Chapter 1

Introduction

1.1 Introduction

Antennas are an essential part of any wireless communication system. They are used to transmit or receive signals in the form of electromagnetic waves. The IEEE standard definitions of terms for antennas defines the antenna as a "means for radiating or receiving radio waves" [1]. Over the years, various types of antennas such as dipole, monopole, loop, horn, aperture, reflector, spiral, log periodic, and patch are developed to fulfill the requirements of different applications. The microstrip antenna consists of a conducting patch printed on a grounded microwave substrate. The microstrip technology has several attractive features such as low profile, simple fabrication process, low cost, and easy integration with other microwave devices [2].

To address the challenges of modern wireless communication technologies, antennas capable of achieving multiple functionalities in a single structure are required. The concept of Reconfigurable Antenna (RA) is proposed in [3] to overcome the limitations of a conventional fixed performing antenna. RA technology is one of the hardware solutions developed to enhance wireless device connectivity. These new classes of radiating elements can adapt their physical characteristics to variations in environmental changes or user density and location. In contrast to the conventional fixed performing antenna, where energy is spent around the surrounding space, the use of RA enables smarter management of radiated power, as the beam can be focused in specific directions. As a result, it is possible to improve data throughput between two devices and significantly reduce interference between adjacent networks. RA incorporates an internal mechanism to redistribute Radio Frequency (RF) currents over its surface, which causes modifications in impedance and radiation characteristics [4]. RA can change its performance features such as resonant frequency, radiation pattern, beamwidth, and polarization by changing its architecture mechanically or electrically. One of the significant challenge faced by RA developers is the linkage between antennas frequency and radiation characteristics. The frequency reconfiguration has an impact on radiation characteristics and radiation pattern reconfiguration will alter the antennas frequency response.

1.2 Classification of Reconfigurable Antenna

RAs are classified based on the parameter that is reconfigured, such as frequency [5], pattern [6], polarization [7], and compound [8–17]. The detailed RA classification is presented in Figure 1.1.

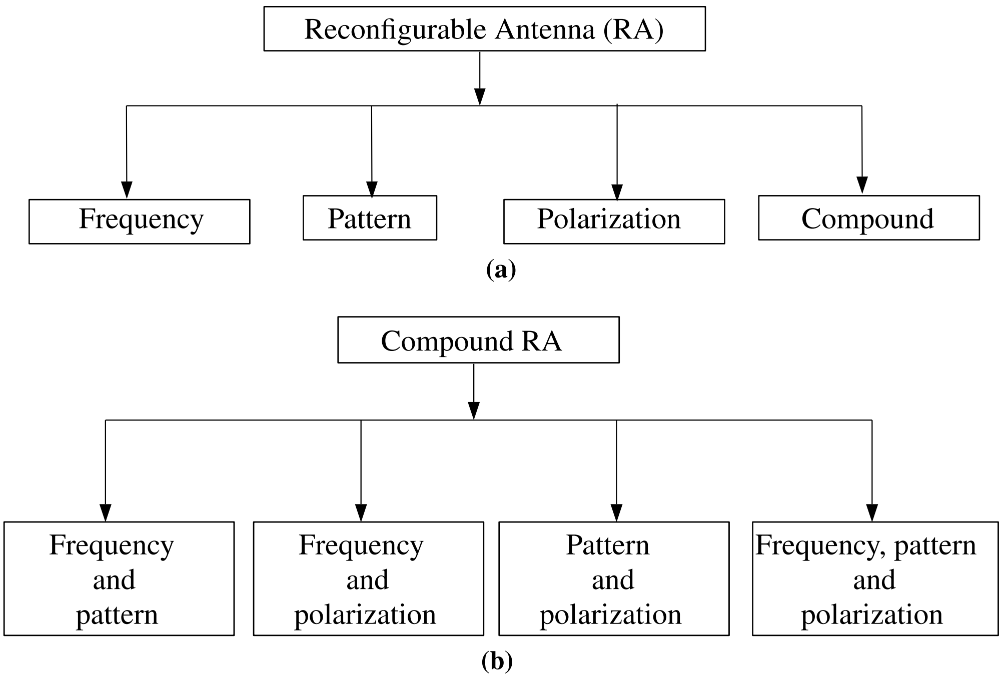


Figure 1.1. Classification of (a) RA and (b) Compound RA.

1.2.1 Frequency Reconfigurable Antenna

Frequency reconfiguration is generally achieved by changing the path of radiating currents on the antenna structure. This causes variation in the effective electrical size of resonant antennas. Frequency RA is highly desirable for wireless communication systems that have different standards and multi-frequency applications [5]. Frequency RAs can adjust their operating band based on spectrum availability and adapt themselves to the changing environment. The frequency RAs are classified into two categories as continuous tuning and discrete switching. Continuous tunable frequency RA allows a smooth transition between operating bands, while discrete frequency RA works at distinct frequency bands. Figure 1.2 shows continuous tuning and discrete switching in frequency RA.

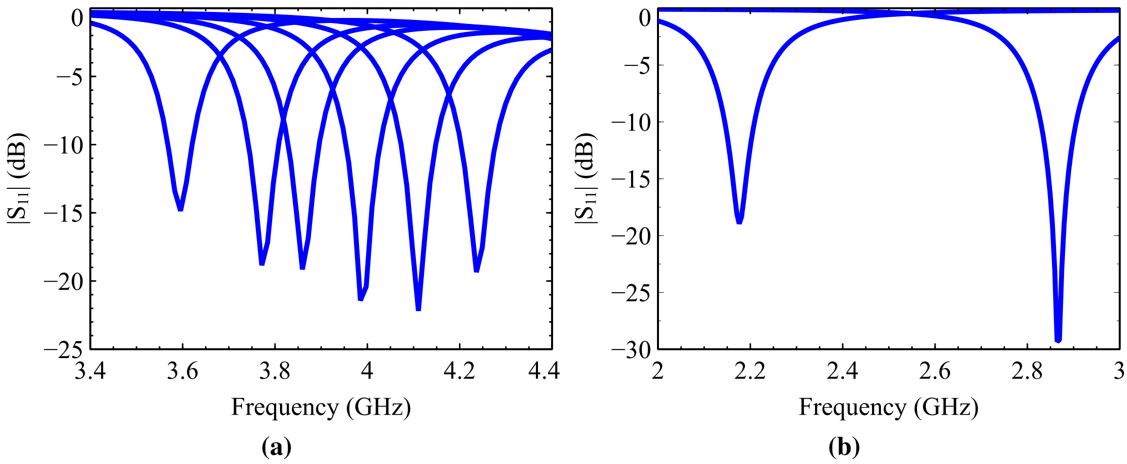


Figure 1.2. Classification of frequency RA (a) Continuous tuning and (b) Discrete switching.

1.2.2 Pattern Reconfigurable Antenna

Pattern reconfiguration is accomplished by changing the source current distribution on the antenna structure. Pattern Reconfigurable Antenna (PRA) avoids noise sources by directing null toward interference and radiating the main beam in the desired direction to improve coverage [6]. PRAs can be classified according to the radiated beam shape and direction of the main beam [4]. PRA produces various radiation patterns such as omnidirectional, conical, broadside, backfire, and endfire, as shown in Figure 1.3. The main beam of PRA can be discretely switched or continuously scanned in a certain angular direction. PRA also involves varying 3-dB beamwidth in narrow and wide beam modes.

1.2.3 Polarization Reconfigurable Antenna

The direction of current flow on the antenna surface determines the polarization in the far-field. Polarization RA helps to avoid multipath fading and doubles the communication capacity by using frequency reuse technology [7]. To achieve polarization reconfiguration, antenna structure, material properties, and feed configuration must change the way current flows on the antenna. Polarization of an antenna is classified into three categories as linear, elliptical, and

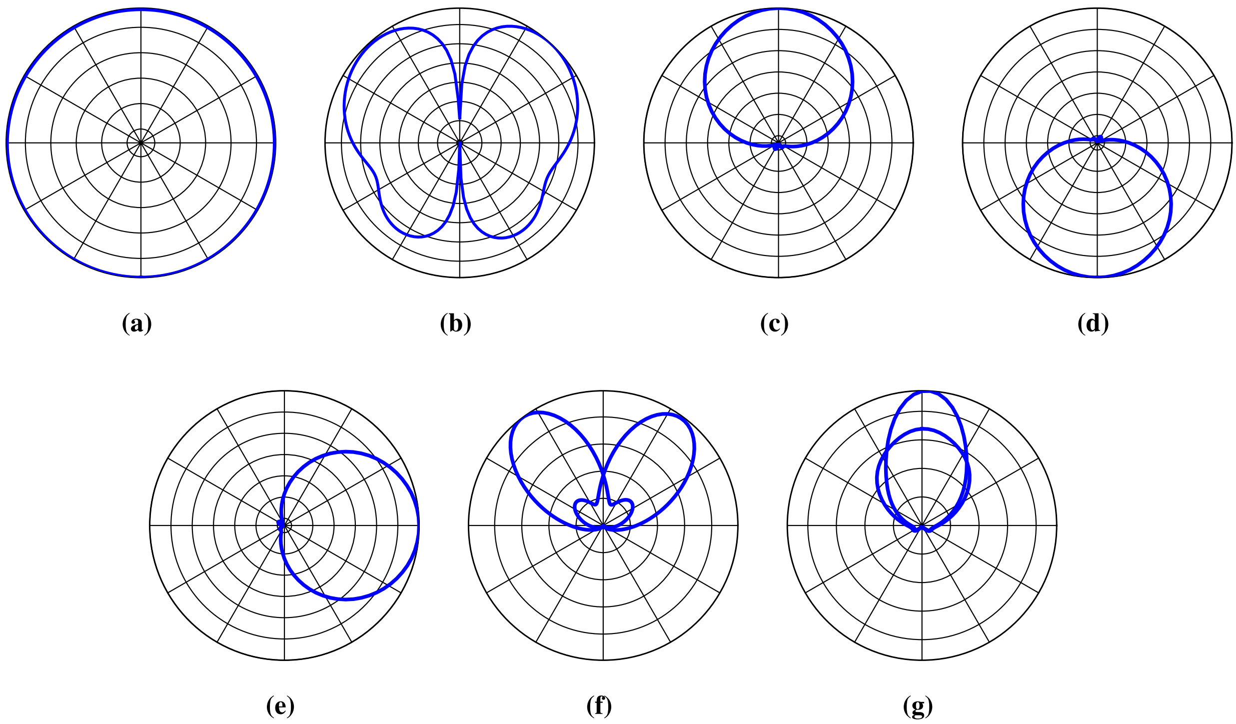


Figure 1.3. Classification of PRA according to radiated radiation pattern (a) Omnidirectional, (b) Conical, (c) Broadside, (d) Backward, (e) Endfire, (f) Beam steering and (g) Beamwidth variability.

circular, as illustrated in Figure 1.4. Linear Polarization (LP) is further classified as Linear Horizontal Polarization (LHP) and Linear Vertical Polarization (LVP). Circular Polarization (CP) is divided into two categories as Right-Hand CP (RHCP) and Left-Hand CP (LHCP). Polarization reconfiguration can occur between different types of LP, different types of CP, or between LP and CP. The main difficulty of this kind of reconfigurability is that this must be accomplished without significant changes in impedance or frequency characteristics.

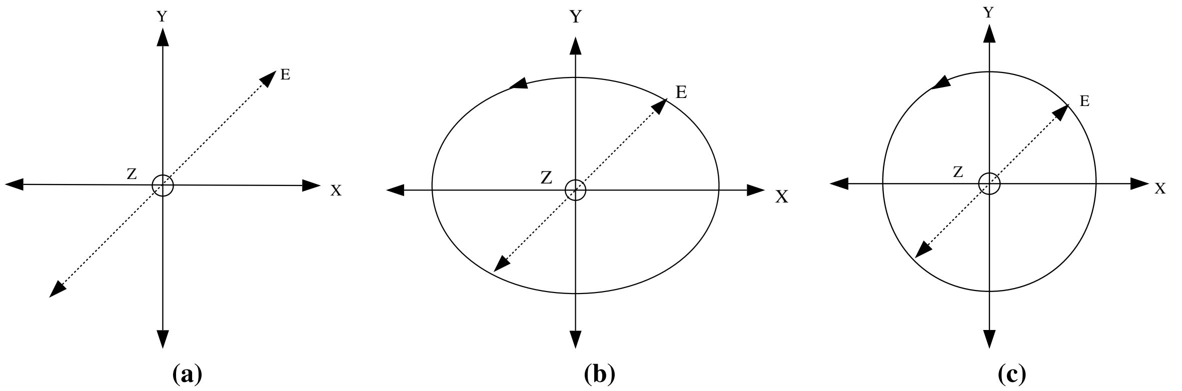


Figure 1.4. Types of polarization (a) Linear, (b) Elliptical and (c) Circular.

1.2.4 Compound Reconfigurable Antenna

The compound RA involves simultaneous reconfiguration of two or more parameters such as frequency and pattern [8–11], frequency and polarization [12, 13], pattern and polarization [14] and frequency, pattern and polarization [15–17]. It is extremely difficult to separate antennas frequency characteristics from its radiation properties. The ultimate goal of a RA designer is to independently select operating frequency, bandwidth and radiation characteristics. It is a serious challenge to realize compound reconfigurability in a compact antenna structure with simple biasing circuit.

1.3 Reconfigurable Antenna Techniques

The RAs are implemented using six major types of reconfiguration techniques, as shown in Figure 1.5. Reconfiguration is achieved by using electrical switches, optical switches, mechanical movement, and smart materials [18].

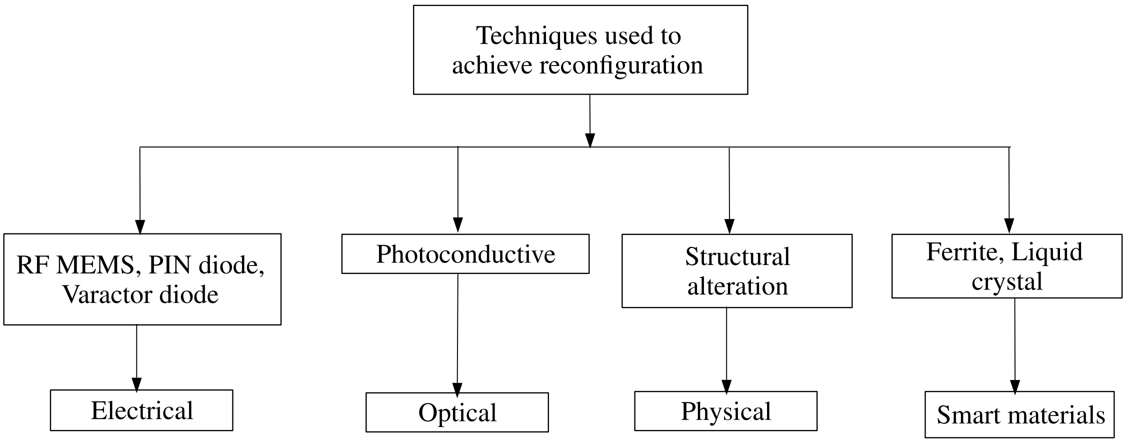


Figure 1.5. Various techniques adopted to achieve reconfiguration in antennas.

In electrical reconfiguration, different RF switches such as PIN diode, varactor diode, Field Effect Transistor (FET), and Micro-Electro-Mechanical Systems (MEMS) are used to redirect surface current on the antenna structure. This technique has an advantage that the switching elements can be easily integrated into the antenna structure. However, separate biasing circuit needs to be designed for activation of switching elements and isolation of RF and DC signals. The biasing circuit should be carefully designed with a minimum number of bypass capacitors and choke inductors to ensure low power consumption and minimal effect on antennas radiation characteristics [19]. The optically controlled RA utilizes photoconductive switching elements, which are activated by using laser light [20]. This technique does not need any complicated biasing circuit and hence provides several benefits such as low loss, reduced unwanted interference of biasing lines, and avoids radiation pattern distortion. However, the activation process of photoconductive switching elements is quite complex. The physical reconfiguration technique involves structural alteration of the antenna radiating parts [21]. This method does not depend on any switching mechanism and laser diode integration. The limitation of this technique is that the structural modification of antenna parts increases size, cost, complexity, and power source requirements of the overall system. Antennas are also made reconfigurable by using smart materials such as liquid crystals [22] or ferrites [23]. The characteristics of liquid crystal and ferrite can be changed by applying an external voltage and static electrical field. The main disadvantage associated with this technique is the low efficiency of these materials at microwave frequencies. In conclusion, it is necessary to select proper reconfiguration technique as per the constraints imposed by the application for which the antenna is designed.

1.4 Applications of Reconfigurable Antenna

Reconfigurable antennas have the potential to improve the performance of wireless communication applications such as Wireless Local Area Network (WLAN) system, Fifth Generation (5G) communication, cellular network, underground mining, Multiple Input Multiple Output (MIMO) system, Wireless Sensor Network (WSN), Electromagnetic Imaging (EMI), Unmanned Aerial Vehicle (UAV) and Direction of Arrival (DoA). In this section, benefits offered by RA in various applications are discussed in detail.

- **WLAN System**: The PRA composed of aperture coupled driven patch and parasitic pixel layer is proposed in [24] to operate in IEEE 802.11 b/g frequency band (2.4-2.5 GHz). The main beam of this PRA can be discretely switched to 30° in the elevation plane for each azimuthal direction with a switching step of 45°. Beam steering capabilities of the antenna are tested in a typical indoor environment. Results show that PRA equipped WLAN system achieves $\sim$ 6 dB Signal to Noise Ratio (SNR) gain compared to the omnidirectional antenna equipped system.
- **5G Communication**: The 5G wireless communication network promises to deliver a higher data rate, more reliable service, and improved coverage. To fulfill the requirements of 5G technologies, a PRA with the capability of joint beam steering and beamwidth variability is developed in [25]. A control algorithm is also proposed to select the optimal operating mode of operation concerning dynamic variations in the wireless communication channel. The performance of this multifunctional RA is tested in 5 GHz band for a hotspot scenario. It is concluded that RA with pattern and beamwidth reconfiguration provides 29% coverage and 16% capacity gain improvement as compared to the conventional patch antennas.

- **Cellular Network**: The performance of the PRA operating at 1.9 GHz is analyzed in a hexagonal homogeneous cellular network to improve cell edge performance [26]. The complete antenna assembly consisting of dipole as a radiating element and metallic reflectors is placed around the base station in three sector configuration. The system analysis is performed using the azimuth beam switching method by varying beamwidth of the antenna between 50° to 180°. Numerical analysis results show that the PRA configuration can provide a 20% increase in typical cell edge capacity by varying beamwidth of the antenna from 60° to 110°.
- **Underground Mining**: The fixed performing antennas are unable to tackle the difficulties of dynamic variation in channel conditions. Performance of the PRA is investigated in underground mining for both Line-of-Sight (LOS) and Nonline-of-Sight (NLOS) propagation scenarios to improve wireless communication link [27]. The experimental results demonstrate that as compared to fixed performing antenna, the PRA attains 20% and 34% improvement in path loss and delay spread, respectively.
- **MIMO System**: Exponential growth in wireless data demand has driven new technological solutions to meet high-performance requirements. In particular, MIMO multi-antenna systems became an integral part of modern wireless devices for enhancing data throughput and maintaining a high quality of service. RA provides additional capacity in MIMO systems to further improve the robustness of wireless links. In [28], the performance of pattern and polarization RA is investigated for narrowband and broadband MIMO systems. Benefits offered by RA are analyzed in both LOS and NLOS scenarios. The pattern reconfiguration is realized by exciting higher-order modes in a two-port circular patch antenna. Whereas, the polarization reconfiguration is obtained by changing the phase shift between two orthogonal modes generated on the same circular patch. The experimental analysis demonstrates that pattern and polarization reconfiguration improves the diversity level of the MIMO system, and capacity improvement of 17.5% is obtained in a narrowband channel.
- **WSN**: Conventionally, monopole and dipole antennas with an omnidirectional radiation pattern are used in WSN nodes. However, PRA with continuous beam scanning characteristics can provide performance enhancement over omnidirectional antennas in terms of energy consumption, communication range, and signal sensitivity. Moreover, the pattern reconfigurability allows the antenna to adapt to its radio environment and find optimum receiving characteristics. In [29], the parasitic slot antenna array is presented, and its performance is experimentally analyzed on a sensor network system. The measurement results show that PRA improves the packet reception rate by 64% and received signal strength by 10 dB, as compared to the uniformly radiating dipole antenna.
- **EMI**: EMI systems consisting of RA, plays a vital role in detecting fluid accommodation inside the torso [30]. A pattern reconfigurable metasurface antenna operating in the frequency range

from 0.8 to 1.05 GHz is proposed to build an EMI system. The main beam of this antenna is switched from $-30°$ to $30°$ and thus can scan the human chest with steerable unidirectional radiation patterns. A complete imaging system is tested to detect 20 ml of fluid accommodation inside the torso, and thus it can distinguish between healthy and unhealthy cases.

- **UAV**: In [31], an experimental testbed consisting of Software Defined Radio (SDR) and PRA is proposed to evaluate the performance of UAV in aerial to ground communication links. The PRA consists of a square-shaped outline with a microstrip line-feed four dipole elements. Total weight of the UAV platform is 2.2 Kg and has 15 minute flight time. The SNR measurements are carried out during various indoor and outdoor flight scenarios. From the experimental results, it is concluded that a system consisting of PRA achieves higher SNR as compared to the omnidirectional antennas in both LOS and NLOS scenarios.
- **DoA**: In [32], a low profile Electronically Steerable Parasitic Array Radiator (ESPAR) is developed to estimate DoA of incoming signals in WSN applications. This antenna provides eight unique main beam directions, which makes it applicable to simple and inexpensive Internet of Things (IoT) sensor node. Results show that the proposed approach provides better accuracy and reduces the overall time required for DoA estimation by 33%.

1.5 Antenna Characterization

This section presents details related to the facilities and equipments used for the proposed antennas characterization. Full-wave simulation of all the proposed antennas has been performed using Finite Element Method (FEM) based commercial software Ansys High Frequency Structure Simulator (HFSS) [33]. Teflon claddings are used to model Sub Miniature version A (SMA) port to produce an accurate impedance response. The airbox and virtual boundaries are placed at a distance of $\lambda/3$ and $\lambda/10$ respectively from the radiating patch, where λ is free space wavelength at the lowest cut-off frequency. The antenna designs presented in this thesis are fabricated in-house using a standard photolithography process.

The performance of the antennas is characterized by different parameters, such as operating frequency, radiation pattern, gain, directivity, efficiency, and polarization. The test facilities used for the experimental measurement include Vector Network Analyzer (VNA), automated antenna positioner, broadband double ridged horn antenna, and anechoic chamber. The reflection characteristics of the proposed antennas are measured using Keysight E5063A VNA. The operating frequency of this VNA is from 100 KHz to 18 GHz. Detailed specifications of this VNA are presented in Table 1.1. The VNA is used to measure two-port network parameters such as S_{11}, S_{12}, S_{21}, and S_{22}. The E5063A VNA is calibrated using the standard Keysight 85052D 3.5 mm calibration kit.

Table 1.1. Specifications of E5063A Vector Network Analyzer (VNA).

Features	Description
Frequency	100 KHz to 18 GHz
Test port	Two-port S-parameter, 50 Ω, Type-N connectors
Sweep type	Linear and log frequency, Segment sweep
Connectivity	USB, LAN, GPIB
Operating system	Windows 7

Radiation characteristics of the antennas are measured in an anechoic chamber (4.5 m $\times$ 2.2 m $\times$ 2.5 m) facility available in the BITS Pilani, Goa campus. Figure 1.6 shows the photograph of the anechoic chamber facility used for the antenna measurements. The shielding effectiveness and quietness level of the anechoic chamber are -80 dB and -40 dB, respectively, which is tested as per IEEE 299 standard. Figure 1.7 shows the experimental setup used in the anechoic chamber to characterize the performance of the proposed antennas. The Antenna Under Test (AUT) is placed on an automatic turntable and connected to one port of the VNA. A wideband horn antenna is used as a transmitter and connected to other port of the VNA. The double ridged broadband horn antenna used in the measurement covers frequency from 800 MHz to 18 GHz with LP and has excellent VSWR performance. Gain of the horn antenna varies from 3.37 to 23.51 dBi across the operating frequency band. Distance between the center of AUT and the front side of horn antenna is greater than $2D^2/\lambda$, which ensures that the radiation pattern is measured in the far-field region of the antenna, where D is the largest dimension of the antenna. The normalized radiation pattern of the antenna is measured in two principal coordinate planes. Radiation efficiency of the antenna is calculated using measured gain and simulated directivity as $\eta = G_{mes}/D_{sim}$ [34].

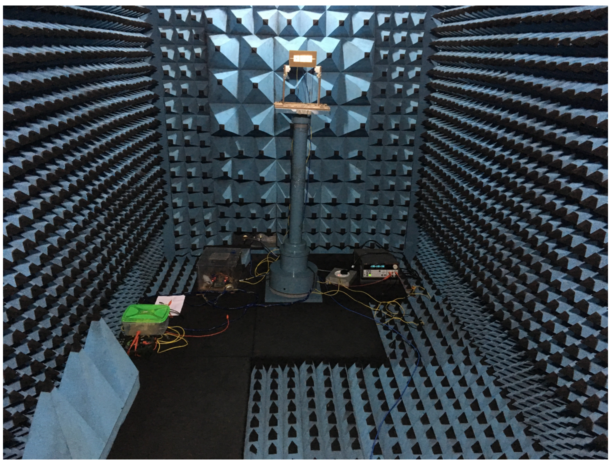


Figure 1.6. Photograph of the anechoic chamber used for the antenna measurements.

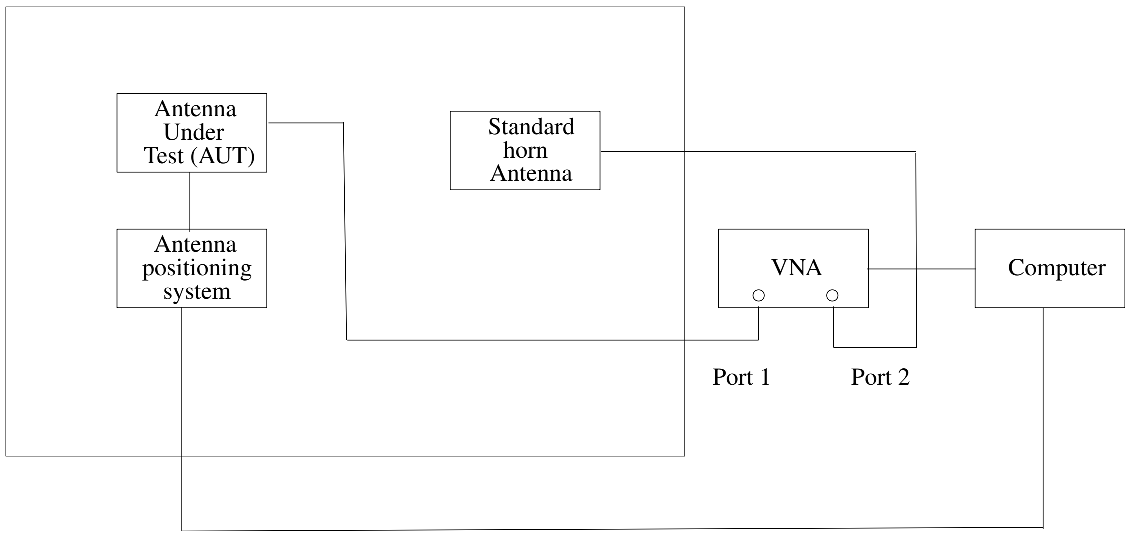
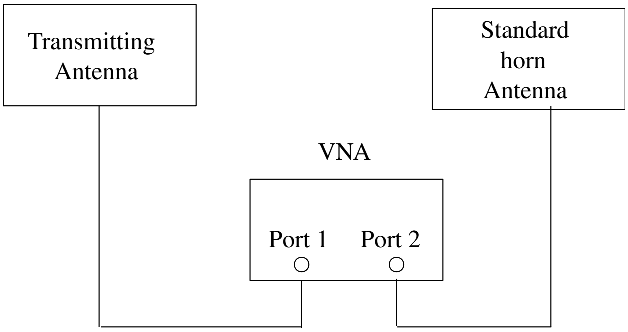


Figure 1.7. Experimental setup used in the anechoic chamber.

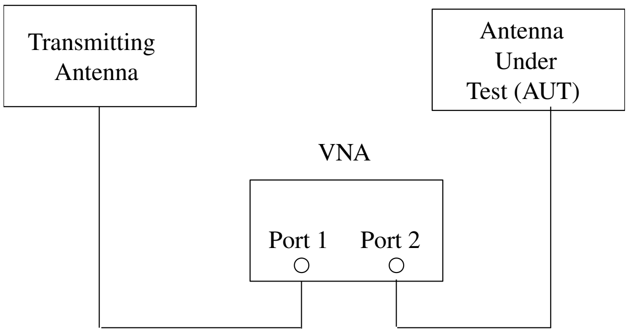
The gain of the proposed antennas in this thesis is measured by using the gain transfer method, which is the most commonly used method as per the IEEE standard test procedure for antennas. Gain of an antenna is defined as the ratio of the intensity in a given direction relative to an isotropic antenna. The gain transfer method needs three antennas, which includes two wideband double ridged horns and one AUT. The Figure 1.8 shows the experimental setup used to measure the antenna gain. Initially, the reference antenna and the standard horn antenna are well aligned in terms of the polarization and direction of the maximum radiation intensity. With this arrangement, the $|S_{21}|$ is measured using the VNA for a certain frequency range of interest. This procedure provides the reference gain for the AUT and is represented as G_{ref} (dBi). Now the reference antenna is replaced with the AUT at the same position and alignment. The transmission coefficient $|S_{21}|_{AUT}$ is recorded, which gives the relative gain. The absolute gain of the antenna is then calculated as,

$$G(dBi) = G_{ref}(dBi) + |S_{21}|_{AUT} \tag{1.1}$$

Circular polarization characteristics of the antenna can be measured through different methods such as polarization-pattern method, rotating source method, multiple-amplitude component method, and phase-amplitude method [35–37]. Polarization characteristics of the antenna design proposed in this thesis are measured by using the phase-amplitude method. The linearly polarized horn antenna is rotated between two angles vertical and horizontal. The transmission coefficient $|S_{12}|$ and phase is noted in each case, which is used to calculate Axial Ratio (AR) and CP radiation patterns. Figure 1.9 presents the polarization ellipse of a typical CP wave, which is characterized by the parameters AR, phase difference ($\Delta\phi$), and tilt angle (τ). AR is an important parameter,



(a)



(b)

Figure 1.8. Antenna Gain Measurement setup using the gain transfer method.

and it determines the quality of CP. Usually, the AR is required to be less than 3 dB for a CP antenna.

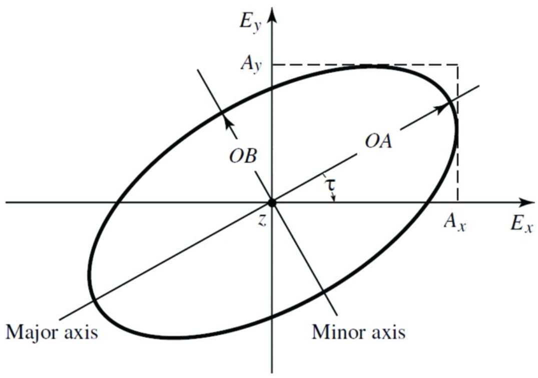


Figure 1.9. Polarization ellipse.

The electric field vector of the electromagnetic wave perpendicular to the direction of propagation can be written as [2],

$$E(t) = \hat{x}A_x \cos(\omega t + \phi_x) + \hat{y}A_y \cos(\omega t + \phi_y) \tag{1.2}$$

where A_x and A_y represents maximum magnitude, ϕ_x and ϕ_y represents phase values of the x and y components, respectively.

The phase difference between the two components is given by equation (1.3),

$$\Delta\phi = \phi_y - \phi_x \tag{1.3}$$

The horizontal and vertical amplitude (A_x,A_y) and phase components (ϕ_x,ϕ_y) quantities are measured at each angle θ in the far-field of the antenna, with source horn orientated at angles ϕ = 0° and ϕ = 90°.

where θ and ϕ are the beam direction in the elevation and azimuth plane respectively.

Ratio of the major axis to the minor axis is described as the AR, and it can be calculated by using equation (1.4),

$$\text{AR} = \frac{\text{major axis}}{\text{minor axis}} = \frac{OA}{OB} \tag{1.4}$$

where OA and OB referred to as the major axis and minor axis of the polarization ellipse and are defined by equation (1.5) and (1.6),

$$OA = \sqrt{\frac{1}{2}\left\{A_x^2 + A_y^2 + [A_x^4 + A_y^4 + 2A_x^2A_y^2\cos(2\Delta\phi)]^{\frac{1}{2}}\right\}} \tag{1.5}$$

$$OB = \sqrt{\frac{1}{2}\left\{A_x^2 + A_y^2 - [A_x^4 + A_y^4 + 2A_x^2A_y^2\cos(2\Delta\phi)]^{\frac{1}{2}}\right\}} \tag{1.6}$$

The tilt angle related to the x axis of the polarization ellipse is represented by the angle τ and is given by equation (1.7),

$$\tau = \begin{cases} \frac{1}{2}\tan^{-1}\left[\frac{2A_xA_y}{A_x^2-A_y^2}\cos(\Delta\phi)\right], & \text{if } A_x \geq A_y \\ \frac{\pi}{2} - \frac{1}{2}\tan^{-1}\left[\frac{2A_xA_y}{A_x^2-A_y^2}\cos(\Delta\phi)\right], & \text{otherwise} \end{cases} \tag{1.7}$$

The co-polarized and cross-polarized components of the CP wave can be calculated as,

$$E_{LHCP} = \frac{1}{\sqrt{2}}\{[A_x\cos(\phi_x) + A_y\sin(\phi_y)] + j[A_x\sin(\phi_x) - A_y\cos(\phi_y)]\} \tag{1.8}$$

$$E_{RHCP} = \frac{1}{\sqrt{2}}\{[A_x\cos(\phi_x) - A_y\sin(\phi_y)] + j[A_x\sin(\phi_x) + A_y\cos(\phi_y)]\} \tag{1.9}$$

The Cross-polarization Discrimination (XPD) in dB can also be calculated using AR as,

$$\text{XPD} = 20\log_{10}\frac{r+1}{r-1} \tag{1.10}$$

where, r is the value of AR in normal units.

1.6 Motivation

Pattern reconfigurable antenna with continuous beam scanning capability provides spatial diversity that can be effectively used to mitigate multipath fading and thereby to enhance the quality and capacity of wireless systems. PRA is the preferred choice for applications such as cognitive radio, satellite communication systems, wearable devices, 5G millimeter-wave networks, WLAN, etc. PRA increases spectral efficiency by directing the signal toward desired direction and thereby avoiding interference. Conventionally, phased arrays are extensively used in wireless communication systems due to several advantages such as higher directivity, fast response to beam steering, and multi-beamforming. However, they are associated with a large number of radiating elements, phase shifters, and complex signal processing circuits, which in turn increases the cost, size, and complexity of the overall communication system. Furthermore, they offer limited bandwidth and suffer from scan loss.

The pattern and polarization RA has a strong capability to enhance the performance of wireless communication systems by providing space and polarization diversity. Pattern and polarization RA have many advantages, including multifunctional capabilities, enhancement of system capacity, avoidance of multipath distortion in wireless channels, the achievement of broad radiation coverage, and polarization coding. Specifically, CP beam scanning antennas are suited for applications such as satellite communication and radar systems. These antennas can handle many issues such as mobility, adverse weather conditions, multipath distortion, and polarization rotation effects.

The microstrip Yagi antenna provides a simple and inexpensive way to achieve beam steering. The planar Yagi antenna is associated with the driven patch and several mutually coupled parasitic elements. Parasitic elements are loaded with switches or reactive components to change the effective electrical size and are thereby used as a reflector or director. A reconfigurable beam steerable antenna designed using parasitic elements provide advantages such as simple design, planar structure, reduced complexity, better isolation between the antenna elements, maintained impedance characteristics and range of available topologies and functionalities.

1.7 Challenges

- The RA should be designed with a minimum number of active switches, as this will help to reduce the cost, power consumption, and complexity of the DC biasing network.
- The significant challenge in One-Dimensional (1-D) beam steerable RA designs is to achieve improved continuous beam scanning with a simple DC biasing network.
- To accomplish continuous beamwidth reconfiguration in both the principal planes along with independent continuous beam scanning.
- To realize the multiple functionalities in a single antenna structure is a difficult task. Very few reported antenna designs can address the challenge to achieve independent pattern and polarization reconfiguration.
- It is noted that the RA design achieving independent reconfiguration of all the three parameters pattern, beamwidth, and polarization in a single antenna structure is not yet reported in the literature.

1.8 Objectives

This thesis aims to design and develop RA that would facilitate independent pattern, polarization, and beamwidth reconfiguration without the use of any matching circuit and complicated biasing network. The proposed antennas are designed to operate in IEEE 802.11 b/g frequency band from 2.4 to 2.5 GHz, where a large number of wireless communication applications exist. The objectives of this dissertation are as follows:

1. Design and develop PRA with improved and continuous beam scanning capability in H-plane.
2. Design and develop RA to achieve pattern and beamwidth reconfiguration in a single antenna structure. This antenna should be able to perform continuous beam scanning in the elevation plane covering the whole azimuth plane and realize beamwidth reconfiguration in the E-plane and H-plane.
3. Design and develop RA to achieve independent pattern, beamwidth, and polarization reconfiguration capability at an operating frequency of 2.45 GHz. The main beam of the antenna must be continuously scanned in the elevation plane for LP (LVP, LHP) as well as CP (LHCP, RHCP) operating mode. In addition to this, realizing individual and simultaneous beamwidth reconfiguration in the E-plane and H-plane with dual orthogonal LP.

1.9 Organization of the Thesis

The thesis is organized as follows:

- **Chapter 1**: This chapter presents the classification of RA. Besides, various techniques used to achieve reconfiguration in the antenna are presented. Applications of pattern and polarization RA are explained in detail. The measurement process adopted to characterize the performance of the proposed RA designs is discussed in detail. Motivation, challenges, and objectives of the thesis are highlighted in the end.
- **Chapter 2**: In this chapter, a detailed literature survey on the pattern and polarization RA is presented. PRA designs reported in the literature are classified according to their radiation capabilities such as 1-D beam steering, Two-Dimensional (2-D) beam steering, beamwidth reconfiguration, and beam steering and beamwidth reconfigurability. This chapter also presents a detailed performance comparison of the pattern and polarization RA designs reported in the literature. The advantages and limitations of the existing pattern and polarization RA designs are summarized.
- **Chapter 3**: In this chapter, a PRA achieving continuous and improved beam scanning is proposed. First, the geometrical design of the three-element microstrip Yagi antenna is presented. The simulated results of the reconfigurable dual-band antenna are discussed in detail. The effect of distance between the elements and size of the parasitic element on antennas reflection and radiation characteristics is analyzed. Simulated and measured results are verified in three operating modes, namely Reflector-Director (RD), Director-Reflector (DR), and broadside. The current ratios are calculated in all the three operating modes to examine the effect of varactor diode capacitance on the mutual coupling. Finally, performance of the proposed PRA is compared with the reported parasitic antenna designs.
- **Chapter 4**: A PRA with the capabilities of continuous beam scanning and beamwidth reconfiguration is presented in this chapter. In the beginning, geometrical design of the reconfigurable cross parasitic is discussed. The mutual coupling is analyzed in detail by placing the parasitic elements in the E-plane and H-plane of the square-shaped driven element. Simulated and measured results are presented in the five operating modes. Lastly, the performance of the proposed PRA is compared with other reported designs, which achieves beam steering and beamwidth reconfigurability in a single antenna structure.
- **Chapter 5**: In this chapter, a RA design is proposed to realize independent pattern and polarization reconfiguration along with beamwidth variability. Initially, a detailed antenna design is presented. Performance of the Reconfigurable Feeding Network (RFN) generating different polarizations is experimentally verified. The simulated and measured results are

discussed in three operating modes, namely broadside, pattern reconfiguration, and beamwidth reconfiguration. In the end, a detailed performance comparison is presented.

- **Chapter 6**: Outcomes of the research work carried out are summarized in this chapter. Also, further improvements that can be made in this research area are listed.