with constant channel response is taken into account in preference to the more complex wide-band channel response. The performance capability of the MIMO system is primarily influenced by the channel matrix H properties. Factors that affect these properties include antenna array size, configuration and impedance matching, element radiation patterns and polarization, mutual coupling and the multipath characteristics. Therefore poor channel optimization would lead to low system performance.

2.2 MIMO Signalling Schemes

Two principal MIMO signalling schemes are outlined in this portion. They include spatial multiplexing and space-time coding.

2.2.1 Spatial Multiplexing

Spatial involves the transmission of distinct data streams simultaneously across parallel channels from each antenna array element at the same frequency. If there are M number of antenna elements then the input data stream is first demultiplexed into M number of substreams. These substreams are then modulated and transmitted all at the same from the individual antenna elements. Provided there is low correlation in the multipath propagation channels then the transmitted signals will be received distinctly at the receive antenna elements. If the channel characteristics are known at the receiver then the signals can be extracted separately from each other. They are then demodulated to reproduce the M number substreams and hence retrieve the original input data stream. Spatial multiplexing therefore delivers an increased capacity linearly with the number of antenna element pairs (Foschini, 1996).

2.2.2 Space-Time Coding

While spatial multiplexing utilises parallel data streams, space-time coding involves utilising the multiple antenna elements to improve performance through diversity gain (Chiau, 2006). This scheme works on the principle of selecting the best possible signal channels in order to increase the chances of higher data rate transmission thereby improving the network throughput. Therefore the probability of utilising signal channels with high packet errors and retransmissions is significantly reduced. In addition, this scheme data streams from the transmit antenna elements are encoded in time and space. Diversity gain is produced at the receiver with effective decoding of the signals. This delivers the desired system transmission improvement as it provides greater performance against signal fading. The advantage of this method is that the transmitter does not need to know the channel information for a successful propagation and reception. Nevertheless it has been shown that space-time coding scheme does not increase capacity linearly with antenna elements as the spatial multiplexing scheme (Chiau, 2006) but rather increase distance coverage of the system. The combination of spatial multiplexing and space-time coding is hence required to achieve an increase in both range and capacity in MIMO systems. This can be seen based on studies in Zheng, Tse (2003) and Tse, Viswanath and Zheng (2004).

2.3 MIMO Capacity

The Shannon channel capacity given for SISO systems in chapter 1 assumes a single transmission line. For a MIMO system with multiple transmission lines the mathematical representation of channel capacity must also incorporate a fixed average receive signal to noise ratio (SNR) and the spatial multiplexing scheme characteristics (Jensen, Wallace, 2004). The transmit power is also assumed to be equally divided among the transmission line. Therefore the channel capacity will be given as the sum of the capacities of each spatial subchannel and can be written as (Chiau, 2006):

$$C = log_2\left(\det\left(I + \frac{\rho}{M_T}HH^+\right)\right) \; bs^{-1}Hz^{-1} \qquad 2.3$$

$Where\ I = identity\ matrix$

$H = channel\ coefficient\ matrix$

$(+) = conjugate\ transpose$

$\det(.) = determinant$

$\rho = signal\ to\ noise\ ratio\ (SNR)$

2.4 Literature Review on MIMO Antenna Design

The superior spectral efficiency and reliability delivered by Multiple-input Multiple-output (MIMO) systems are achieved through antenna arrays with wide lobe patterns, high gain and isolation between the elements (Vaughan, Anderson, 1987). MIMO antenna design is aimed at optimizing these characteristics. The antenna array configuration and propagation environment have a strong impact on system performance (Abouda, El-Sallahi et al, 2006). Therefore a lot of research on antenna array design is being focused on the influence of varying diversity methods and environmental factors (Clerckx, Craeye et al, 2008)(Zhou, Dai,2006). Propagation environments are broadly categorized into indoor and outdoor environments. The propagation characteristics in these environments differ quite distinctly. Indoor propagation research rose into prominence with the evolution of MIMO systems due to the importance of the arrays to channel capacity (Ellingson, 2005). Notwithstanding, there is a need for further research in two key areas of wireless propagation models (Iskander, Yun et al, 2000). The first is the development of deterministic models that consider complex indoor/outdoor propagation environments. The second is the development of parameter requirements for the simulation of practical systems and networks.

2.4.1 Review Objective and Findings

This literature review is focused on general MIMO antenna design with an emphasis on configuration aspects, mutual coupling analysis, diversity and indoor propagation. The objective is to extract the principle design considerations for MIMO system antenna design in compact systems. A discussion of the findings on these aspects is also presented in the next section.

2.4.2 Antenna Orientation

MIMO antennas (also smart antennas) deliver higher capacity, improved quality of service (QoS), enhanced power control and longer battery life in portable systems ((Boukalov, Haggman, 2000). This is buttressed by evidence in various reports including: Ericsson-Mannesman (Anderson, Forssen et al, 1997), NTT DoCoMo (Boukalov, Haggman, 2000) and the European Commission sponsored TSUNAMI Project (Tsoulos, 1999). In Single-input Single-output (SISO) systems the primary optimality criterion is the Mean Effective Gain (MEG) which refers to the average ability of the antenna to receive energy from the electromagnetic field (EMF)(Anderson, Hansen, 1977)(Taga, 1990). This is an indicator of transferred signal power (TSP). In Suvikunnas, Salo et al (2008), a MIMO system considers both the TSP and the ability to optimize parallel spatial channels. This is represented by a new Figure of merit called the Mean Effective Link Gain (MELG) which is a mean of TSP and is directly proportional to the Signal-to-Noise ratio (SNR). Practically, the effect of the MELG is also reduced with more received antenna elements. This means that individual antenna elements contributions become less important in larger MIMO systems.

The comparative study of MIMO antenna configurations in Suvikunnas, Salo et al (2008) also showed that TSP is strongly dependent on antenna orientation. The maximum number of elements (at both transmit TX and receive RX) tested were two by two (2x2) antenna elements. It was concluded that antenna orientations with dual-polarization were best suited for environmental variations. It was adjudged that otherwise, single-polarized arrays were more robust. In addition, vertically polarized dipole antennas yielded the highest capacity and reliability at low outage probability levels of 1%. Antenna array orientation is either broadside (where the angle of arrival $AOA = 0°$) or inline (where the angle of arrival $AOA = 90°$) (Shiu, 1999). Li and Nie (2004) have shown analytically that array orientation has significant effects on spatial correlation. Simulation results showed that channel capacity was highest when orientation at both transmit and receive arrays was broadside and lowest when inline. The angular spread associated with the array orientation also affected capacity considerably. Capacity was increased with orientations having smaller angular spread and decreased progressively in orientations with larger angular spread.

2.4.3 Printed Antennas

Printed antennas are practical for applications where space is limited (Neyestanak, Danideh). They are also inexpensive, light and have low profile. For indoor applications fewer elements will be required but as seen in Jensen, Wallace (2004), high capacity can still be achieved. Mobile stations use printed antennas such as microstrip patches, printed-inverted-F antennas (PIFAs) and inverted-F antennas (IFAs) (Vaughan, Anderson, 2003) which can also be used in wireless local area network (WLAN) systems. Other printed antennas include the meander-line ceramic chip antennas (Choi, Kwon, Lee, 2001) and planar monopole antennas (Wong, Lee, Chiou, 2003). The meander-line chip antenna is expensive due to its complex production process (Choi, Kwon, Lee, 2001). The planar planar monopole antenna is easier to fabricate and compact but its broadband characteristics are limited at that size. Microstrip (patch) antennas have the problem of reduced radiation efficiency due to excited TM_0 surface wave mode with zero cut-off (Pozar, 1983)(Robert, Terret et al, 1985). Another common problem is the radiation distortion as a result of edge diffraction as stated by Salehi and Tavakoli (2005) whose research covers microstrip antennas extensively. Nevertheless, in Bellofiore, Balanis et al (2002), microstrip patch antennas are regarded as the best method for portable devices because they are cheaper, lighter, versatile and easy to fabricate. Planar antenna microstrip array analysis results showed that the number of elements influence the main beamwidth. A narrower main beam with lower side lobes and more nulls ensures an enhanced resolution of the Signal-of-Interest (SOI) and rejection of the Signal-Not-of-Interest (SNOI). The trade-off of is that this is more expensive as more hardware is required. Rectangular patch antennas are the most common due to low cross-polarization (Balanis, 1997).

Omnidirectional elements increase capacity according to Browne, Guterman et al (2007) but this is measured against sectored elements and where element spacing is about two wavelengths (2λ). The aim was to achieve low mutual coupling between elements. However with compact antenna arrays for indoor applications, capacity is optimized through reduction in size and omnidirectionality (Morrow, 2005). Therefore larger element spacing, which generally increases capacity, would in such a case increase size and omnidirectionality, which is undesirable. Regarding substrates, the study in Salehi and Tavakoli (2005) shows that those with higher permittivity are better suited with Monolithic Microwave Integrated Circuits (MMICs). Thicker substrates have better bandwidth properties yet experience greater losses due to surface wave excitation. Substrate performance is generally reduced due to surface wave action. Synthesized substrates with low effective dielectric constant are recommended for minimising the negative impacts of surface waves (Gauthier, Courtay et al,1997)(Papapolymerou, Fraytou et al, 1998)(Colburn, Rahmat-Samii, 1999).

2.4.4 Mutual Coupling Analysis

Channel capacity in MIMO systems is principally determined by the joint correlation between the transmit and receive array (Browne, Manteghi et al, 2006). However reducing correlation alone in a MIMO link may not be enough to optimize capacity especially in compact designs. According to Nabar, Bolcskei et al (2002), cross polarization discrimination (XPD) and antenna array directivity also determine channel capacity. Factors that cause subchannel correlation are low diversity performance in the propagation multipath and particularly mutual coupling between elements (Shiu, Foschini, 2000)(Balanis, 1997). Subchannel correlation itself is dependent on array geometry and increases with smaller element spacing (Lee, 1973)(Gupta, Ksienski, 1983). Therefore mutual coupling analysis becomes a crucial factor for portable system designs where the array element spacing is measured in fractions of the resonant wavelength (λ) in order to achieve the required compactness. The mitigating effects of mutual coupling on MIMO channel capacity are shown clearly in several works (Svantesson, Ranheim, 2001)(Janaswamy, 2002)(Wallace, Jensen, 2004)(Waldschmidt, Schulteis, 2004). Mutual coupling also introduces additional problems of reduced radiation efficiency caused by impedance mismatching (Lee,1970) and power loss (Wallace, Jensen, 2004). The study in Browne, Manteghi et al, (2005) conducted on a MIMO testbed states that mutual coupling has little or no effect on a 2×2 paired dipole array with $\geq \lambda/4$ (quarter wavelength) element spacing.

Compact designs for portable devices particularly mobile handsets may easily have smaller element spacing than $\lambda/4$. Achieving the required decorrelation in such systems is therefore imperative. The study in Browne, Manteghi et al (2006) proposes a novel PIFA design for this purpose. PIFA arrays are regarded widely as very compact MIMO arrays. They are resistant to surrounding radiating elements due to their low profile and nearness to a ground plane which results in minimal mutual coupling effects. They also have good omnidirectional-like radiating patterns. The study showed that PIFA arrays provided a compact design solution to mutual coupling effects without the use of matching networks to eliminate the impedance mismatches that resulted. It also concluded that with the presence of mutual coupling in any or both antenna ends (TX & RX), capacity increase was not directly proportional to the number of transmit/receive antenna pairs.

On the other hand, while mutual coupling between antenna elements has been shown to decrease capacity, it has also been shown to increase capacity in certain cases experimentally in Jungnickel, Pohl, Helmolt (2003). A more detailed analysis and explanation of this is given in Wallace, Jensen (2002). Mutual coupling is measured by the rank k of a MIMO channel which is a function of the propagation channel and array (Ellingson, 2005). The study in Mbonjo and Hansen (2004) reached two primary conclusions regarding mutual coupling effects on channel capacity when spatial correlation is neglected. Firstly, smaller element spacing reduces channel rank and hence decreases capacity. Secondly, smaller element spacing may translate to an increase in either transmitted or both transmitted and received power thus increasing capacity. Therefore a compromise in array design is necessary to optimize both effects.

2.4.5 Diversity

Diversity techniques are employed in antenna configuration, radiation pattern, polarization and multimode excitation to reduce correlation between the MIMO multipath signals and thus achieve the desired increase in capacity (Jensen, Wallace, 2004)(Andersen, 2000)(Shiu, Foschini et al, 2000). The diversity techniques which may be applied to MIMO systems to increase capacity are spatial, pattern and polarization diversities (Chiau, 2006).

Spatial diversity requires that there is adequate spacing between antenna elements such that the relative phases of the multipaths at the elements are distinctly different. Large phase variations lead to less correlation between the signals at the antennas. Therefore correlation would decrease inversely with antenna element spacing. A standard guideline on element spacing is that it should be a multiple of the frequency wavelength (Shiu, Foschini et al 2000)(Pohl, Jungnickel et al 2002). However this method is effective only with sufficient inter-element distance otherwise mutual coupling will be introduced which would lead to input impedance changes and an attendant radiation pattern distortion (Janaswamy, 2002)(Odzemir, Aslan et al, 2003)(Balanis, 1997). Pattern diversity in Ali and Thiagarajah (2007) involves the presence of distinct radiation patterns at antenna elements. Angle diversity is achieved when antenna directions for transmit and receive ends are in the angles of departure (AOD) and angles of arrival (AOA) respectively. The result is low correlation effect. The angle diversity performance is highest when antennas receive multipath signals from many directions. This yields narrower angle spacing and greater directivity due to non-overlapping patterns. These orthogonal patterns produce low correlated signals. Lastly, polarization diversity is employed by using two or more differently polarized antennas at transmit and receive ends respectively to produce separate uncorrelated signals at each antenna.

For optimum performance, vertically polarized signals are found to propagate better than horizontally polarized signals (Kyritsi, Cox, 2001). In indoor MIMO propagation environments multiple antenna polarization with both vertically and horizontally polarized antenna pairs are suggested for improved performance (Ellingson, 2005). For compact designs, spatial diversity is hence rendered ineffective due to very small element spacing. Therefore pattern and polarization diversity are applied. Combinations on diversity techniques are being employed in the quest to improve capacity performance (Ali, Thiagarajah, 2007).

2.4.6 Indoor Propagation

Floors and ceilings in buildings are mostly conductive while walls possess lossy dielectric properties. This presents a situation where signals are almost completely penetrative in some cases and almost totally reflected in other cases (Bertoni, 2000). Cross-polarization (when power is received with a polarization orthogonal to transmitted polarization) caused by several factors is high within rooms and quite low (about $-15dB$) in passage ways (Kyritsi, Cox, 2001). The experiment conducted by Mitsui, Otani et al (2003) shows that antenna array configuration has significant effects on capacity in indoor environments. This is because capacity is also affected by the MEG (described earlier in this review). Higher MEG means higher TSP and hence higher channel capacity. In Ellingson, 2005 vertically polarized dipole or monopole arrays are preferred. This is because angular spread is wide in azimuth and narrow in elevation. Microstrip patches, slots etc are other suitable arrays for indoor models. Brown, Manteghi et al (2006) experimented with various 2-element, and 4 element ULA dipole and PIFA arrays with spacings between $\frac{\lambda}{4}$ $and \frac{\lambda}{2}$. The results showed that the PIFA arrays performed better than the dipole configurations and the 2 element PIFA array outperformed the 4 element PIFA arrays. Three dimensional (3D) antenna arrays have also been shown to be effective in indoor environments (Chen, Parini). The ray tracing method was used to model 4x4 linear dipole ($\lambda/2$ spacing) and 3D arrays (no antenna coupling) respectively. The results confirmed the 3D arrays with higher capacity than the linear dipole arrays. In Morrow (2005), an attempt is made to analyse the essential design parameters for indoor MIMO antenna systems. Four element linear and square dipole arrays and three element linear and triangular dipole arrays respectively were simulated with different orientations and angular spread. The dipoles were vertically polarized throughout. The triangular array produced the best performance with the least omnidirectionality, followed by the linear array.

2.4.7 Summary

The reviewed studies and reports have provided various facts on aspects of MIMO antenna design with a focus on considerations and requirements for indoor propagation environments. The main design factors to be considered are antenna array configuration and architecture, which would include geometry, orientation, polarization, types of element and element spacing. Other factors are diversity performance, mutual coupling analysis and the characteristics of the environment itself, in this case an indoor environment.

A number of the concepts are generally acceptable. It is generally held that broadside orientation at both array ends achieves higher capacity. Vertical polarization is also more productive than horizontal polarization. It is also agreed that a combination of both polarizations would most likely be better suited for indoor environments. There is a significant degree of flexibility with regards to types of element. Most of the studies used monopole or dipole arrays for their simplicity and low cost in addition to performance. However patch antennas are preferred in other circumstance especially where compactness is required. They are even easier to implement across a broader range of applications. Specifically, microstrip antennas are used because they are cheap, light, versatile and easy to produce.

Then there are other aspects that are not quite clearly harmonised. One of such is omnidirectionality which appears a desirable criterion in some cases and undesirable in others. Nevertheless it is clear that it depends on the nature of the design and the propagation environment. A definite threshold for the minimum element spacing in which mutual coupling is negligible is also inconclusive. However most results show that spacing $\leq \lambda/4$ would produce such effects and spacing $> \lambda/2$ are likely to be negligible. The contention is between $\frac{\lambda}{4} and \frac{\lambda}{2}$. Mutual coupling in itself reduces capacity but increase it in compact designs where diversity is employed. Generally, the findings reveal that a lot of considerations and trade-offs are involved and a variety of approaches can be adopted for similar situations.

CHAPTER THREE
ANTENNA PERFORMANCE

3.0 Introduction

MIMO system performance is known to be determined by the correlation characteristics of the multipath signal (Ali, Thiagarajah, 2007). The channel rank is defined as the number of uncorrelated channel path gains (Gesbert, Shafi et al, 2003). Channel capacity is highest when the transfer matrix is full rank (Jensen, Wallace, 2004). This is achieved with low antenna signal correlation. This chapter discusses various aspects of antennas that are linked with mutual coupling as outlined in chapter one and influence correlation and hence, MIMO system antenna performance. They are divided into general antenna parameters and antenna diversity.

3.1 General Antenna Parameters

This section provides a brief discussion of some important antenna parameters that affect antenna performance. They include antenna radiation pattern, directivity, gain, polarization and input impedance. The parameters are defined generally except for the radiation pattern and polarization parameters which are discussed more closely to their relation with MIMO antenna performance.

3.1.1 Radiation Pattern

The radiation pattern of an antenna refers to the plot of the of the radiation properties of the using space coordinates (Balanis, 1997). This is usually represented in the far-field region and is specified by the elevation angle θ and the azimuth angle $\emptyset$. The radiation pattern is also a graphical representation of the power radiated from an antenna per unit solid angle which is equal to the radiation intensity which is a property of radiation (Balanis, 1997). Considering an isotropic antenna which radiates uniformly in all directions with a power P covering a sphere of radius r, the power density S can be given thus (Balanis, 1997):

$$S = \frac{P}{4\pi r^2} \qquad 3.1$$

The radiation pattern (isotropic) U_i is therefore given as (Balanis, 1997):

$$U_i = r^2 S = \frac{P}{4\pi} \qquad 3.2$$

However the isotropic antenna with perfect characteristics is impractical. Realistically, directional antennas are obtained where power is radiated in variations of magnitude and direction. There are also a number of other radiation properties which include the power flux density, field strength, directivity and polarization (Balanis, 1997). The most important property is the radiated energy that can be seen by observation along a particular direction or boundary of fixed radius. An illustration of the typical radiation pattern of a directional antenna is shown in Figure 3.1

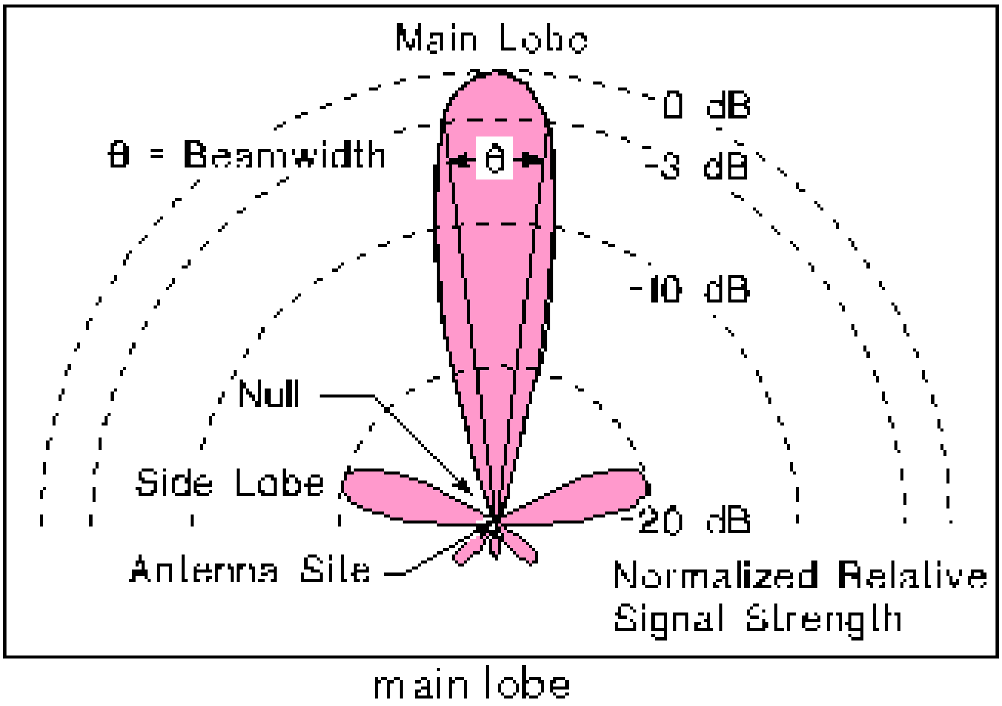


Figure 3.1 Antenna Radiation Pattern (www.its.bldrdoc.gov)

A number of definitions from Figure 3.1 are given (Nakar, 2004):

- Beamwidth (θ): Also known as the half-power beamwidth (HPBW). This refers to the angle between the half-power points on the main lobe
- Main Lobe: Also known as the main beam this refers to the "radiation lobe containing the direction of maximum radiation" (Balanis, 1997).
- Minor Lobe: This refers to any lobe other than the main lobe. Minor lobes are measured as a ration of power density of each lobe to that of the main lobe, in decibels dB.
- Side Lobe: This refers to any minor lobe which radiates in an undesired direction.

- Back lobes: These are any lobes positioned at $180°$ to the main lobe.
- Null: This refers to any gap between any two lobes where the radiated pattern is zero.

In MIMO systems angle diversity refers to the condition where transmitted scatter signals arrive at the receive end at slightly different angles. These angles are also paths moving through different scatter volumes in the troposphere. Angle diversity is produced when antennas have clearly separated radiation patterns. Signal correlation is ρ_p expressed mathematically in (Vaughan, Andersen, 1987) for two antennas with phase centers at the same point or closely separated. A single incident wave polarization is assumed and the arrival angles of the multipath elements are according to a probability distribution function (PDF). The equation is given by:

$$\rho_p = \int f_\Omega (\Omega) e_1(\Omega) e_1{}^*(\Omega) d\Omega \qquad 3.3$$

where $e_1\Omega$ is the pattern of the ith antenna and should be small

The significant angle diversity caused by the close proximity of the antenna phase centers also causes majority of the small elements to produce a largely omnidirectional radiation pattern. This in turn produces high which results in low capacity. Therefore the key design aim would be to create radiation patterns that reduce ρ_p as much as possible in order to achieve the desired capacity improvement. A primary way of optimizing radiation patterns is through antenna designs that produce patterns with high orthogonality. It has been shown in Svantesson (2002) that multi-mode antennas which produce different patterns for the different modes produce orthogonality which reduces formula and hence correlation. Therefore designs which yield such high orthogonality must be considered in order to achieve increased MIMO capacity through low correlation in antennas. The second major consideration of element radiation patterns is with regards to how the antenna influences the multipath environment. The more energy from the antenna is directed at the position or location of the multipath elements, the higher the probability of increased capacity. This assertion is shown by the study in Waldschmidt, Fugen et al (2002) where dipole antennas were compared against spiral antennas. Spiral antennas have higher gain and radiation patterns that are directed at elevation angles of $45°$ and $135°$ while dipoles have narrower angles in elevation. Both measured and simulated approaches to determining capacity in an indoor environment were employed. The results showed the dipoles had a 10% higher capacity. This was attributed to the fact that the dipoles directed a greater amount of energy into the horizontal plane in which the multipath elements were mostly present.

3.1.2 Directivity

Balanis (1997) defines antenna directivity as “the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions”. Therefore the directivity D of an antenna is the ratio of its radiation intensity to that of an isotropic antenna in a fixed direction:

$$D = \frac{U}{U_i} = \frac{4\pi U}{P} \qquad 3.4$$

$Where\ U = radiation\ intensity\ of\ the\ antenna\ in\ Watts\ per\ unit\ solid\ angle$

$U_i = radiation\ intensity\ of\ an\ isotropic\ antenna\ in\ W\ per\ unit\ solid\ angle$

$P = total\ radiated\ powe\ in\ Watts$

The directivity of an isotropic source is unity and when direction is not given then the maximum directivity U_{max} is assumed:

$$U_{max} = \frac{4\pi U_{max}}{P_{max}} \qquad 3.5$$

Directivity is a dimensionless quantity but is usually expressed in dBi which stands for decibels relative an isotropic source. The radiation pattern of an antenna can be used to determine its directivity. Directivity is proportional to the width of the main beam. Hence narrower beams have higher directivity and vice-versa.

3.1.3 Gain

Antenna gain is related to the directivity and incorporates both the directional characteristics and efficiency of an antenna. Gain 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. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π” (Balanis, 1997). However relative gain of an antenna is most commonly considered and is defined as “the ratio of the power gain in a given direction to the power gain of a reference antenna in its referenced direction” (Balanis, 1997). The reference antenna is usually an isotropic source or other type of antenna with a known gain. The input power of the two antennas must be equal. Then the gain G will be given as (Balanis, 1997):

$$G = \frac{4\pi U(\theta,\emptyset)}{P_{in(isotropic\ \ source\ )}} \qquad 3.6$$

Gain is also a dimensionless quantity. However it is also usually expressed in $dBi.$ Therefore an isotropic antenna would have a 100% efficiency with gain being equal to the directivity. Nevertheless since this is impractical all antennas have varying directivity and the gain would then be measured as the power transmitted in a specific direction relative to the power lost in other directions (Ulaby, 1999). Hence the antenna gain is usually measured with reference to the main lobe where the highest radiation intensity is directed (Nakar, 2004).

3.1.4 Polarization

Polarization of an electromagnetic wave refers to the orientation of the electric field vector. An antenna radiates energy in the form of an electromagnetic wave that consists of electric and magnetic fields that are orthogonal to each other and orthogonal to the direction of travel of the wave. As the wave travels, the polarization of the wave is determined by the geometric figure traced on a stationary plane that is orthogonal to the direction of wave propagation. Generally, this produces an elliptical shape which may also be transformed to a line or circle when the field vectors have equal magnitude and are perpendicularly out of phase. Hence there are three major types of polarization: Elliptical, linear and circular polarization. Furthermore, linear polarization may be horizontal, vertical or slanted.

3.1.4.1 Linear Polarization

Consider the plane E-field wave given by the equation:

$$E = \cos(2\pi f\left(t - \frac{z}{c}\right))\hat{x} \qquad 3.7$$

The E-field is directed at the +X direction, magnetic field in +Y direction and the wave is travelling in the +Z direction. The plane wave may also be represented graphically as in Figure 3.1.

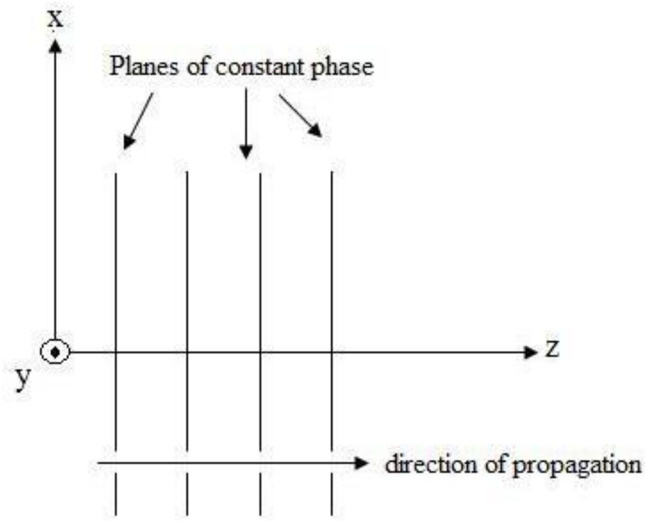


Figure 3.2 Graphical representation of plane wave (www.phys.hawaii.edu)

If we take the field at (x,y,z)=(0,0,0) and plot the amplitude for different points as a function of time, the output is given in Figure 3.2:

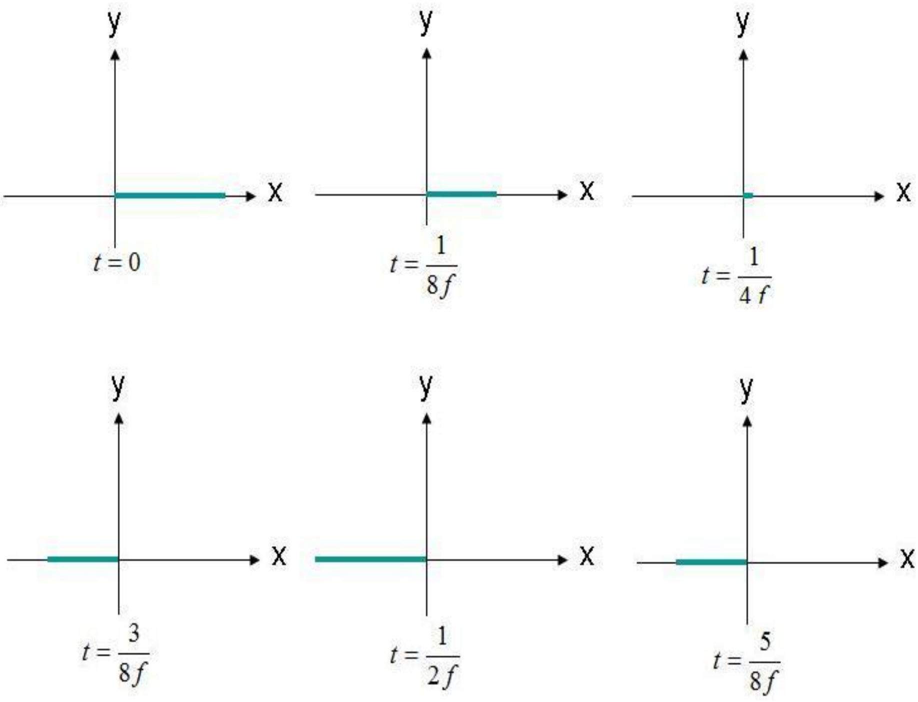


Figure 3.3 Plot of E-field (x,y,z=0,0,0) at different times (www.phys.hawaii.edu)

The E-field is considered to be linearly polarized because the amplitude changes continuously along a straight line on the x axis. If the x axis is parallel to the ground then the field is horizontally linearly polarized while if it is along the y axis then it is vertically linearly polarized. However if the E-field has x and y components that are equal in magnitude and phase and also vary at the same rate then the field's linear polarization would be slanted. This is represented by equation 3.3 and graphically by Figure 3.3.

$$E = \cos\left(2\pi f\left(t-\frac{z}{c}\right)\right)(\hat{x}+\hat{y}) \qquad 3.8$$

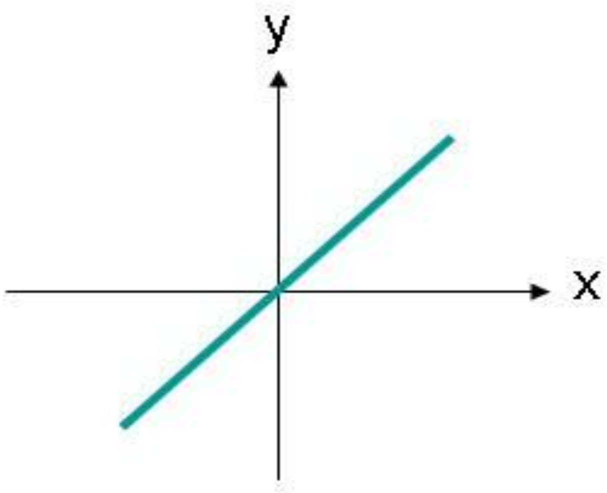


Figure 3.4 Slanted Linearly Polarized Field for Plot of Equation 3.8 (www.phys.hawaii.edu)

3.1.4.2 Circular Polarization

Consider the E-field represented as equation 3.9:

$$E = \cos\left(2\pi f\left(t-\frac{z}{c}\right)\right)\hat{x} + \sin(2\pi f\left(t-\frac{z}{c}\right))\hat{y} \qquad 3.9$$

The x and y components are perpendicularly out of phase. The E-field plot at (x,y,z)=(0,0,0) against time is given in Figure 3.4.

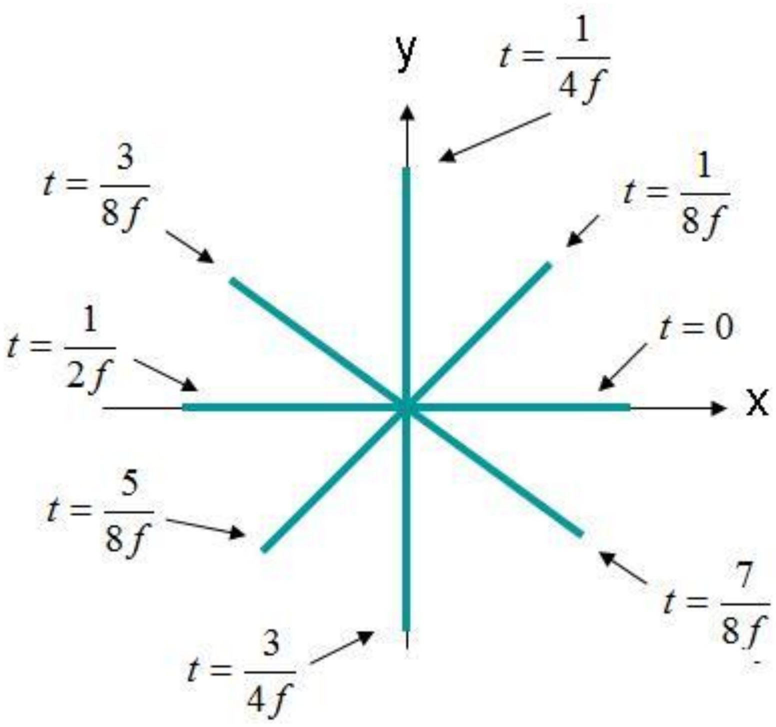


Figure 3.5 E-field Plot at Different Times for Equation 3.9 (www.phys.hawaii.edu)

The E-field now moves in a circular orientation and is hence circularly polarized. The following conditions must be satisfied for circular polarization of the E-field:

1. There must be two orthogonal components
2. The components must have equal magnitude
3. The components must 90° out of phase with each other

The field is said to be right hand circularly polarized (RHCP) if turns in the anticlockwise direction and left hand circularly polarized (LHCP) if it turns in the clockwise direction.

3.1.4.3 Elliptical Polarization

Consider the E-field takes in the form of equation 3.10:

$$E = \cos(2\pi f\left(t - \frac{z}{c}\right))\hat{x} + 0.3\sin(2\pi f\left(t - \frac{z}{c}\right))\hat{y} \qquad 3.10$$

This implies that the components are perpendicularly out of phase but have different magnitudes. A plot of the locus of points of the tip of the E-field vector is given in Figure 3.5

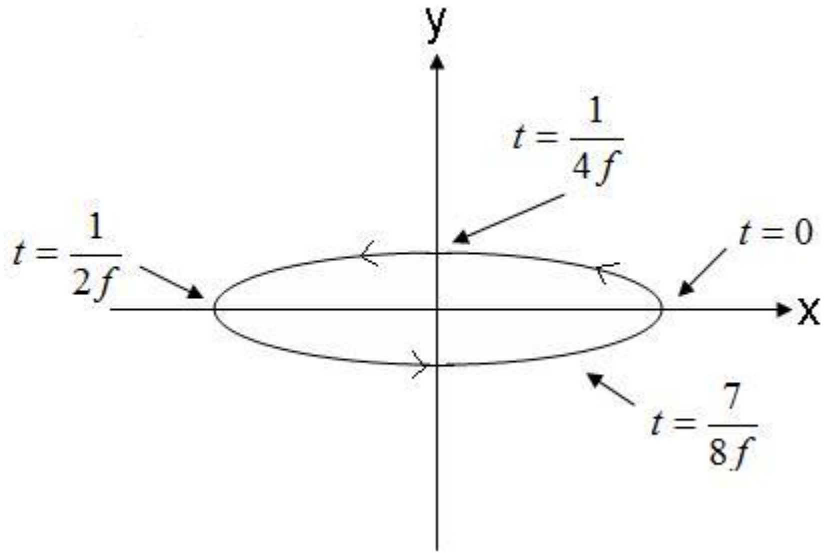


Figure 3.5 Plot of Locus of Points of Tip of E-field for Equation 3.10 (www.phys.hawaii.edu)

Therefore from Figure 3.5 it can be seen that the E-field is elliptically polarized.

If the field rotates in the anticlockwise direction it is right hand elliptically polarized and if it rotates in the clockwise direction then it is left hand elliptically polarized. The eccentricity of the wave is given by the ratio of magnitude of the (cos) component by the (sin) component. For equation 3.5 this is $\frac{1}{0.3} = 3.33$. Essentially, all cases of E-field waves are elliptically polarized and are characterized differently based on the eccentricity. When the eccentricity is 1.0 then the polarization becomes circular and when it is infinite then it is considered linearly polarized. Finally elliptically polarized waves can be characterized by the major axis of points which can be located at any angle in the plane.

Generally, most MIMO studies reviewed reveal linearly polarized antenna elements that are either horizontally or vertically polarized. Vertically polarized propagation has been shown to produce better results than horizontally polarized propagation (Kyritsi, Cox, 2001). However, studies have shown that a combination of horizontal and vertical polarization produces orthogonally polarized channels with higher capacity (Wallace, Jensen, 2003)(Kyritsi, Cox, 2001)(Kyritsi, Cox et al, 2002). This is applicable for all kinds of indoor and outdoor environments no matter the characteristics because there is a certainty that the dual polarization will produce two parallel channels.

3.1.5 Input Impedance

The last parameter to be discussed in this section is the input impedance. Balanis (1997) defines antenna input impedance as “the impedance presented by an antenna at its terminals or the ratio of the voltage to the current at the pair of terminals or the ratio of the appropriate components of the electric to magnetic fields at a point”. Impedance Z_{in} is given as (Balanis, 1997):

$$Z_{in} = R_{in} + jX_{in} \qquad 3.11$$

$Where\ R_{in} = resistance\ at\ the\ terminals,\ X_{in} = reactance\ at\ the\ terminals$

X_{in} is also equal to the power in antenna near field. R_{in} consists of the radiation resistance R_r and the loss resistance R_L. The power radiated with the former is the required antenna radiated energy while the power radiated with the latter is given out as heat energy as a result of dielectric losses.

3.2 Diversity

This section describes antenna diversity based on the work in Chiau (2006). Diversity in antennas traditionally refers to the transmission of multiple copies of a signal with the aim of increasing signal reliability at the receiver. The objective is to resolve the problems arising from signal dispersion caused by scattering during propagation. If multiple uncorrelated signals are transmitted, then the effects of the multiple multipath signals created are reduced heavily. The combined signal at the receiver is more likely to have a mean signal-to-noise ratio (SNR) than a single signal. This results in a diversity gain. Good antenna diversity is known to reduce subchannel correlation (Browne et al, 2006) thereby improving performance in MIMO systems. There are five types of diversities: frequency diversity, time diversity, spatial diversity, pattern diversity and polarisation diversity. However only spatial, pattern and polarisation diversity techniques are employed in antennas as antenna diversity. These techniques are used to improve MIMO system performance by exploiting the channels and their discussion will be preceded by an outline of diversity combining techniques.

3.2.1 Diversity Combining

Antenna diversity requires that the receiver is able to receive several different signals and combine them with combining circuitry. There are four different combining techniques which include switched combining, selection combining, maximal ratio combining (MRC) and equal gain combining (EGC).

3.2.1.1 Switched Combining

Considering that there are N numbers of antenna elements or branches at both transmit and receive ends of the antenna system. The switched combining technique makes use of a single receiver radio for signal combination. The receiver is connected to a particular branch without being transferred to another branch as long as the SNR does not fall below a specified threshold. Other combining techniques utilise N numbers of receiver radios for all the branches transmitted from N number of elements. This method is commonly employed in mobile terminal applications where the compact nature of the system requires optimization of design, space and power (Tarkiainen, Westman, 1997).

3.2.1.2 Selection Combining

While in the switched method a single receiver is used, the selection method uses N numbers of receivers (equal to N transmit elements) to track the SNR at every branch simultaneously. The output is considered as the output from the branch with the highest SNR. Basically this means that the incoming signal at the receiver branch with the highest SNR is selected as the output (Jankiraman, 2004). It is the simplest method and is less costly also since no extra radio frequency (RF) chains are needed as a single one is used by the receive antenna elements (Jankiraman, 2004).

3.2.1.3 Maximal Ratio Combining

Here, since the signals from the N number of branches may differ in their SNRs, each branch is weighted separately and then the sum of them is taken. This is aimed at producing a higher overall SNR and is achieved by aligning all the signals in phase with each prior to summation. During weighting signals with higher SNRs are also given a higher weighting.

3.2.1.4 Equal Gain Combining

This method is similar to the maximal ratio method except that the signals from the branches are weighted collectively and not individually. Therefore the signals are also not in phase with each other. The branches are instead each combined with a complex phasor to produce an overall zero phase before collective combination. This results in a performance slightly less than the maximal ration combination but is also easier to implement.

3.2.2 Antenna Diversity Techniques

It was mentioned earlier this chapter that three types of diversity techniques are employed in MIMO systems to improve performance. They include spatial diversity, pattern diversity and polarization diversity.

3.2.2.1 Spatial Diversity

Spatial diversity makes use of adequate spacing between two or more transmit/receive antenna elements to ensure that low signal correlation between the elements. This is the fundamental diversity technique. The element spacing is aimed at ensuring that the relative phases of the multipath components at the elements are different. These differences are also linearly related to the distances between the scatterers and individual antennas and both are reciprocal to correlation. Therefore larger element spacing leads to larger phase differences and distances between scatterers and lower correlation. Spatial diversity is hence aimed at exploiting the spatial resources between antenna elements to produce uncorrelated signals. It is has been noted that mutual coupling between elements is introduced at much smaller spacings which increases correlation. It has been suggested that coupling for element spacing below $(\frac{1}{4})\lambda$ adversely affects diversity performance (Wallace, Jensen, 2004). Chiau (2004) states that a spacing of $(\frac{1}{2})\lambda$ achieves uncorrelated signals in a mobile terminal.

3.2.2.2 Pattern Diversity

Pattern diversity, in Ali, Thiagarajah (2007) involves configuring antennas with different radiation patterns. Low correlation is achieved by exploiting the angle spacing between the transmit (TX) and receive (RX) signals. Angle diversity is employed where the angle of departures (AOD) and angle of arrivals (AOA) of the transmitter and receiver respectively are distinguished using directional antennas. This produces the desired low correlation as the TX and RX signal are separated. Angle diversity is also high when the individual antenna elements receive multipath signals from numerous directions (Sasaoka, 2001). This produces narrower angle spacing with orthogonal non-interfering patterns with low correlation. In contrast smaller antennas with larger angle spacing produce wider, conflicting patterns with high correlation (Jensen, Wallace, 2004). Another method of achieving pattern diversity is through multimode diversity (Ali, Thiagarajah, 2007). Multimode antennas have the capability of producing orthogonal radiation patterns when excited in different modes. TEM mode excitations create multiple orthogonal patterns and hence can replace the need for multiple antenna elements which are employed generally in the various diversity techniques (Svantesson, 2000) (Svantesson, 2002). This is because a single element eliminates the issues of multiple element spacing and design. Furthermore, Svantesson (2000b) again shows that the single multimode antenna can generate several excitation modes at the same frequency.

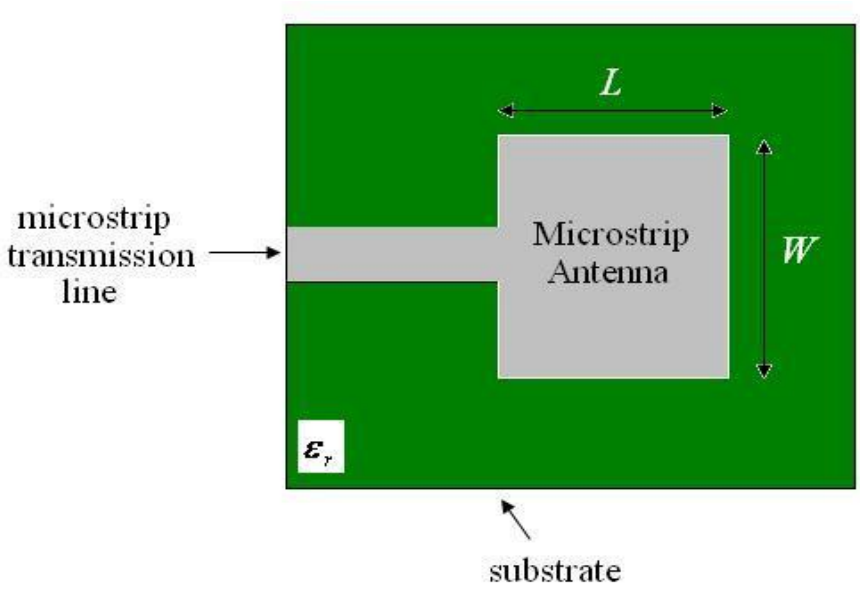
3.2.2.3 Polarization Diversity

Like spatial diversity, polarization diversity can be employed to counter the effects of mutual coupling Zhang, Wang et al, 2008). It has been stated earlier that MIMO systems with linear polarization have been generally studied in this work and that vertical polarization produces better performance than horizontal polarization. In polarization diversity, distinct polarizations are combined at the TX and RX antennas and it would be anticipated that combining vertical polarizations would achieve best results. However, it is the combination of vertical and horizontal polarizations that yield higher performance. This technique results in highly orthogonal polarizations that produce distinct, uncorrelated signals at the individual antennas. In Kyritsi and Cox (2001), pairing vertically polarized antennas causes cross-polarization in MIMO systems in indoor environments due to the reflective surfaces. Cross-polarization is a situation where the received signal polarization is orthogonal to the transmitted signal polarization. Therefore the multiple polarization method prevents this for the indoor applications (Ellingson, 2005). In the case of other antenna polarizations such as circularly polarized antennas, Kajiwara (2000) suggests that combining right-hand polarized and left-hand polarized antennas would best reduce correlation in similar fashion to the linear polarization combination method. Polarization diversity is widely used for compact designs and is especially useful for mobile terminals and base stations Chiau, 2006). Recent studies have revealed the possibilities of combining spatial and polarization diversities (Eggers et al, 1994) or all of the aforementioned diversity techniques to produce even better results (Ali, Thiagarajah, 2007).

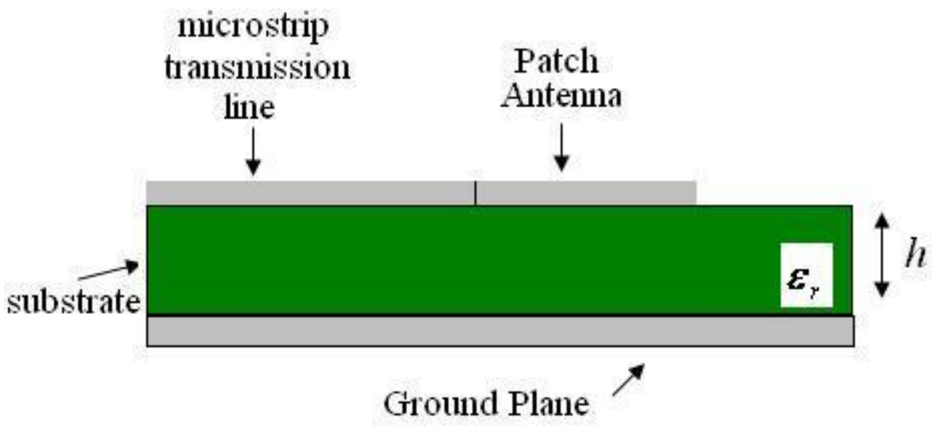
CHAPTER FOUR
MICROSTRIP ANTENNAS

4.0 Introduction

The microstrip or patch antenna (used interchangeably) is a single-layer antenna design that is fabricated by etching a metallic element pattern or array of patterns on an insulating substrate panel with a metallic layer on the opposite side of the panel which forms the ground plane (10-11). This is represented by Figure 4.1.The element pattern which forms the patch is usually made from thin copper foil, which may also be lined with metals like gold, nickel and tin. The patches commonly have rectangular, circular and square shapes but can assume any continuous shape such as triangular, elliptical and other desired shapes. This is illustrated in Figure 4.2. It is necessary to employ shapes that will aid in accurate analysis and performance prediction. The rectangular patch is particularly used generally as a reference. In some cases the substrate material is excluded and the patches are suspended in air over the ground plane with dielectric spacers in-between. This provides a technique which is less robust but with higher bandwidth. Substrate thickness is usually in the order of 0.01-0.05 free-space wavelength (λ_0) (Huang, 2006).



Top View



Side View

Figure 4.1 Microstrip Patch Antenna (www.antenna-theory.com)

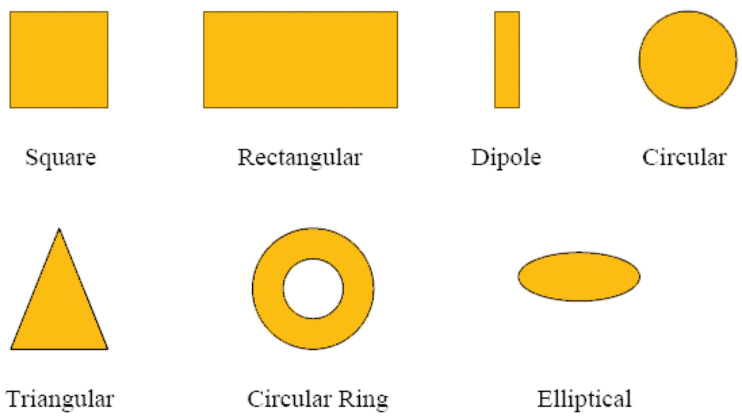


Figure 4.2 Common Microstrip Patch Shapes (Reddy, Rana, 2009)

Substrate materials are easily characterised by the dielectric constant (ε_r) and can be grouped in the following order (11):

1. ε_r =1.0-2.0. Includes materials such as air, polystyrene foam and dielectric honeycomb.
2. ε_r=2.0-4.0. Includes material containing largely fibreglass reinforced Teflon.
3. ε_r=4-10. Includes materials containing ceramic, quartz or alumina

Materials with an ε_r of 1-10 are the most commonly used but those above are also available.

4.1 Methods of Analysis

Two major theoretical methods of analysis of microstrip antennas are the transmission line model and the cavity model which will be outlined briefly. These methods assume an analysis based on the typical rectangular or square patch structure as a reference.

4.1.1 Transmission Line Model

Radiation in patch antennas is caused by the fringing fields produced from the patch and ground plane on each of the two edges of the patch length. The length of a patch antenna is its resonating dimension and hence determines the resonating frequency (Huang, 2006). One edge (of the length) radiates the electric fields form the ground plane to the patch while the opposite edge radiates the electric fields from the patch to the ground plane. This is illustrated in Figure. Narrow points exist on the substrate surface on both edges of the patch length where the fields are radiated into the patch. This creates 2 equivalent slots each of width δL and patch height h on either edge of the patch length. This is depicted in Figure. Therefore the transmission line model essentially represents a microstrip patch as a $\frac{1}{2}\lambda$ long transmission line (Huang, 2006). This model is simple and easily realized with computer simulations. However it lacks a high level of accuracy because it does not take into consideration the non-radiating edges of patches and mutual coupling effects. It is also limited to rectangular and square patches.

4.1.2 Cavity Model

This model regards a microstrip antenna as an open cavity which is enclosed by the patch and its ground plane. Two assumptions are made. Firstly, the fields are Z directed only and due to the thin substrate they do not vary in the Z direction (Huang, 2006). Secondly, the magnetic fields have only transverse components H_x and H_y in the area bounded by the patch and the plane with the electric walls at the $+Z$ and $-Z$ directions (Reddy, Rana, 2009). Patch excitation produces a smiliar charge distribution on the patch and the ground plane surface. The interactions of charge on the top and bottom of the patch and ground plane result in current densities J_t an J_b at the surface and bottom of the patch respectively (Parthasarathy). Again, due to the thin substrate and the interactions between like and unlike charges, the charges are aligned at the bottom of the patch. See Figure 4.3. In addition, the four edges of the patch are represented as radiating magnetic walls (Huang, 2006) shown in Figure 4.4.

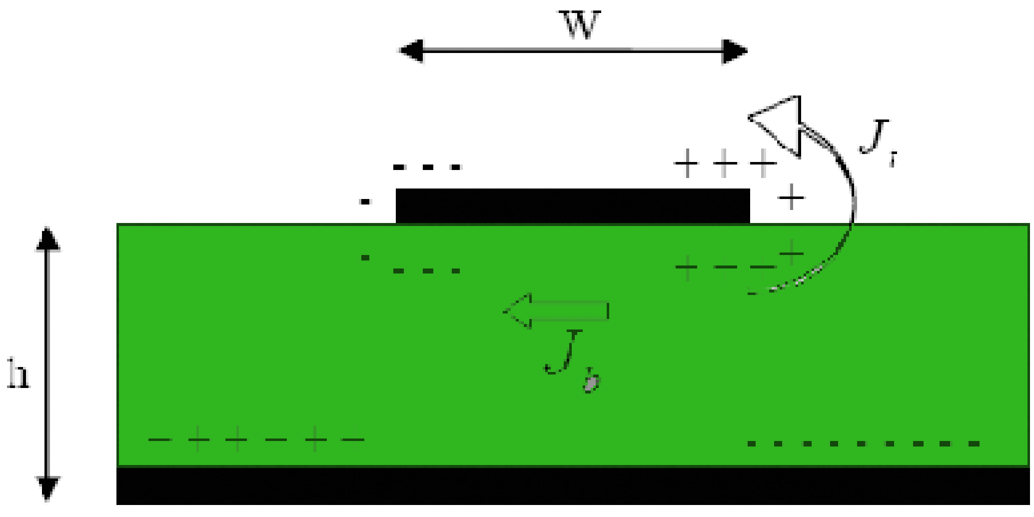


Figure 4.3 Current Densities and Charge Alignment (Reddy, Rana, 2009)

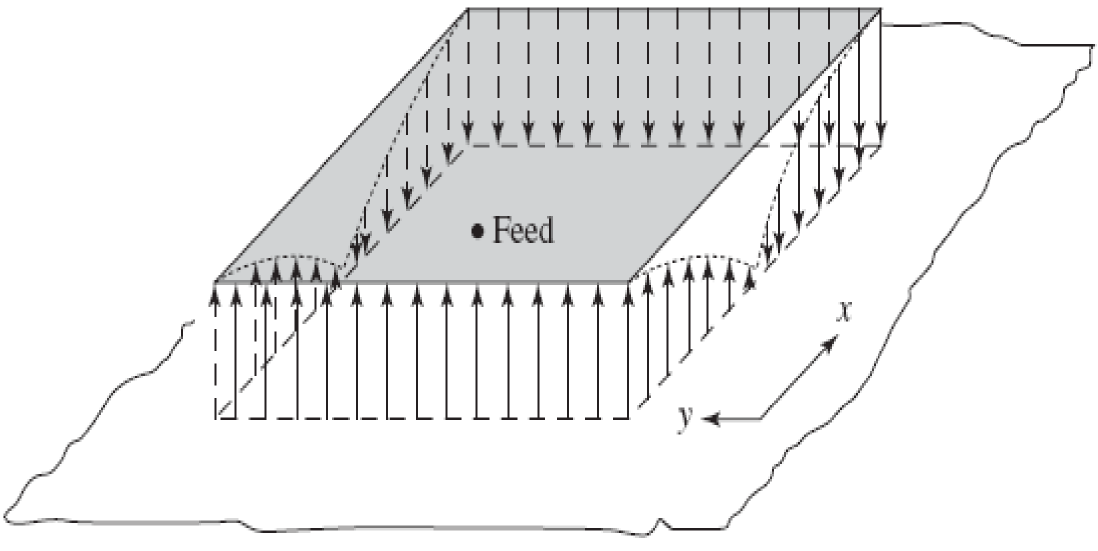


Figure 4.4 Patch Edges Represented as Radiating Magnetic Walls (Huang, 2006)

To describe the radiation in the cavity a loss cavity is assumed with a total effective loss tangent δ_{eff} for the patch antenna given by (Parthasarathy, 2006):

$$\delta_{eff} = tan\delta + \frac{\Delta}{h} + \frac{P_r}{\omega_r W_r} \qquad 4.1$$

Where $\delta = loss\ tangent\ of\ dielectric$

$h = substrate\ thickness$

$\Delta = skin\ depth\ of\ conductor$

$P_r = radiated\ power$

$\omega_r = angular\ resonant\ frequency$

$W_r = total\ energy\ in\ the\ patch$

4.2 Advantages and Disadvantages

The microstrip antenna has many advantages which make it a ready choice for application in wireless communications. Nevertheless it possesses a number of disadvantages as well therefore it is important to understand the trade-offs that are associated in the design process.

4.2.1 Advantages (Huang, 2006):

1. Very low profile making it light in weight and assuming a low volume thereby utilising very small portions of the surfaces it occupies. In addition this attribute makes it conformal to non-flat surfaces, aesthetically and aerodynamically adaptable.
2. The simplified etching process and 2-dimensional physical geometry makes it easy to fabricate multiple arrays in large quantities and at low costs.
3. It can be easily integrated with microwave integrated circuits (MICs).
4. It can be implemented for multiple frequency band operations using various means.
5. Supports polarization diversity as both linear and circular polarization can be effected (Nakar, 2004).

4.2.2 **Disadvantages** (Huang, 2006):

1. Generally has a narrow bandwidth. For instance a single patch of $0.02\lambda_0$ thickness possesses a narrow bandwidth of below 5%. However bandwidths can be improved with advanced technologies which generally have the trade-off of increased physical volume.
2. Low gain and efficiency (Nakar, 2004).
3. Low power handling capability which permits only far much less than a 100W of average power.
4. Higher ohmic insertion loss associated with surface wave excitation and radiation from feeds and edges.

4.3 Feed Techniques

There are various methods of feeding or excitation of the microstrip patch antenna in order to cause radiation. A number of typical types are discussed here (Huang, 2006):

4.3.1 Coaxial Feed

A coaxial or probe feed can be fed to a microstrip patch by passing it through the underside of the ground plane. The exterior conductor is soldered to the ground plane while the core conductor is passed through the substrate and patch where the tip is soldered to the patch surface. The coaxial cable is usually a 50Ω line and the aim is to position the termination point on the patch where the impedance is also 50Ω in order to achieve the required matching. Different types of coaxial cable are use depending on the frequency. The most common are N, TNC and BNC types for VHF, UHF and low microwave frequencies while OSM and OSSM are use generally for microwave frequencies. The OSSM, OS-50 and K-connnector are used for millimetre-wave frequencies. An illustration is given in Figure 4.5.

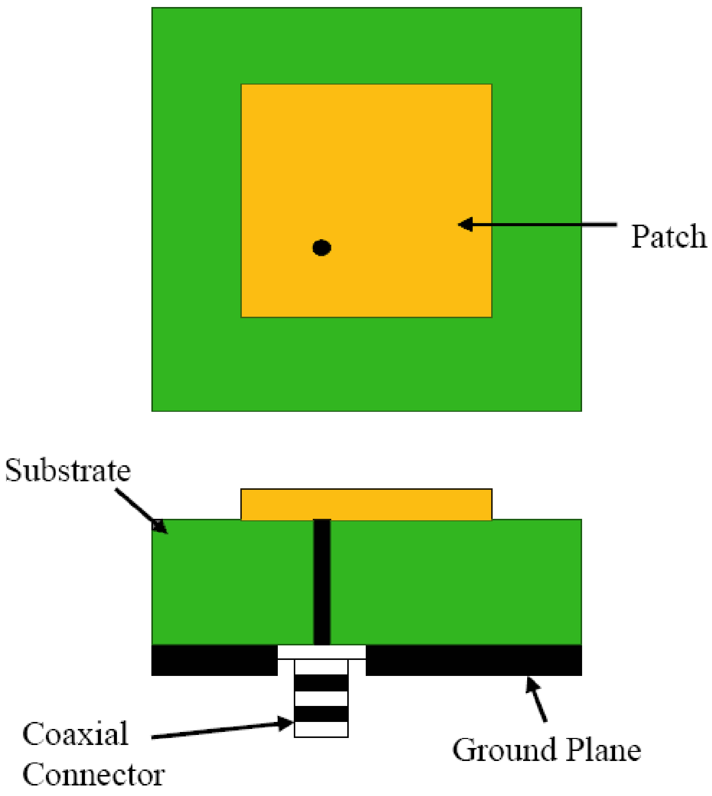


Figure 4.5 Coaxial Feed (Reddy, Rana, 2009)

4.3.2 Microstrip Line Feed

In this method a microstrip line is connected to the microstrip patch edge directly as seen in Figure 4.6. The impedance at the patch edge is usually much larger than 50Ω therefore the conducting line must be connected with an inset cut in order to match the impedances without extra elements such as quarter-wave impedance transformers. The advantage is that the feed line is positioned on the substrate producing a planar structure. This makes the process simple and more elements can be integrated at easily at relatively low cost. However as dielectric thickness is increased the antenna suffers the problem of surface wave excitation and spurious feed fields which reduce bandwidth (Behera, 2007). Leakage radiation also leads to adverse cross-polarization.

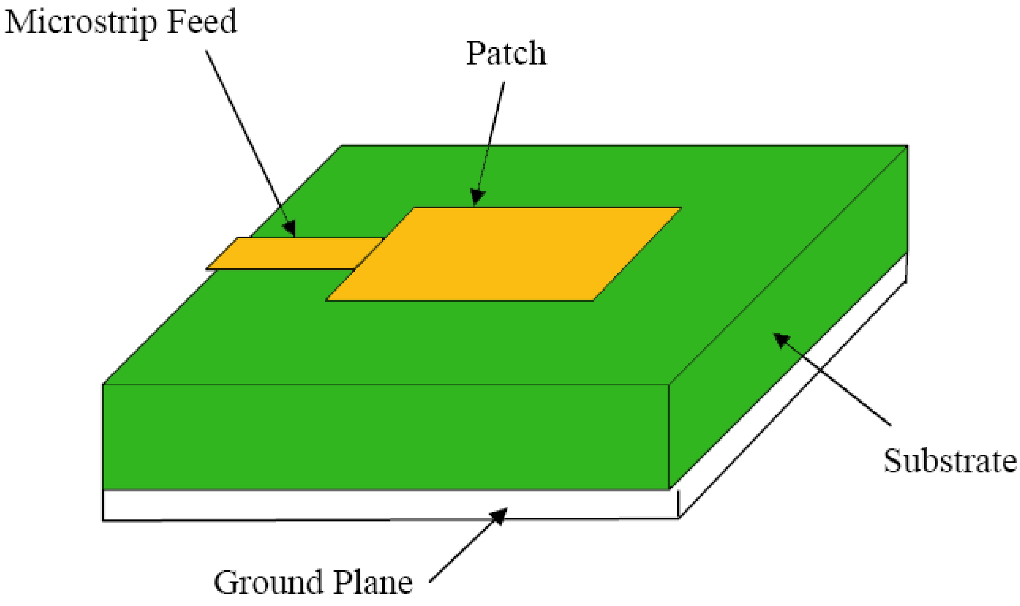


Figure 4.6 Microstrip Line Feed (Reddy, Rana, 2009)

4.3.3 Aperture Coupled Feed

This type of feed (Reddy, Rana, 2009) entails placing the radiating patch and microstrip feed line on either side of the ground plane as seen in Figure 4.7. A slot or aperture is created in the ground plane usually directly under the patch and provides the path for coupling between the patch and feed line. The aperture's geometrical characteristics determine the magnitude of this coupling. The separation of the patch and feed line with the ground plane reduces unwanted distortion caused by other harmonic frequencies and the desired radiation itself is improved by using material with a higher dielectric constant for the lower substrate and a lower dielectric constant material for the upper substrate (Behera, 2007). The aperture itself is a radiator and resonator and therefore provides greater bandwidth than the coaxial feed (Huang, 2006). The major drawback with this method is the complexity and larger volume produced by the use of multiple layers.

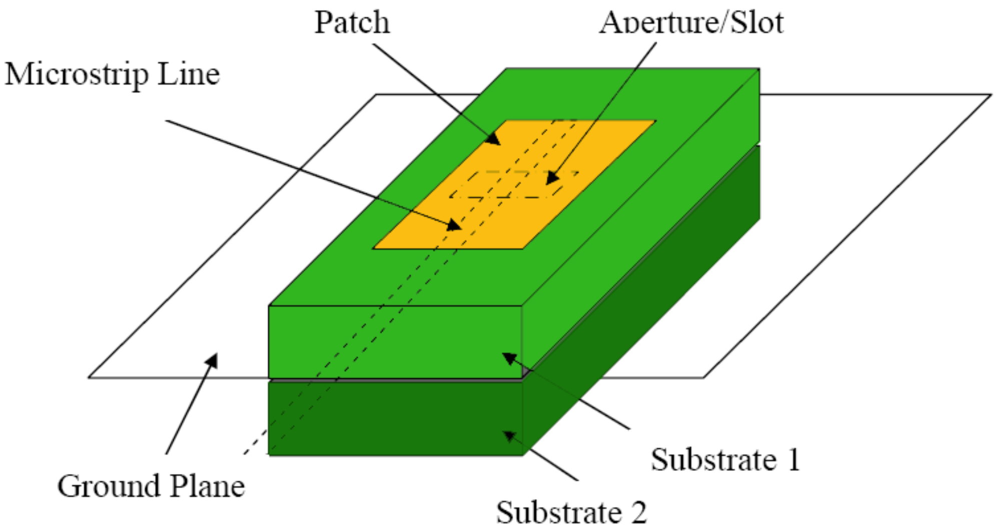


Figure 4.7 Aperture Coupled Feed (Reddy, Rana, 2009)

4.3.4 Proximity Coupled Feed

In this method (Reddy, Rana, 2009), the feed line is placed between two dielectric substrates and the patch is positioned on the upper substrate. Therefore the patch is separated from the feed line by a substrate as shown in Figure 4.8. There is no soldering required and coupling is achieved electromagnetically.This method is free of distortion from other harmonic frequencies and also increases the bandwidth due to the large combined substrate thickness. The substrate materials can also be varied for the patch and feed line respectively to improve performance. The feed line is matched to the patch by adjusting its length and the "width-to-line ratio" (Reddy, Rana, 2009). This method has similar disadvantages with the aperture coupled feed and greater accuracy is required.

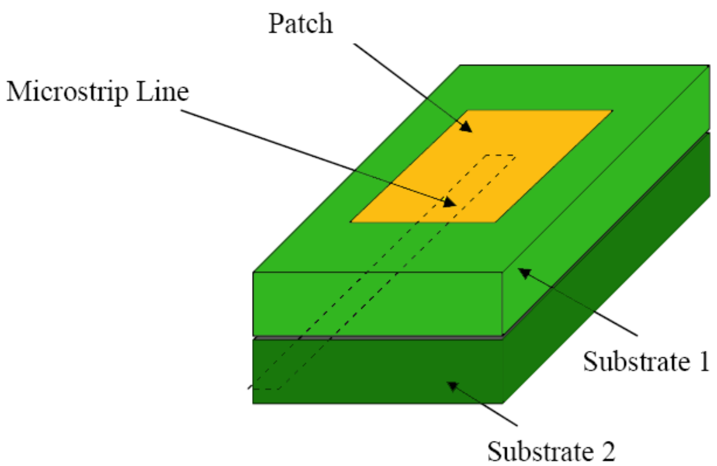


Figure 4.8 Proximity Coupled Feed (Reddy, Rana, 2009)

4.4 Design Methodology

We now look at the various factors affecting the design of microstrip patch antennas and the design parameters for rectangular patch antenna design.

4.4.1 Design Factors

The important variables that are required for antenna design are series or parallel feed, single or multiple layers, substrate thickness, dielectric constant, size, patch shape and element separation or spacing. Selection is based on several factors such as antenna gain, bandwidth, insertion loss, beam angle, polarization and power requirements. Greater element separation is generally desired to accommodate transmission lines and discrete components and also reduce mutual coupling effects. As mentioned earlier in the chapter patch elements can take on various forms and shapes as seen in Figure 4.2 from typical shapes such as rectangular, circular and square shapes to a variety of other forms. They can also take on various combinations of shapes and complex geometries. The more common rectangular patch is preferably used for linear polarization requirements and has better bandwidth properties than square or circular patches. Yet it cannot be used to achieve circular polarisation like the square and circular patches using a single or double feed excitation. Circular patches can also be used to achieve higher order mode excitation (Huang, 2006). A major drawback in square and circular patches is that they experience higher cross-polarisation compared to rectangular patches when used with linear polarization. Therefore patch shapes and geometries have their peculiar characteristics which can be used to meet varying design requirements.

The primary purpose of the substrate is to sustain a good separation and mechanical balance between the patch and ground plane. Higher substrate dielectric constant leads to reduced patch physical dimensions. The dielectric loading of the microstrip antenna also influences its radiation pattern and bandwidth. Therefore higher substrate dielectric constant also yields a decrease in antenna bandwidth which increases the quality (Q) factor and hence decreases the impedance bandwidth (antenna-theory.com). Materials with an ε_r greater than 10 have the tendency of decreasing the radiation efficiency due to the small patch size and volume they produce. The most common material is Teflon which has a dielectric constant of 2-3. The choice of material should be determined based on the desired properties which include, but are not limited to, patch size, bandwidth, insertion loss and cost. In commercial applications cost is the predominant determining factor.

4.4.2 Rectangular Patch Antenna Design

Since patches may take on a wide variety of shapes as seen already, equations determining patch dimensions and other parameters are not available for all such shapes. However standard close-form equations are obtained for the more common rectangular or square patches and circular patch. The more fundamental rectangular patch equations are presented from Balanis (1997)(Bahl, Bartia, 1980):

For efficient radiation, the patch width W is:

$$W = \frac{c}{2f_o\sqrt{\frac{\varepsilon_r + 1}{2}}} \qquad 4.2$$

$c = speed\ of\ light\ (3 \times 10^8 ms^{-1}\ in\ all\ cases$

The fringing fields at the patch edges cause distortions in the electrical length of the patch. The effective dielectric constant ε_{reff} is defined in order to determine the accurate patch length for the desired resonance frequency for a substrate of h thickness.

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \qquad 4.3$$

The effective length L_{eff} for a given resonance frequency f_0 is:

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{reff}}} \qquad 4.4$$

The width of the equivalent slots δL described in the transmission line model is given by:

$$\delta L = 0.412h\frac{\left(\varepsilon_{reff} + 0.3\right)(\frac{W}{h} + 0.264)}{\left(\varepsilon_{reff} - 0.258\right)(\frac{W}{h} + 0.8)} \qquad 4.5$$

Since there are 2 slots, the effective patch length therefore becomes:

$$L_{eff} = L + 2\delta L \qquad 4.6$$

And the actual patch length L is given by:

$$L = L_{eff} - 2\delta L \qquad 4.7$$

CHAPTER FIVE
SIMULATION RESULTS AND DISCUSSION

5.1 Introduction
This chapter presents the results and discussion of the rectangular patch antenna design and simulations. Firstly, a single linearly polarized antenna is designed separately using the theoretical rectangular patch antenna design technique outlined in the previous chapter and computer simulation. The design results and simulation performance are compared. Secondly, two patch antennas are combined and simulated for different element separation (or spacing) and position similarly to the work in Parthasarathy (2006). The results are used to perform a mutual coupling analysis between two antenna elements with variations in element separation and position.

5.2 Rectangular Microstrip Patch Design
The primary design parameters to be predetermined are the resonant frequency of operation f_0, the substrate material type, dielectric constant ε_r and height h. A resonant frequency of 2.65 GHz is chosen as the study generally requires any frequency within the microwave or mobile wireless communications spectrum. The substrate to be used is the flame retardant #4 epoxy (FR4) substrate with a dielectric constant of 4.55 and a height of 1mm. The FR4 substrate is a high frequency printed circuit board (PCB) insulator and widely preferred to other substrates because of its low cost which makes it better suited for mass production and general commercial considerations. Finally, higher dielectric constant values ensure smaller patch antenna dimensions while smaller substrate thickness makes the antenna less bulky respectively. These are both desirable because given the application of the antennas in mobile systems, a compact design is required. Therefore the initial parameters are:

$$f_0 = 2.65\ GHz$$

$$\varepsilon_r = 4.55$$

$$h = 1\ mm$$

Step 1: Calculation of the Width (W):

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_0 + 1}{2}}} \qquad 5.1$$

Substituting $c = 3 \times 10^8\ m/s$, $\varepsilon_0 = 4.55, f_0 = 2.65\ GHz$ we get:

$$W = 33.98\ mm$$

Step 2: Calculation of the effective dielectric constant ($\boldsymbol{\varepsilon_{reff}}$):

$$\varepsilon_{reff} = \frac{\varepsilon_0 + 1}{2} + \frac{\varepsilon_0 - 1}{2}[1 + 12h/W]^{-1/2} \qquad 5.2$$

Substituting $\varepsilon_0 = 4.55, h = 1\ mm, W = 33.98\ mm$ we get:

$$\varepsilon_{reff} = 4.33$$

Step 3: Calculation of the effective length $\boldsymbol{L_{eff}}$:

$$L_{eff} = \frac{c}{2 \times f_0 \times \sqrt{\varepsilon_{reff}}} \qquad 5.3$$

Substituting $c = 3 \times 10^8 m/s$, $\varepsilon_{reff} = 4.33$:

$$L_{eff} = 27.2\ mm$$

Step 4: Calculation of length extension $\boldsymbol{\Delta L}$:

$$\Delta L = 0.412h\frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} \qquad 5.4$$

Substituting $\varepsilon_{reff} = 4.33, W = 33.98\ mm, h = 1\ mm$ we get:

$$\Delta L = 0.4612\ mm$$

Step 5: Calculation of actual length L:

$$L = L_{eff} - 2\Delta L \qquad 5.5$$

Substituting $L_{eff} = 27.2\ mm, \Delta L = 0.4612\ mm$ we get:

$$L = 26.2776\ mm$$

Step 6: Finding the feed point:

The coaxial probe-feed method will be used for the line feed. The ground plane dimensions are assumed equal to the $W\ and\ L$ for this purpose. The feed point is required to be located where the input impedance Z_i is equal to the characteristic impedance Z_c which is taken as 50Ω ($ie\ Z_i = Z_c = 50\Omega$). This is also the point where the return loss RL is most negative or minimum. Therefore the rectangular patch is designed and centred with an origin of $(x, y) = (0,0)$ and the feed point is arbitrarily estimated at $(x, y) = (1,0)$ on the patch since generally the advantage of the coaxial feed is that it can be located randomly (Reddy, Rana, 2009).

5.3 Simulations for Single Patch Antenna

The simulator utilised for this work is the Zeland Incorporation's IE3D Evaluation License Software. The IE3D is a full-wave electromagnetic simulator based on the method of moments (MoM). Training manuals are available with the software.

5.3.1 Optimization and Tuning

The IE3D has a special feature for antenna optimization and tuning. Therefore the dimensions of the microstrip patch antenna can be adjusted to match the desired resonant frequency. Hence the rectangular patch antenna design was first optimized with the simulator. The initial values of $f_0,\ \varepsilon_r\ and\ h$ uses in the previous section were utilised while the patch dimensions $W\ and\ L$ were set at $40\ mm\ and\ 20\ mm$ respectively in order to test the performance of the optimization against the calculated design results. The feed point was also located arbitrarily at $(x, y) = (1,0)$. However for the simulation, the IE3D simulator will automatically position the probe feed at the point of best fit for impedance matching. The result of the simulated feed point positioning can be verified further by simulating the return loss for different points obtained on the $x - axis$ along the length L of the patch antenna. The resulting geometry of the optimization and tuning is shown in Figure 5.1.

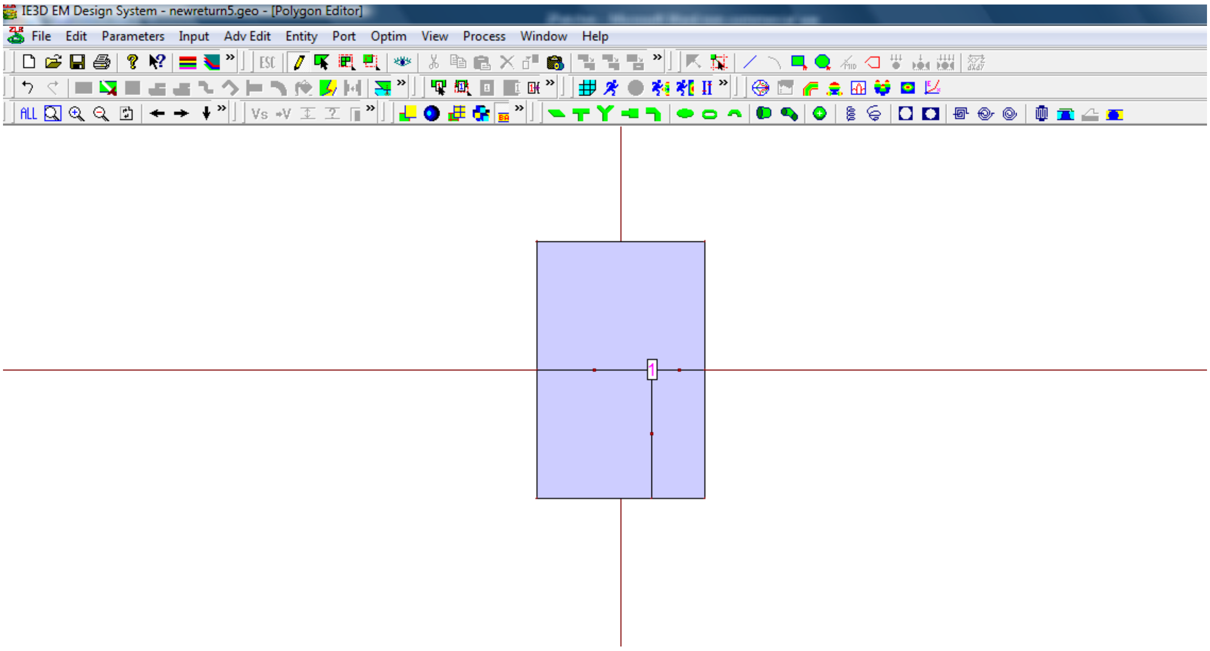


Figure 5.1 Rectangular Patch ($40 \times 26\ mm$) Geometry in IE3D

The final patch dimensions produced were $W = 40\ mm\ and\ L = 26\ mm$. This is against the calculated dimensions of $W = 33.98\ mm\ and\ L = 26.2776\ mm$ with the rectangular patch equations. The coaxial feed probe was also positioned at (5,0) as against the set (1,0).

5.3.2 Return Loss

The coaxial feed probe location was tested to confirm its accuracy by using the simulator to determine the return loss from the S –parameter S_{11} in dB against frequency in GHz for different locations of the feed point starting from $(x, y) = (1,0)$ and varied along x to the right side of the patch length $L = 26\ mm$. The results of the return loss for the different locations are shown in Figure 5.2.

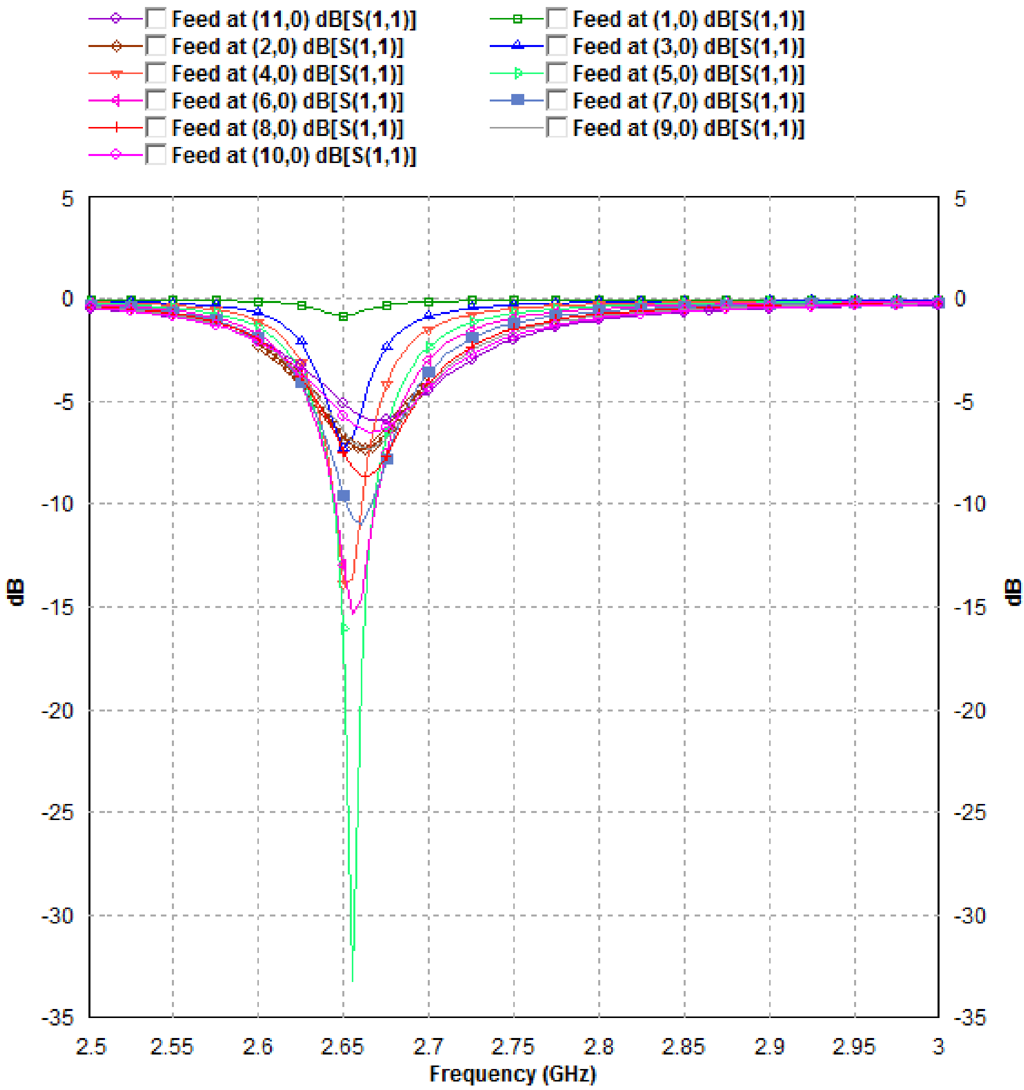


Figure 5.2 Return Loss Plots for Different Feed Points (x,y) on Patch Antenna

Figure 2 shows that the feed at initial (1,0) yields the highest (poorest) return loss of about 1.5 db. The lowest and desired Figure is obtained clearly with the feed point at (5,0) with an S_{11} value of approximately $33dB$. The centre frequency is just slightly above the design frequency of 2.65 GHz. This result confirms the simulated feed point location of (5,0) and the corresponding centre frequency of $2.65\ Ghz < f_0 < 2.6625\ GHz$ reveals an acceptable accuracy. Locating the feed point at (5,0) ensures that Z_i is as close as possible or equal to Z_c so that there will be a minimum energy loss between the patch antenna and the coaxial feed transmission line. The patch in Figure in 5.1 hence represents the final rectangular patch configuration to be used for the simulations. This patch antenna design and probe feed setup produces a linearly polarized which is the requirement for the mutual coupling investigation.

The polarization can be determined visually through the current distribution which is shown in Figure 5.3.

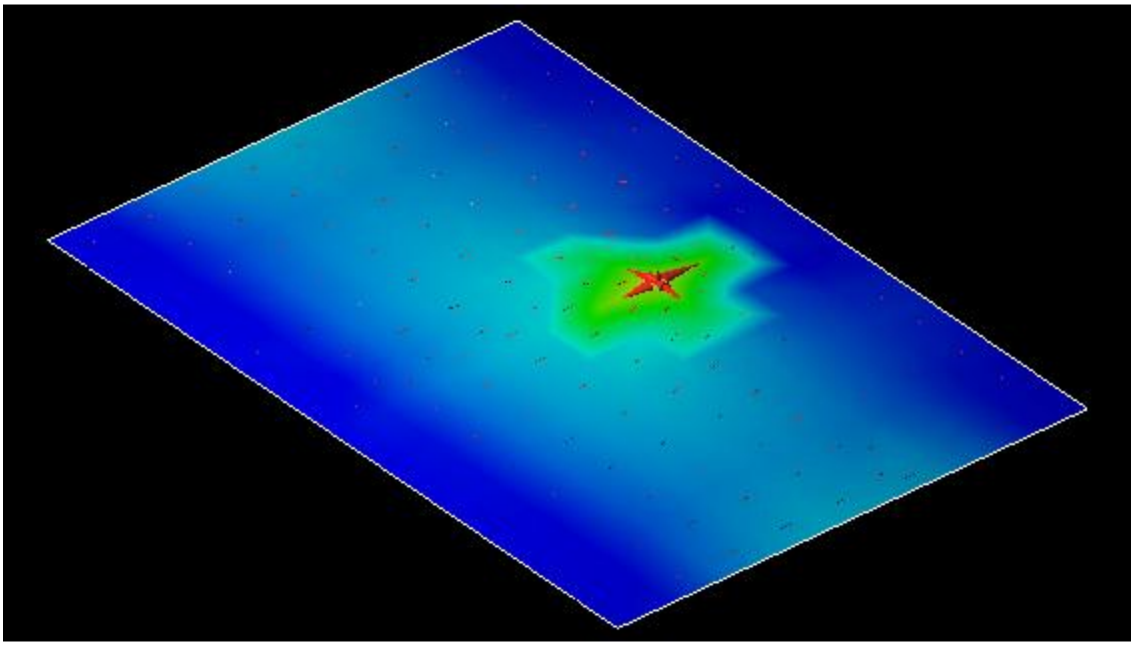


Figure 5.3 Linearly Polarized Rectangular Patch Antenna

The Figure 5.3 shows the current elements which are radiated and distributed in a linear pattern across the patch surface.

5.4 Mutual Coupling Between 2 Rectangular Patch Antennas

Two rectangular microstrip patches, with the same dimensions as previously outlined in Figure 5.1 are combined and simulated in parallel and collinear positions separately. These are illustrated in Figures 5.4 and 5.5 for parallel and collinear configurations respectively. Each configuration is also simulated with different element separations of 4, 3, 2.5, 2, 1.5, 1, 0.5 and 0.25 wavelengths respectively. The wavelengths are calculated from the standard equation:

$$c = \lambda f \qquad 5.6$$

Where $c = 3 \times 10^8\ m/$s,

$f = 2.65\ GHz$

$\lambda = wavelength.$

Therefore substituting these values in (5.6) we get $4\lambda = 452.8\ mm, 3\lambda = 339.6\ mm, 2.5\lambda = 283, 2\lambda = 226.4\ mm$, $1\lambda = 113.2\ mm$, $\frac{1}{2}\lambda = 56.6\ mm\ and\ \frac{1}{4}\lambda = 28.3\ mm$ respectively. The mutual coupling is measured by the S parameter S_{21}. In Parthasarathy (2006) it was shown that the values of S_{12} and S_{21} are the same and that these represent the measure of mutual coupling between antenna elements. Therefore either of the two maybe utilised. The linear magnitude of the S parameter was also used which has no unit. This work uses both the linear magnitude and the dB equivalent. It can also be seen from Zhang et al (2008) that mutual coupling can be measured by the isolation between 2 elements given by the S_{ij} parameters.

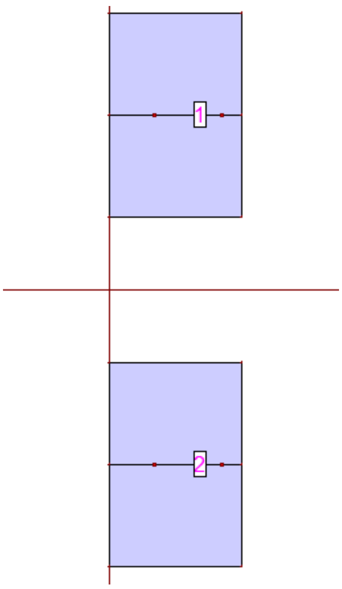


Figure 5.4 Two Rectangular Patches in Parallel Position

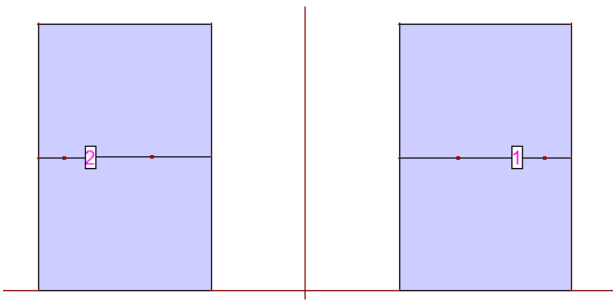


Figure 5.5 Two Rectangular Patches in Collinear Position

5.4.1 Mutual Coupling in Parallel Position

The simulated plot of the variation of mutual coupling $S_{21}(dB)$ with frequency GHz for different element separation in the parallel position is shown in Figure 5.6. The results are tabulated in Table 5.1 with mutual coupling represented as S_{21} in the equivalent linear units and then plotted using Microsoft Excel to show the variation of the mutual coupling with distance more clearly for a better analysis of the outcome. The plotted graph is shown in Figure 5.7.

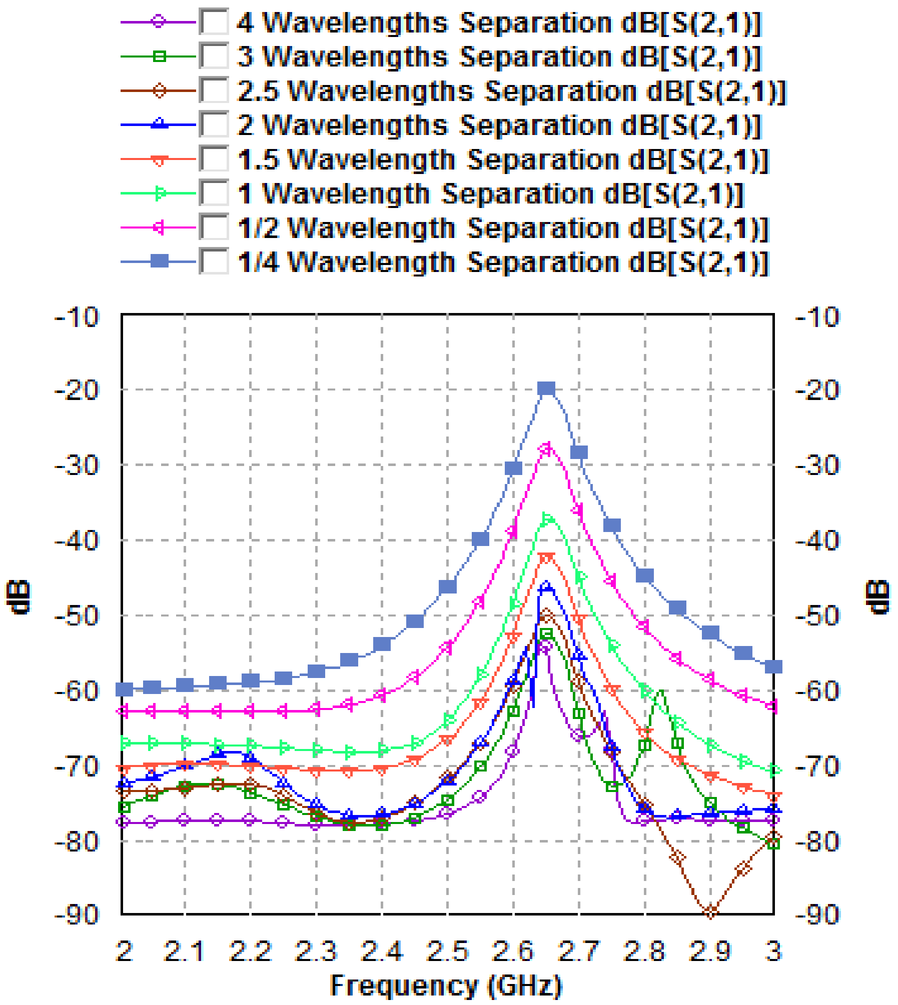


Figure 5.6 Mutual Coupling (S21) at different Parallel Element Separation at 2.65 GHz

Element Separation (λ)	Mutual Coupling (S_{21} Linear Magnitude)
4	0.001995
3	0.002239
2.5	0.003162
2	0.004467
1.5	0.007943
1	0.014125
0.5	0.039810
0.25	0.089125

Table 5.1 Mutual Coupling in Parallel Position

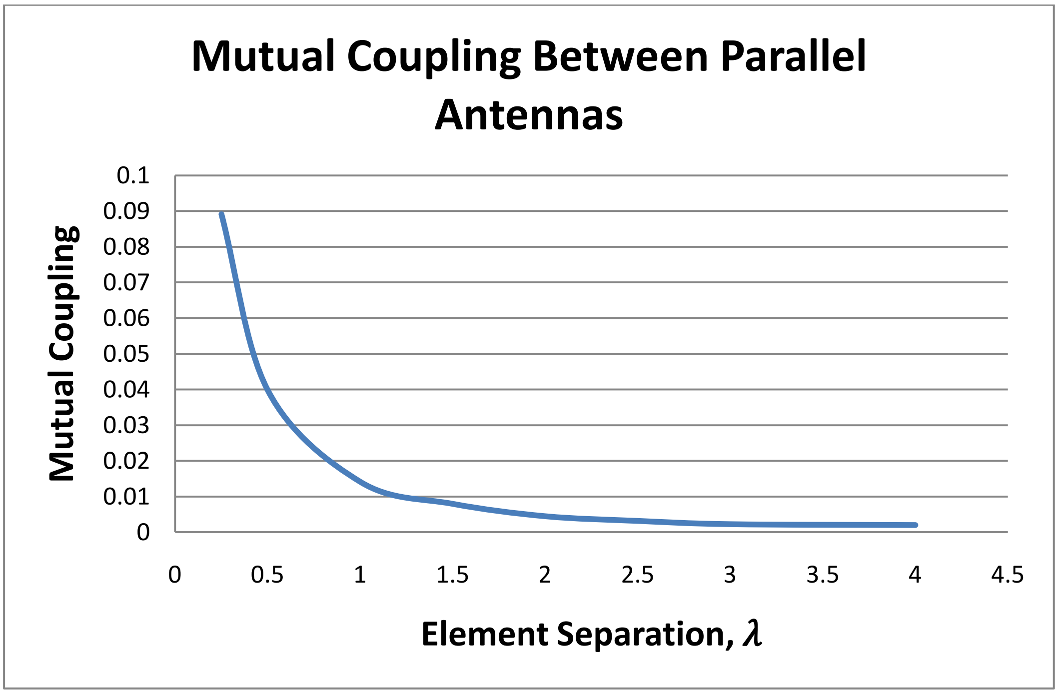


Figure 5.7 Mutual Coupling between Parallel Antenna Configurations

5.4.2 Mutual Coupling in Collinear Position

The simulated plot of the variation of mutual coupling $S_{21}(dB)$ with frequency GHz for different element separation in the collinear position is shown in Figure 5.8. The results are also tabulated in Table 5.2 with mutual coupling represented as the S_{21} in the equivalent linear units and plotted in Microsoft Excel for a better description since the graph is quite congested. The plotted graph is shown in Figure 5.9.

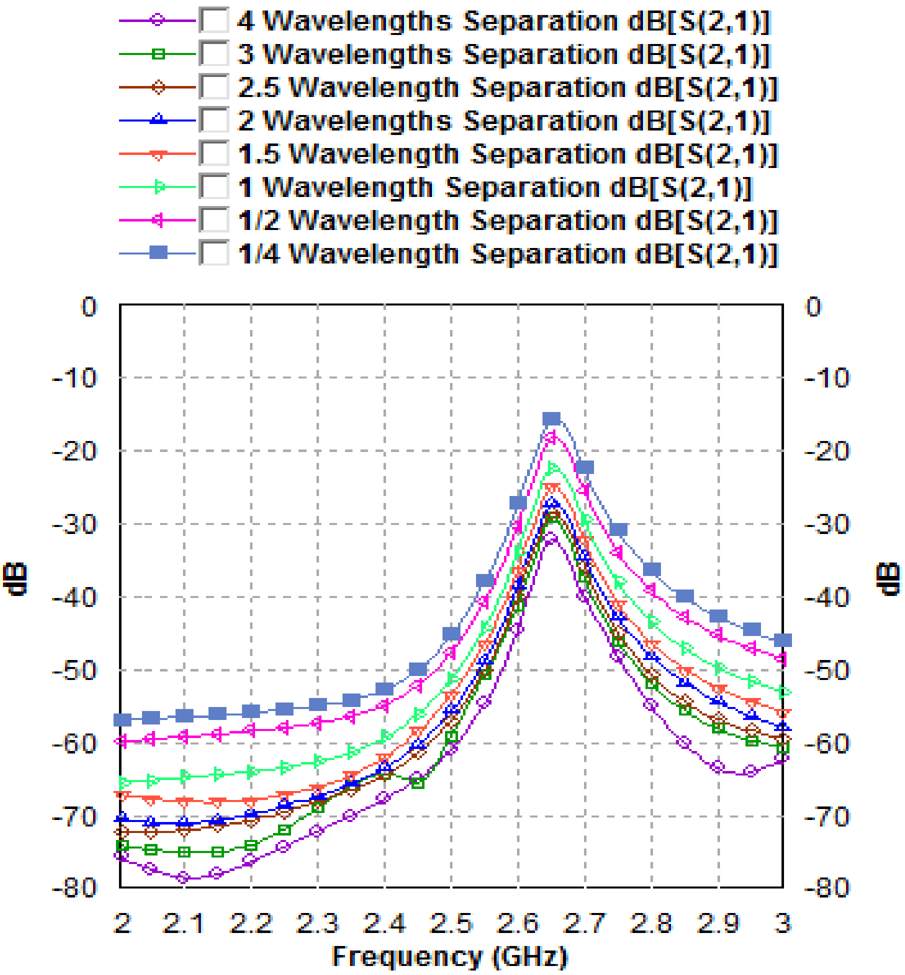


Figure 5.8 Mutual Coupling (S21) at different Collinear Element Separation at 2.65 GHz

Element Separation (λ)	Mutual Coupling (S_{21} Linear Magnitude)
4	0.025119
3	0.031623
2.5	0.039811
2	0.044668
1.5	0.056234
1	0.070795
0.5	0.125893
0.25	0.158489

Table 5.2 Mutual Coupling in Collinear Position

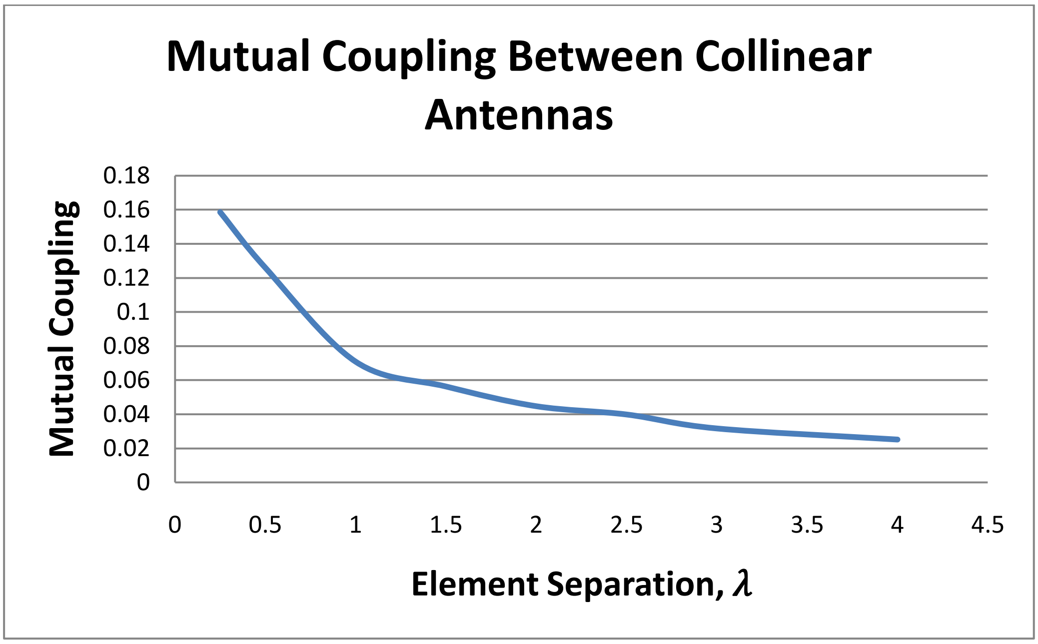


Figure 5.9 Mutual Coupling between Collinear Antenna Configurations

5.4.3 Mutual Coupling of Combined Positions

The results of the mutual coupling in both parallel and collinear positions are combined and presented in Figure 5.10 in order to compare them more easily.

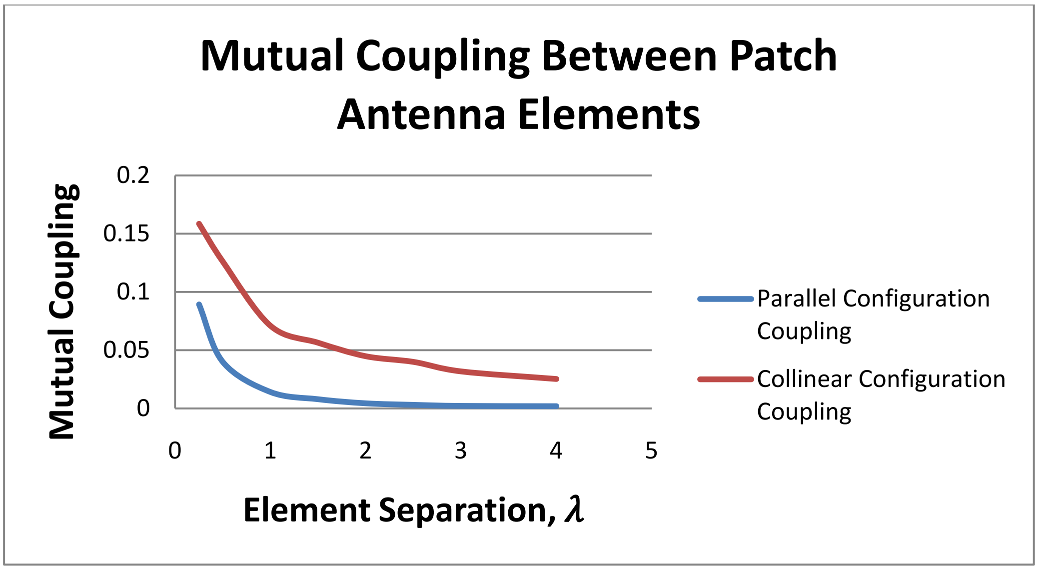
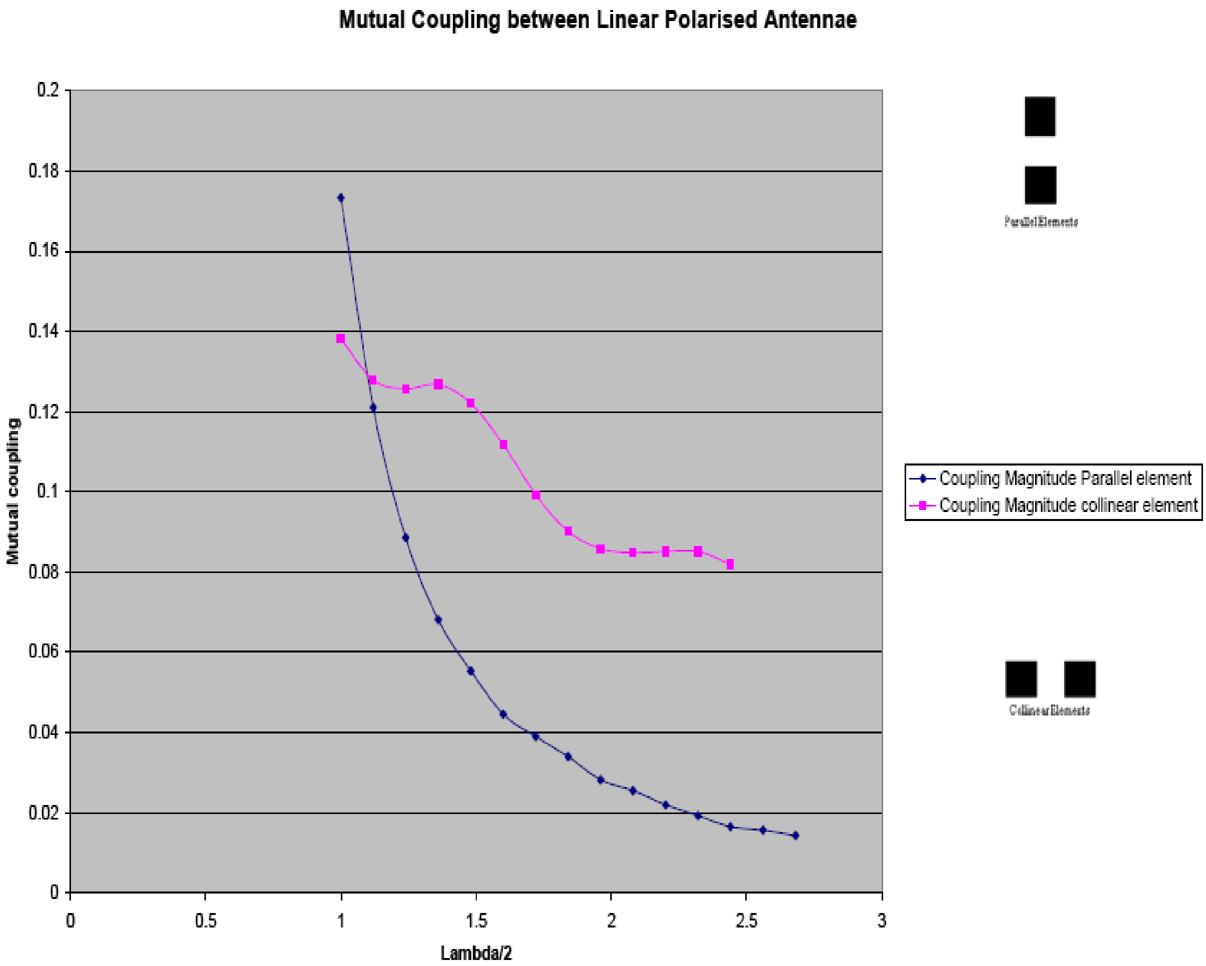


Figure 5.10 Mutual Coupling in Parallel and Collinear Positions



5.11 Mutual Coupling Between Linear Polarised Antennae from Parthasarathy (2006)

5.5 Discussion

This section presents a discussion on the results of the single rectangular patch antenna design and mutual coupling between two antennae.

5.6.1 Single Patch Antenna Design

The rectangular patch antenna design dimensions obtained through the Equations 5.1-5.5 yielded a patch width of $33.96mm$ and patch length of $26.2776mm$. Whereas the computer simulated design produced an optimized design with a patch width of $40mm$ and patch length of $26mm$. The initial dimensions fed into the simulator were $W = 40mm,\ L = 20mm$ arbitrarily since computer aided designs generally require the initial parameters to be defined by the user. These results are tabulated in Table 5.3.

Dimension	Theoretical	Simulation	Difference
Length	$33.98\ mm$	$40\ mm$	$6.02\ mm$
Width	$26.2776\ mm$	$26\ mm$	$0.2776\ mm$

Table 5.3 Single Patch Design Results

The lack of change in the simulated width was due to the fact that the optimization and tuning was performed on the patch length and probe feed. This is because the desired aim was to achieve a resonant frequency at $2.65\ GHz$ and the patch length is the resonating dimension. The patch width improves the radiation efficiency which is not specifically required. Therefore with a width difference of $0.2776\ mm$ the theoretical and computer aided designs are practically agreeable. Hence the simulated antenna design is deemed accurate and can be used for further simulations.

5.6.2 Mutual Coupling in Two Rectangular Microstrip Antennas

It can be noticed from Figures 5.7 and 5.9 that for both the parallel and collinear positions, the mutual coupling effects increased with decreased separation or distance between the antenna elements. In addition it can also be observed that in both cases these effects were greater from the smallest separation of a quarter wavelength ($\frac{1}{4}\lambda$) up to one wavelength (1λ) separation. Beyond this point the effects were much less as the changes were only present in very small proportions and the mutual coupling approached closer to zero. Therefore the effects of mutual coupling were found to be greater when the separation between the antenna elements was below one wavelength. Hence this confirms the conclusions of Parthasarathy (2006) on mutual coupling with element spacing (separation) between two linearly polarized rectangular patch antennas.

Figure 5.10 provides a plot of the mutual coupling for both parallel and collinear antennae positions. It can be noticed that the magnitude of coupling in the collinear position is greater. The slope of the parallel antennae position curve is greater than that of the collinear antennae position curve. This is because the changes in coupling effects with separation are less in the collinear antennae position as seen in Figure 5.8. This suggests the fact that position does have some impact on mutual coupling effects (Parthasarathy, 2006).

However an analysis of the result in Parthasarathy (2006) in Figure 5.11 reveals some slight variations from the result in Figure 5.10. The blue curve indicates the parallel element setup while the pink line indicates the collinear element setup. Coupling in the collinear curve is not greater than that of the parallel curve for all separations. This is seen (Figure 5.11) between $1lamda/2$ and $1.5lamda/2$ separations with the collinear curve intersecting the parallel curve at some point. The wavy or undulating nature of the collinear curve is not accounted for in the study. No additional factors or conditions been introduced for the collinear antennae simulation. Therefore the graphical result obtained in this report in Figure 5.10 presents a more reasonable visual representation of the desired results. Since all the design parameters are identical save the positions, a consistent trend should be seen in both parallel and collinear positions of the elements. Nevertheless both Figures 5.10 and 5.11 show quite distinctly that considerable changes in the mutual coupling effects are evident from $\frac{1}{4}\lambda$ to 1λ separation beyond which there are little appreciable changes. These findings provide the basis for more complex models of mutual coupling analysis.

These results also provide a basic understanding of mutual coupling considerations for practical MIMO antenna designs. Antennas in base stations and other outdoor or indoor propagation environments where the element separation is larger than 1λ require less or no concern about adverse coupling effects. Antenna designs for applications such as mobile phones and other compact devices must however be implemented to eliminate or reduce such effects. The relative positions of the elements also become more important as the mutual coupling effects increase due to reduced element separation.

CHAPTER SIX
CONCLUSIONS AND FURTHER STUDY

6.0 Conclusion

In this thesis, two major goals were originally stipulated. Firstly, a linearly polarized rectangular microstrip antenna was to be designed with two different methods and the results compared. The methods include a theoretically based approach and computer simulated approach. Secondly, two linearly polarized rectangular microstrip antennas were to be simulated with different element separations and positions in order to investigate the mutual coupling effects between them. These goals have been achieved accordingly:

A linearly polarized rectangular microstrip antenna was designed at a resonant frequency of $2.65\,GHz$ using analytical equations and the IE3D software simulator. A difference of approximately $6\,mm$ was found in patch width and $0.2776\,mm$ for patch length respectively for the two methods. The result is considered to show an acceptable level of agreement. This is due to the fact the design was aimed principally at achieving the desired resonant frequency of $2.65\,GHz$ and it has been shown that the patch length is the resonating dimension while the patch width improves the radiation efficiency.

The simulation software was used to determine the mutual coupling effects between two linearly polarized rectangular microstrip antennas. This was with variations of patch element separation from $\frac{1}{4}\lambda$ up to 4λ and parallel and collinear positions. The results showed that the mutual coupling effects in both positions were significant from $\frac{1}{4}\lambda$ to 1λ with appreciable changes. Beyond 1λ up to 4λ the effects were minimal with little changes with separation. The magnitude of mutual coupling effects in the collinear position was also seen to be higher at each point of separation.

Therefore it can be concluded that:

- The validity of microstrip antenna theoretical equations and the accuracy of computer simulation (in this case the IE3D) in designing microstrip antennas have been verified.
- Mutual coupling effects are dominant up to an element separation of 1λ beyond which point they remain marginally dominant.

- The relative position of antenna elements also plays a role in determining the mutual coupling effects between them.

Consequently, the conclusions in Parthasarathy have been confirmed and the thesis' aims and objectives have been achieved.

6.1 Further Study

A couple of areas of further study have been deducted from this work:

- The mutual coupling effects were considered for linearly polarized antennas in general. It would be useful to ascertain the coupling effects with horizontal and vertical polarizations. This would providence greater evidence on the role played by polarization. It has been reported that vertical polarization yields better antenna performance (Kyritsi, Cox, 2001). This fact can be tested to determine its influence on mutual coupling.
- While it remains clear concerning mutual coupling effects beyond an element separation of 1λ, more concrete conclusions are required for smaller separations. Therefore additional studies would focus on separations below 1λ. For instance Kyritsi and Cox (2001) have also reported that mutual coupling effects have adverse effects with separations of $< \frac{1}{2}\lambda$. Numerous applications such as mobile phones and PDAs require antenna element separations of $< \frac{1}{4}\lambda$. More concrete evidence of mutual coupling effects in such conditions are hence necessary for accurate practical implementations.

Mutual coupling effects are generally considered to have harmful effects on channel capacity and system performance but as it has been mentioned earlier in chapter one, several studies have reported capacity enhancements both conditionally and unconditionally. Therefore clearer and concise characterisations on these aspects would be essential in achieving the capacity potentials of MIMO systems.

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