

Introduction and Literature Review

This chapter starts with a brief introduction of traditional antennas and their limitations in the present communication environments. This further motivates the investigation of reconfigurable antennas for increasing the system's performance. Different types of reconfigurable antennas, their advantages and disadvantages, and their applications in different communication scenarios are discussed in detail. Several challenges in designing the reconfigurable antennas are also discussed. A detailed literature review is carried out on the reconfigurable antennas with pattern reconfigurability, polarization reconfigurability, and hybrid reconfigurability associated with the scope of the present thesis, and their limitations are also identified. Finally, based on the identified findings, some reconfigurable antennas with single and multiple reconfigurability functions are investigated to fill the research gap and fulfil the objective of this thesis.

1.1 Introduction

This chapter explores the reconfigurable antennas, delving into their underlying principle, design techniques, and applications for wireless communication networks. In the last few decades, wireless communication systems have grown towards multi-functionality to enable secure and reliable communication services. This feature not only provides the advantages of high data rates in congested environments for many civilian and military applications but also enables mobile services with innovative wireless solutions and highly secure data transmission. These intelligent systems require adaptive signal processing and revolutionary hardware for their full potential application. Antennas, which are indispensable and one of the most critical components, play an important role in determining the optimum performance of any wireless communication system [1]. According to the IEEE standard definition [IEEE std (145-1983)], an antenna is defined as “a means for transmitting or receiving radio signals in the form of electromagnetic waves” [2].

Presently, the day to day life activities are dependent and supported by the versatility of wireless connectivity. Most of the present communication systems, such as mobile phones and laptops, are equipped with fixed-performing antennas having a fixed frequency, polarization, and radiation pattern. However, integrating several fixed characteristics antennas in a single device to support several communication services makes the device bulky, increases complexity, and reduces isolation between different wireless standards. Due to these limitations, the present modern communication systems require versatile electronic gadgets that can support high data rates, multiple radios, seamless connectivity, and many other advanced features. Additionally, as the technology advanced, the need for multifunctional and smart antennas that are adaptive to the changes in system requirements became apparent. Hence, the requirement of the current and future wireless systems has led the antenna designers to develop the antenna with flexible and controllable properties.

These antennas stand out as a transformative technology, offering adaptability and efficiency that a traditional fixed characteristics antenna can not match.

Over the last few decades, some innovative concepts of realizing the reconfigurability in an antenna have been investigated. Some of the most used techniques are– using individual excitation to each element, using a partial or full mechanical movement of the geometry, and utilizing a reconfigurable feeding network. Each technique has its own uniqueness and limitations, showing a new path to propose some novel ideas and design approaches to develop multi-functional and highly efficient reconfigurable antennas. The objective of this thesis is to develop some new design concepts to realize the compact, easy-to-control, and low-profile reconfigurable antennas with single and hybrid reconfigurability functions using a single antenna aperture to overcome the limitations and shortcomings of the existing reconfigurable antennas.

1.2 Overview of Reconfigurable Antennas

As per the IEEE standard definition released in 2014, the reconfigurable antenna is defined as “an antenna capable of modifying its performance characteristics, i.e., frequency, polarization, and radiation pattern in a controlled and reversible manner by using some electrical, mechanical or other means” [3]. These modifications are usually accomplished by redistributing the antenna surface currents, which alters the electromagnetic field and effective aperture of the antenna to produce the reversible performance characteristics of the antenna [4-5]. Thus, under this definition, the traditional beam steering and beam forming approach using the phased array antenna does not fall into the reconfigurable antenna category because their performance is controlled by the external phase shifters, while the basic operating mechanism of the antenna remains the same [4].

Reconfigurable antenna can address complex system requirements by modifying its structure and electrical behavior, thereby adapting to changes in environmental conditions

or system requirements (i.e., enhanced bandwidth, change in operating frequency, polarization and radiation pattern). The first patent on a reconfigurable antenna was reported by Schaubert in 1983, in which the concept of frequency reconfigurability and polarization diversity using the microstrip patch antenna was introduced [6]. After that in 1999, an organization, Defense Advanced Research Project Agency (DARPA, USA), launched a multi-university program among twelve well known universities and research institutes to investigate further the potential applications of the different types of reconfigurable antennas [7].

1.2.1 Classification of Reconfigurable Antennas

Reconfigurability in context to the antenna is described as deliberately changing its operational characteristics. Hence, depending on the property that is reconfigured, the reconfigurable antennas can be majorly classified into four categories, as shown in Fig. 1.1 [8].

1.2.3 Frequency Reconfigurable Antenna

The radiating element that possesses the ability to change its resonating frequency or notch frequency within a frequency tuning range is called a frequency reconfigurable antenna. Fig. 1.1 shows the presentation of tuning the resonating frequency of an antenna at different frequencies.

Frequency reconfigurability is realized by varying the electrical length of an antenna by means of electrical switching or material tuning. These antennas are useful for interference filtering because of their dynamic frequency behaviour. Thus, frequency reconfigurable antennas can replace the requirement of multiple fixed performing antennas (FPAs) in different applications scenarios where multiple single characteristics antennas are used separately to cover different wireless standards.

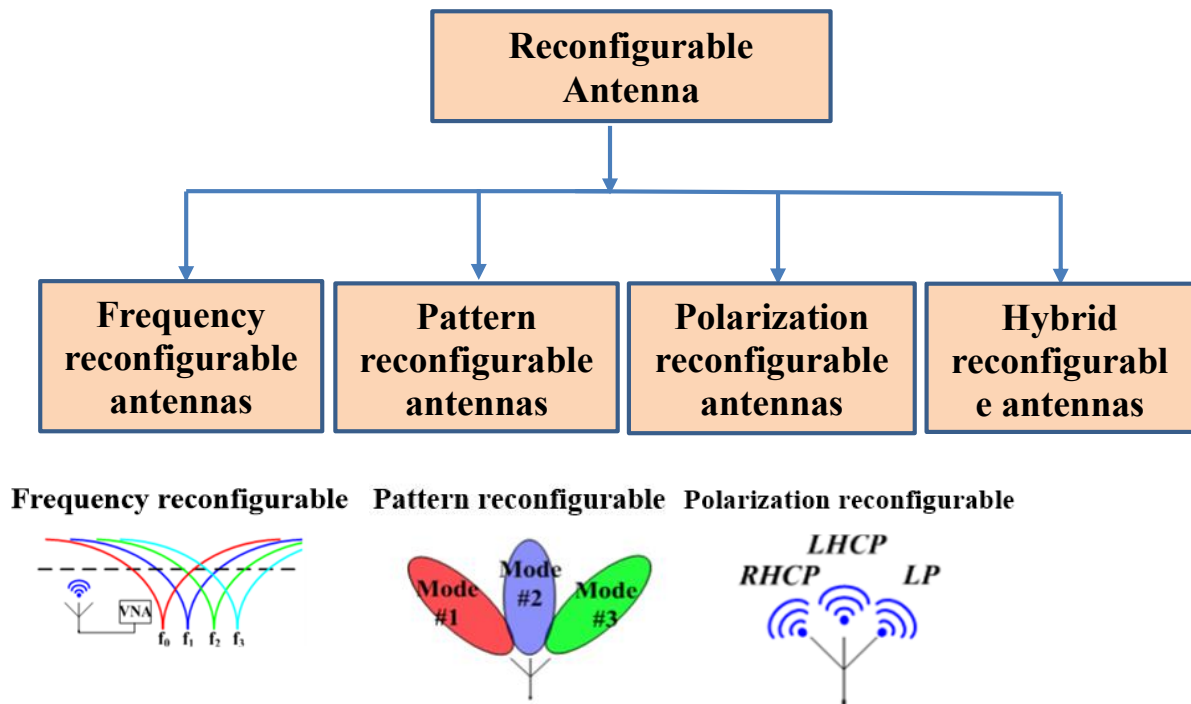


Figure. 1.1: Classification of reconfigurable antennas.

1.2.1.2 Pattern Reconfigurable Antenna

Another useful characteristic of the antenna is the radiation pattern. A radiating structure that is able to change its radiation pattern in terms of shape, gain, and direction is named as radiation pattern reconfigurable antenna. These antennas have the ability to switch their main beam or null direction. These antennas can be a good candidate for greater pattern coverage. Additionally, by adjusting the direction of the beam towards the intended direction, the performance of the communication systems can be greatly enhanced by avoiding interference, improving security, and saving the system energy [9].

Pattern reconfigurability from an antenna can be realized by deliberately modifying the spherical distribution of its radiated field by adapting the switchable parasitic elements, switchable feeding network, and mechanical movement of the geometry.

1.2.1.3 Polarization Reconfigurable Antenna

A polarization reconfigurable antenna is a type of reconfigurable antenna where the polarization of the antenna can be reconfigured while maintaining the frequency and pattern characteristics of the antenna. Polarization of the antenna can be switched from horizontal

linear polarization to vertical linear polarization, or right hand to left hand circular polarization, or from linear to circular polarization. Usually antenna radiates in a pre-defined polarization mode, which is determined by the orientation of the electric field in the direction of the wave propagation. To avoid the loss of the signal, the transmitter and the receiver should have identical polarization. Polarization reconfigurable antennas improve the capability of the wireless communication system by reducing the fading losses caused due to the multipath effects, reducing the interference, and ensuring strong signal reception [10].

Polarization reconfigurability can be realized using different feeding arrangements, material tuning, or structural changes.

1.2.1.4 Hybrid Reconfigurable Antenna

The last classification of the reconfigurable antenna is the hybrid or compound reconfigurable antennas where multiple reconfigurability can be derived using the same antenna aperture by different control mechanisms. Hybrid reconfigurable antennas can alter their operating frequency with change in the polarization mode or can scan the radiation beam with change in the operating frequency or polarization or it can also change all three characteristics frequency, polarization, and radiation pattern simultaneously.

1.3 Advantages and Disadvantages of Reconfigurable Antennas

Reconfigurable antennas have the ability to support more than one wireless standard and thus provide a performance similar to multiple antennas. Therefore, reconfigurable antennas have the following advantages [5, 11-13]:

1. Since these antennas can support more than one wireless standard, it minimizes the cost, volume requirement, and simplifies the integration within the system. It also improves the isolation between different wireless standards.
2. Due to its multifunctional capabilities, it can act as a single element or as an array,

provide both narrowband as well as wideband response, and can change its functionality according to the system requirements

3. Provides good out of band rejection and reduced front end-processing.
4. Suitable candidate for software defined radio because of its ability to learn and adapt to new surroundings.
5. A single reconfigurable antenna can replace the requirement of multiple antennas, therefore reducing the number of required antennas and having simplified associated circuitry and low circuit losses.

While reconfigurable antennas are potential candidates for wireless and space applications.

Still, there are some disadvantages associated with it, which are summarized below as:

1. Increased the complexity of the antenna geometry due to the addition of the biasing circuits for activation and deactivation of the switches.
2. Increased the cost of the system due to increased power consumption, which comes from the incorporation of the active switches in the antenna circuit.
3. Requirement of fast switching or tuning in the antenna output radiation characteristics to ensure the proper functioning of the antenna.

1.2.3 Design Techniques of Reconfigurable Antennas

Design techniques to implement reconfigurability in an antenna can be grouped into four major categories as shown in Fig. 1.2. Reconfigurable antennas implemented using radio-frequency micro-electromechanical systems (RF-MEMS) [14-17], PIN diodes [18-22] and varactor diodes [23-25] to alter their surface current distribution are called electrically reconfigurable. While antennas based on photoconductive switches [26, 27] are called optically reconfigurable antenna. Physically reconfigurable antennas can be derived by modifying the structural geometry, position and orientation of the antenna [28].

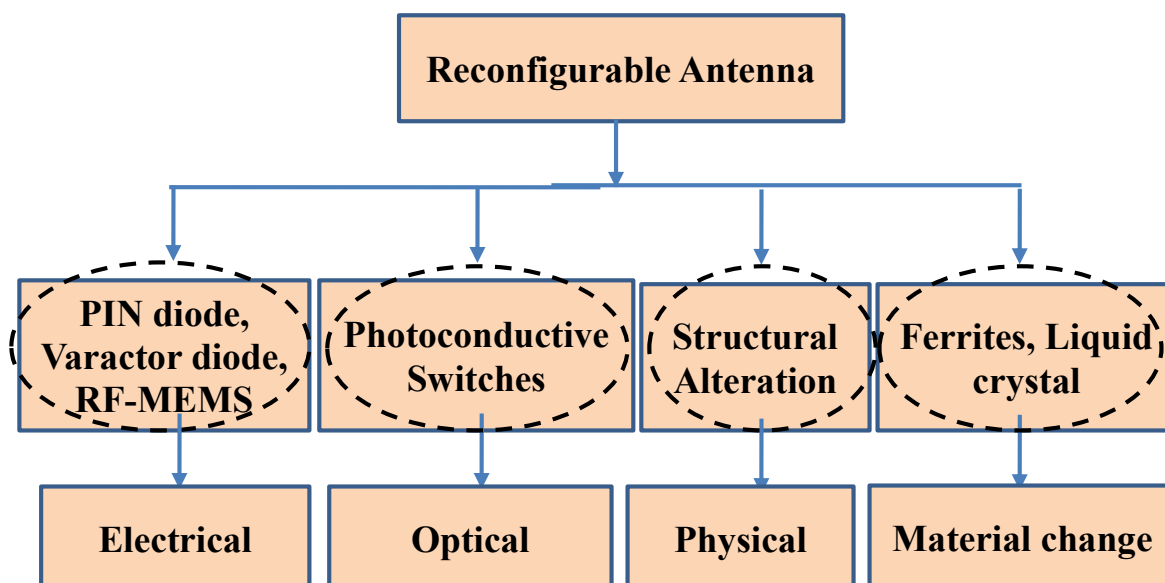


Figure 1.2: Various design techniques to realize reconfigurable antenna.

Finally, reconfigurable antennas can also be implemented using smart materials such as ferrites and liquid crystals [29, 30]

1.2.3.1 Electrically Reconfigurable Antennas

Reconfigurable antennas are realized with electronic switching components such as PIN diodes, varactor diodes, and RF-MEMS to redistribute the antenna surface current by altering the antenna structural geometry or radiating edges. The ease of integration of switching components with the antenna structure to achieve the desired reconfigurability functions has attracted antenna designers to design electronically reconfigurable antennas despite of having the numerous issues associated with these antennas. These issues include the losses, interference, nonlinearity of the switching components, and adverse effects of biasing circuits used to control the switching states of the switches on the antenna radiation characteristics.

PIN diodes are widely used semiconductor microwave switches in electrically reconfigurable antennas [31]. It consists of a lightly doped intrinsic layer sandwiched between heavily doped p-type and n-type regions. PIN diodes offer very low resistance in forward bias and offer high resistance, resulting in an open circuit in reverse bias. The PIN

diode is a current controlled device and has good power handling capability. Due to their low cost and less switching speed, these diodes are very popular in the RF industry. They are easily available in many packages with various dimensions. High power consumption is one of the major drawbacks of PIN diodes.

Varactor diodes are another widely used switch in electrical techniques. Unlike PIN diodes, these diodes have a very thin depletion layer that works as an insulating layer, and the P- and N- region acts as conducting plates. Varactor diodes can vary their junction capacitance with changes in applied bias voltage, which is used for continuous frequency tuning of the antennas. Since the width of the depletion region decreases with an increase in the reverse bias voltage, and hence junction capacitance decreases with increased reverse bias. Like PIN diodes, they also require a DC power source for activation of switches. The advantages of varactor diodes are low DC power consumption, low series resistance in reverse bias, and a wide range of tuning capacitance. The major drawbacks of these diodes are low power handling capability and high value of series RF resistance used to limit the DC current for biasing, which reduces the efficiency of the system.

The last category in this technique is the RF-MEMS switches. MEMS switches are small mechanical switches built on substrates such as silicon, quartz, and glass [16]. Unlike the PIN diodes and varactor diodes, MEMS switches are mechanical switches.

Compared to PIN diodes and varactor diodes, the MEMS switches have the advantages of low power consumption, high isolation, low insertion loss, and a wide range of operating frequencies. Despite of having several advantages, these switches have some limitations, such as higher cost and size, high losses, and limited power handling capability [32].

1.2.3.2 Optically Reconfigurable Antennas

An optically reconfigurable antennas are designed employing the optically controlled switch as a switching mechanism. An Optically controlled switch is formed by the

movement of electrons from the valance band to the conduction band when a laser light of appropriate wavelength incident on a semiconductor material such as silicon or gallium arsenide.

The major advantages of integrating optical switches are their linear behaviour and the absence of biasing circuits, which lead to interference with antenna radiation characteristics. The need for a stable and controllable source of light for the activation of these switches on the antenna structure is the main concern of this reconfiguration technique.

1.2.3.3 Physically/Mechanically Reconfigurable Antennas

This section discusses the alternative techniques to implement the reconfigurable antennas. The reconfiguration technique, which does not rely on any switching element, and uses some actuators, motors, or some other mechanical tools to move some part of the antenna structure, is called physical reconfigurable antennas. The movement of any part in the antenna structure changes the antenna radiating edges, which results in the change of surface current or electromagnetic fields on the antenna that alters the desired operating characteristics of the antenna.

The importance of this technique is that it does not require any switching components, biasing lines, or the integration of any laser diodes. However, the requirement of driven actuators for controlling the mechanically reconfigurable antennas can be power consuming and bulky in size, and hence, the miniaturization of these actuators needs attention while using this technique. The tuning speed of actuators is definitely slower than any other switching component, and yet it is proven to be sufficient for most applications.

1.2.3.4 Reconfigurable Antennas Based on Smart Materials

To reconfigure antenna characteristics, antenna engineers have also resorted to certain material characteristics such as graphene, liquid crystals [29], and ferrites [30]. Changes in

the material characteristics such as electric permittivity or magnetic permeability, results in desired antenna reconfigurability.

For example, the dielectric constant of the liquid crystal, which is a nonlinear material, can be varied by changing the orientation of the liquid crystal molecule under the different applied voltages. Similarly, an applied static electric/magnetic field can alter the relative material permittivity or permeability in ferrites.

1.2.3.5 Comparison Between Various Reconfiguration Techniques

A comparison between various techniques is presented in Fig. 1.3. Electronic switching is the most widely used technique to reconfigure antennas. One of the major advantages of electronic switching components is their good isolation, low loss, and easy integration into the antenna. Although RF-MEMS emerges as an innovative switching mechanism, yet their response is slower than the PIN and varactor diodes, which have a response time of the order of nanoseconds [33-34]. Therefore, all these switching elements facilitate the versatility of reconfigurable antennas.

The fully functional operation of these switches requires the biasing lines, which may have adverse effects on the antenna radiation pattern and it contribute more losses to the antenna. As the number of switches increases, the complexity of the antenna structure increases due to the need of additional biasing components, which increases the power consumption of the whole system.

Compared to electrical switches, especially RF-MEMS, optical switches represent a reliable reconfiguration mechanism. The excitation of the optical switches through the light from the laser diode does not produce any harmonics or intermodulation distortion due to their linear behavior. Additionally, the photoconductive switches are integrated into the antenna without any additional biasing circuits, which eliminates radiation pattern

distortion, losses, and unwanted interference. Despite of having all these advantages, they require a complex excitation mechanism and exhibit lossy nature.

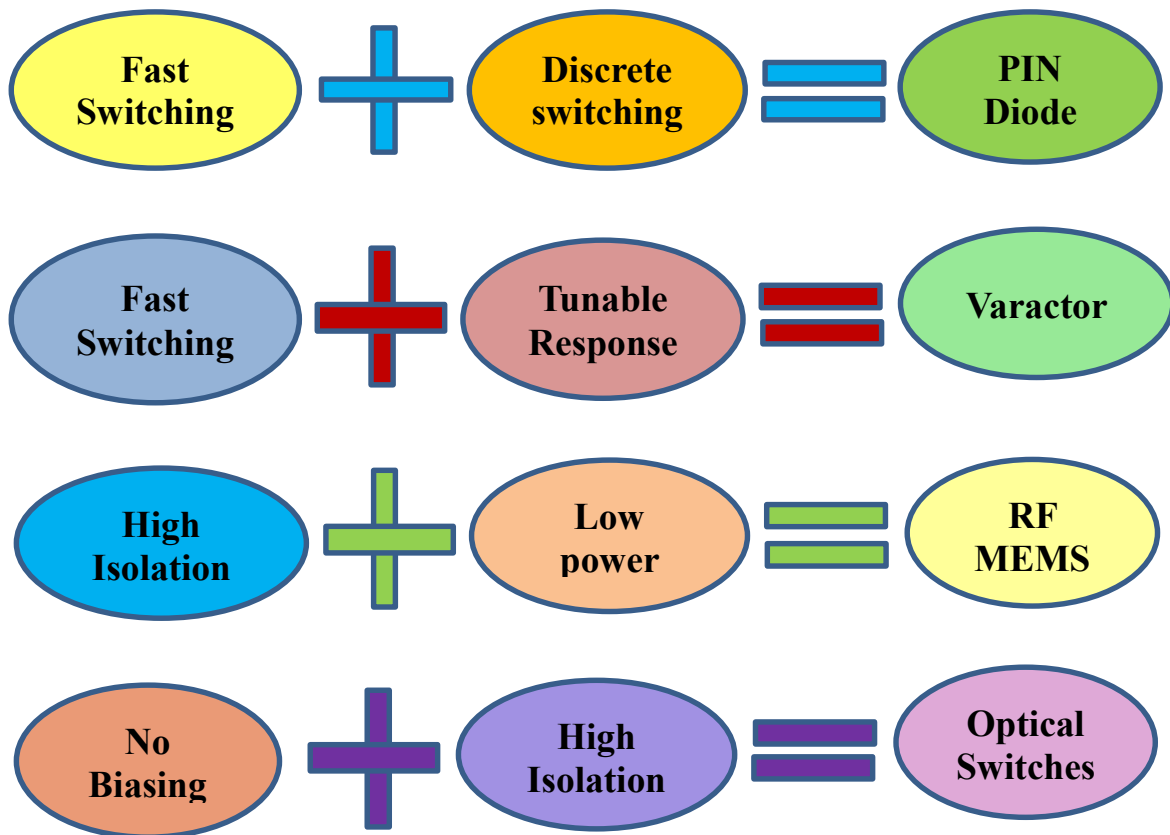


Figure 1.3: Comparison between different design techniques [11].

The physical/mechanical technique does not require any bias line or laser diodes or optical fibers. However, their extra power source requirement, cost, size, complex integration and slower response are the major drawback.

The advantage of ferrite or liquid crystal-based antennas is their smaller size that is due to their higher relative permittivity and permeability. Low efficiency is the main disadvantage of this technique which is usually a common concern at microwave frequency for both ferrites and liquid-crystal-base antennas

It is very important to identify the best reconfiguration technique for each application. The choice of the reconfiguration technique should be such that it should satisfy the several constraints of the application for which the antenna is designed. Therefore, it is the sole

decision of the antenna designer to select the appropriate reconfiguration technique for a particular application.

1.2.4 Application of Reconfigurable Antennas

Reconfigurable antennas can be used to cover different wireless standards that are spread over a wide frequency range. These antennas are used in several applications, including cognitive radio, MIMO systems, biomedical applications, satellite applications and industrial and military applications. The cognitive radio (CR) uses frequency reconfigurable antennas to improve spectrum efficiency. While the MIMO system utilizes pattern/polarization reconfigurable antennas. This section discusses some applications of reconfigurable antenna in detail.

1.2.4.1 Frequency Reconfigurable Antennas for CR System

The demand for huge frequency spectrum is increasing due to the rapid growth in communication systems, which leads to a shortage in RF spectrum. Mainly, the shortage in RF spectrum arises due to limited frequency spectrum allocation. Therefore, to overcome this communication problem, cognitive radio systems are used, which effectively increases the frequency spectrum utilization.

The cognitive radio system minimizes interference with the other wireless systems and increases spectrum usage efficiency by monitoring the unused frequency spectrum within the fixed frequency spectrum that is not occupied by the wireless systems. The sensing of the available frequency spectrum is the key feature of cognitive radio. This capability of the cognitive radio system can be achieved by using an “ultra-wideband (UWB) sensing antenna, which continuously searches for unused carrier frequency in the RF spectrum, and a “reconfigurable antenna” to transfer the data between transmitter and receiver.

1.2.4.2 Pattern Reconfigurable Antenna Applications

With the ability to change radiation patterns according to the requirement, pattern reconfigurable antenna is a potential candidate for various wireless applications such as vehicle to vehicle communication, radar and satellite applications, and tracking and remote sensing. Beam scanning and placing the null in the desired direction are the most attractive feature of these antennas. To maintain the strong and stable line-of-sight (LOS) between the portable devices the moving wireless devices, beam scanning antennas can redirect their stable and high gain pattern in the targeted direction.

Another targeted application of pattern reconfigurable antennas is MIMO systems. A MIMO system employs multiple antennas at both the transmitter and receiver ends. The advantages of using such configuration is that it increases the communication spectral efficiency in a multipath environment by sending the multiple copies of the same information simultaneously. Use of pattern/polarization reconfigurable antenna gives another degree of freedom to improve link capacity, minimize the spatial correlation of the system and thus improve the system performance.

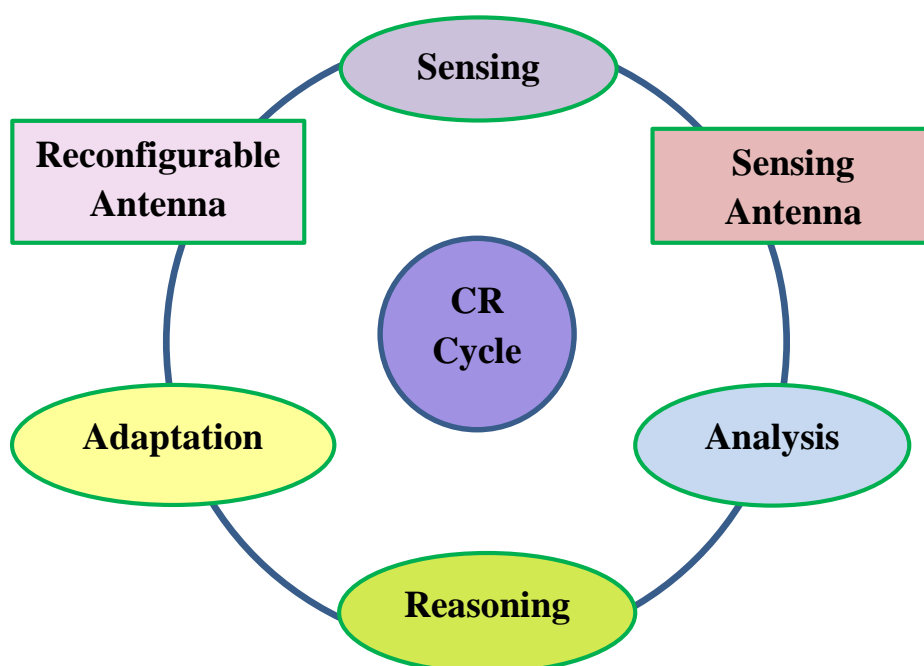


Figure 1.4: A cognitive radio cycle.

1.2.4.3 Polarization Reconfigurable Antenna Applications

Polarization reconfigurable antennas are very promising candidate in a multipath environment to reduce the signal losses due to the polarization mismatch between the transmitting and receiving antenna. Polarization reconfigurable antennas minimizes the fading losses caused by the multipath effects. Additionally, because of its switchable orthogonal polarization it can also be exploited for a dual transmission channel for frequency reuse. One such application is shown in Fig. 1.5 (a), where two separate channels can operate in same frequency band for different applications due to the orthogonality of the two CP components. One LHCP carrier signal can handle positioning or data transfer at frequency f_0 and other RHCP signal can be used for telecommunication at the same frequency f_0 .

Another application scenario of polarization reconfigurable antenna is shown in Fig. 1.5 (b) for body-centric wireless communication system application where on-body implantable device, communicating with the external or receiver antenna may experience polarization mismatch due to random orientation of the implantable device and complex indoor environment. In such complex environment, polarization mismatch can be easily avoided by using the polarization reconfigurable antenna having the dual or multi-polarized capability.

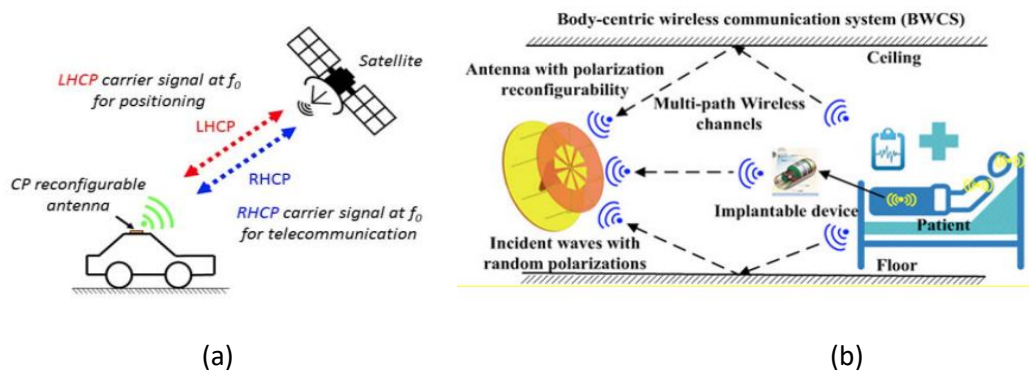


Figure 1.5: Application scenario of polarization reconfigurable antenna. (a) reconfigurable CP antenna for satellite application [35], (b) polarization reconfigurable antenna for body-centric wireless communication system [36].

1.2.4.4 Hybrid Reconfigurable Antenna Applications

Compound reconfigurable antennas are well suited for the scenario where the multiple operating conditions or communication standards are need to accommodate. For example, frequency reconfigurability combined with the pattern reconfigurability can be used to enhance the spectral efficiency of the system by shifting the frequency to the less congested area in the spectrum and steering the beam in different target direction simultaneously. This way interference suppression can be achieved by using the frequency selectivity for out of band interference filtering and pattern selectivity to suppress the in band interference rejection. Further in adaptive MIMO system, the pattern and polarization diversity feature of the pattern and polarization reconfigurable antennas can be explored to improve the system capacity.

1.3 State of the art Review on Reconfigurable Antennas

With the advancement of the wireless technology, antenna with adaptability and multiple functionality are of great interest among the antenna designers. Extensive research has been performed to explore the reconfigurable antennas by means of different design techniques discussed. This section presents a brief literature review on different types of reconfigurable antenna using the electrical technique, which is related to the scope of this thesis.

1.3.1 Pattern Reconfigurable Antenna

Pattern reconfigurable antennas utilizes different switching techniques to redistribute the antenna surface current to control the antenna radiation characteristics. The varactors diodes are used for the continuous beam steering while the switches like PIN diodes and MEMS are employed to design the discrete beam switching antennas. Maintaining a good impedance matching while altering the current distribution at different reconfigurable states, is a great challenge in designing these antennas. Generally, radiation pattern reconfigurability can be achieved in two ways: 1) shifting the main beam in different

directions or 2) changing the shape of the beam. There is extensive research have been carried out on the design and development of the beam steering antenna.

One of the most adopted method is using switchable parasitic element with the driven element [37-39]. This method does not affect the input impedance of the driven antenna because there is no electrical contact between the two. The direction of the beam shifted due to the coupling currents between the parasitic and the driven element. In [37], a linearly polarized pattern reconfigurable microstrip parasitic array was designed at 2.4 GHz with pattern directed at three different angles 0° and $\pm 30^\circ$. The antenna structure consists of one driven dipole and two parasitic strips loaded with two copper strips for pattern switching. By controlling the gaps on the parasitic elements using the copper strips, the parasitic can work as either director or reflector similar. Based on the same concept one more parasitic array is designed at 5.6 GHz in [38] having the beam direction of 0° and $\pm 25^\circ$. Instead of using the copper strips this antenna employed MEMS switches to reconfigure the pattern at three different directions. In [39], a slot loaded Yagi-patch antenna with one driven element and four slot loaded parasitic elements was proposed. The proposed antennas can direct its radiation beam in E-plane at different frequency bands by changing the states of the switches installed on the slots etched on the parasitic elements. Three radiation direction at -7° , $+33.5^\circ$ and -40° with common impedance bandwidth from 9.15-9.45 GHz and other two modes with the beam direction of $+58.5^\circ$ and -62.5° at 10.3 GHz were achieved.

In [40], a rectangular spiral antenna with four switches over a high impedance surface (HIS) was designed for pattern reconfigurable applications. Nearly 360° beam scanning was realized by using various possible combinations of the switches. In [41], a single-feed microstrip antenna having patch-slot-ring structure with a capability to steer its beam in four different directions i.e., 65° and 130° at elevation plane and 20° and 335° at azimuth plane was designed. The antenna structure consisted of one inner patch, one outer patch and a ring between the inner and outer patch. The inner patch was excited by a coaxial

probe at the center of the inner patch. By modifying the current distribution on the microstrip ring and patch using the PIN diode switches, beam shaping was achieved. A beam steering microstrip patch antenna with a U-slot was designed for wearable fabric applications [42]. The antenna was designed on the fabric substrate at 6 GHz. Using the proximity coupled feeding technique and U-slot, three different beam directions of 0° , $+30^\circ$ and -30° was reconfigured.

In [43], a pattern reconfigurable design based on the two element dipole array model was designed. Initially a two element dipole loaded with varactor diode was investigated. Further, its pattern characteristics were studied and explained through the phased array theory. Finally, a patch top-loaded monopole pattern reconfigurable antenna was designed to steer its beam from -28° to $+28^\circ$. In [44], a partially reflecting surface (PRS) antenna was designed for beam steering applications. Beam steering mechanism was employed by using a non-uniform partially reflecting surface with two-element microstrip patch antenna phased array to achieve variable reflection phases. Reconfigurable PRS structure employs 6×6 non-uniform square patch cells with two PIN diodes on each cell, which were divided into left and right parts with respect to the center of the structure. Due to the reflection phase inconsistency between the two parts of the PRS structure realized by switching the diodes states, a consistent beam steering from -15° to $+15^\circ$ was achieved. In [45], a grounded square patch antenna with four ports was designed to generate twelve radiation beams of different shapes and directions. These are eight tilted beams, two tilted conical beam, one semi-donut beam and one axial beam generated by using either single or multiport feeds and the three external phase shifters.

In 2018, a beam steerable slot antenna with wideband characteristics using the artificial magnetic conductor (AMC) was designed. It consists of a cross-shaped driven radiating slots, two parasitic slots with PIN diodes working as a reflector or director and an AMC surface. The electrical length of the driven slot was chosen as one wavelength for wideband

operation. The AMC surface, working as a reflector was added to achieve the unidirectional radiation pattern with high gain and low back lobe. By turning the states of the PIN diodes ON/OFF, the main lobe of the radiation pattern was switched among 0° , $+36^\circ$ and -36° [46]. Further, a pattern switchable antenna with multi switchable beam from right end-fire ($+90^\circ$), 45° , boresight (0°), -45° to left end-fire (-90°) was designed by reconfiguring the parasitic striplines using PIN diodes around the radiating dipole and reflecting metal piece under the dipole [47]. Again in 2019, a magneto-electric dipole antenna was designed using the Huygens source theory. Magneto-electric dipole antennas create unidirectional radiation pattern with superposition of the electric and magnetic dipole. Thus, if the radiation pattern of any one dipole changes the overall radiation pattern would change accordingly. A beam steering of $\pm 26^\circ$ was achieved by controlling the effective length of the two arms of the dipole [48]. In the same year, a beam steering antenna based on the phase gradient metasurface was presented. Seven different high gain switched beams at 0° , $\pm 7^\circ$, $\pm 15^\circ$ and $\pm 23^\circ$ were realized using the phase gradient surface as the multifunctional radome [49].

In 2020, a circularly polarized 2-bit reconfigurable beam-steering antenna array was proposed. By cascading a 90° digital phase shifter with the patch antenna four quantized phases (0° , 90° , 180° and 270°) required for the 2-bit element were realized to get the beam steering from -49° to $+49^\circ$ [50]. Further, one more pattern reconfigurable antenna array, having omnidirectional, bi-directional, and scanning beam, was proposed using circularly polarized antenna elements. A 3-D array was developed using the CP element and pattern reconfigurability was obtained by stacking the four subarrays in a sequential-rotation manner [51]. Further, in the same year, a switched-beam bow-tie antenna with a beam shift at -25° , 0° and $+25^\circ$ was developed. The bow-tie antenna was divided into three collocated sub-bow-tie arms and connected with feed using six PIN diodes. The disconnected bowtie worked as a parasitic for the excited bow tie and reflected its electric field towards the

direction of excited element to steer the radiation pattern [52]. Thereafter, in 2021, a shared aperture planar quasi-yagi antenna with high isolation and compact size was proposed using coplanar waveguide structure with even-odd mode feedings. After that pattern diversity with four different radiation patterns (omnidirectional, broadside and two tilted beams) was realized by controlling the feeding states of the quasi-Yagi antenna. The pattern diversity also yielded different polarization beam which was limitation of the work [53]. Further a metamaterial inspired pattern reconfigurable antenna with cross slot couple feeding structure and T-shaped slot as a director on the ground plane was presented to achieve wide bandwidth and high isolation for 5G application. Further, T-shaped director slot loaded with PIN diodes was explored to realize pattern tuning among -30° , 0° , $+35^\circ$ [54]. A pair of folded dipoles, a microstrip-to-via feeding balun and two reconfigurable parasitic strips excited with near field dipole pair to reconfigure among three modes of operation including, one omnidirectional and two unidirectional radiation modes was utilized. Four pairs of PIN diodes were utilized to redistribute the surface current on the parasitic strips to achieve the desired mode of operation [55]. Followed by, Wenjin Li introduced a simple loop patch antenna to generate conical and broadside reconfigurable beams for indoor applications. Two different radiation modes was achieved by slotting the loop patch antenna and analyzed by the characteristics mode analysis. Further to achieve the reconfigurability, a reconfigurable feeding network was designed to switch among the two radiation modes [56].

A literature review on the pattern reconfigurable antenna is carried out based on which chapter 2 of the thesis is presented.

1.3.2 Polarization Reconfigurable Antennas

Polarization reconfigurable antennas play a special role in communication due to its ability to mitigate interference, improve signal quality and adaptive to changing scenarios.

Especially, the switching of circular polarization is very important aspect of these antennas in a multipath environment due to their insensitivity to transmitter/receiver orientation and it also reduces the transmission loss occurred due to the misalignment of a static and a mobile terminal. Several techniques have been employed to switch polarization among linear polarization (LP) to circular polarization (CP) or right-hand circular polarization (RHCP) to left-hand circular polarization (LHCP) and vice versa or to generate multi-polarization.

In 2002, a reconfigurable patch antenna with LHCP and RHCP was proposed [57]. Two orthogonal slots with two PIN diodes were utilized to switch the polarization. -10 dB impedance bandwidth from 4.5 GHz to 5.1 GHz and 3 dB axial ratio bandwidth of 3% from 4.6 GHz to 4.7 GHz was achieved. After that a corner truncated square microstrip patch antenna was designed to achieve three polarization states i.e., LP, LHCP and RHCP by connecting or disconnecting the triangular corners from the patch using PIN diodes [58]. The proposed antenna had the 1.5% impedance bandwidth combining all modes. However, the AR data of the antenna was missing in the literature.

In 2008, a single feed circular microstrip antenna with reconfigurable polarization capability was proposed. A radiating circular patch, five PIN diodes, three matching stubs and a 50 ohm microstrip line was used to generate four reconfigurable states with two state for LP, one state for LHCP and one state for RHCP. Besides three matching stubs were used for matching every polarization states [59]. An U-slot microstrip antenna with polarization agility was proposed for wireless local area network (WLAN) applications. The length of the slot was made tunable by adding the PIN diodes to alter the polarization states. Two separate antennas for switching the polarization between LP and CP and between the LHCP and RHCP were demonstrated to achieve the common impedance bandwidth of 2.8% for both -10 dB impedance bandwidth and 3 dB AR bandwidth [60]. Further, an X-shaped slot was etched on the single feed rectangular cross-shaped microstrip

patch antenna to switch the polarization between LP and CP by changing the shape of the slot according to the states of the PIN diodes. The proposed antenna had the operating bandwidth of 18 MHz for both LP and CP [61]. Followed by, a reconfigurable patch antenna with three polarization states LP, LHCP and RHCP was proposed and sense of polarization was controlled by perturbing the direction of currents on the two loop slots in the ground plane with the help of two PIN diodes. -10 dB impedance bandwidth for both LP and CP mode was 30 MHz and the 3 dB axial ratio bandwidth for both CP states was 20 MHz [62].

Further, a circular polarization reconfigurable wideband E-shaped patch antenna for wireless communication was presented. The antenna was capable to switch its polarization from LHCP to RHCP and vice versa. Two RF switches were placed on the slot region in E-patch antenna. When one switch is OFF and other is ON the two slots lengths become unequal, thus circular polarization was generated due to the asymmetric slots lengths. The antenna had the operating bandwidth of 7% from 2.4-2.57 GHz [63]. A polarization reconfigurable metasurface antenna was proposed by placing a metasurface on top of a slot antenna without any air gap to make the antenna compact. By rotating the metasurface around the center with respect to the slot antenna, the three polarization modes with linear polarization, left-hand and right-hand circular polarization was achieved. An operating fractional bandwidth of 11.4% from 3.3-3.7 GHz was achieved [64]. Further a stacked square-ring patch antenna was proposed with quad polarization diversity. A 1-to-4 reconfigurable feeding network with quasi-lumped quadrature coupler (QLQC) and 6 PIN diodes was used for polarization switching. By controlling the DC voltages of these PIN diodes, the feeding network was realized with four different excitation methods to realize four different operating modes to generate a specific polarization [65]. Further, a rhombus shaped patch, a Y-shaped feedline and two PIN diodes were utilized to achieve polarization reconfigurability. Two PIN diodes were inserted in the gap between rhombus-shaped patch

and Y-shaped feedline and one of the diode was turned ON to realize either LHCP or RHCP modes. The 10-dB reflection coefficient bandwidth of 5.62% and 3-dB axial ratio bandwidth (ARBW) of 2% was achieved [66]. A polarization reconfigurable mechanism based on a polarization-rotation artificial magnetic conductor (PRAMC) surface was proposed. A multi-polarized dipole antenna, PRAMC surface and a simple reconfigurable network using RF-integrated circuit (RFIC) switches was utilized to reconfigure the polarization among LHCP, RHCP and $+45^\circ$ LP respectively. A 3-dB axial ratio bandwidth of 15.5% and impedance bandwidth of 20.5% was obtained [67].

In 2016, a partially reflecting surface antenna was introduced to switch its polarization electronically among LP, LHCP and RHCP. An annular patch antenna as the source element, a PRS surface to enhance the gain and a reconfigurable Wilkinson power divider loaded with PIN diodes as the feed network was utilized to reconfigure the polarization. An overlapped 10-dB impedance bandwidth and 3-dB axial ratio bandwidth of 13.1% from 4.7-5.36 GHz was achieved [68]. Further, an aperture fed patch array antenna was designed to realize $\pm 45^\circ$ polarizations. Initially a single patch antennas was designed by introducing a cross aperture on the ground to feed the patch antenna. For polarization switching four RF switches on the cross aperture was inserted. Further a 1×4 antenna array was demonstrated for $\pm 45^\circ$ linear polarization switching by controlling two DC voltages. A 9.3% overlapped impedance bandwidth for both polarization was achieved to cover 2.4 GHz WLAN band [69]. Further, a switchable cross-feed probe structure with three PIN diodes was used to excite the patch antenna with different polarization switching. By controlling the switching states of the PIN diodes three different polarization modes with LP, LHCP and RHCP were realized. A wide impedance bandwidth of 21% and axial ration bandwidth of 19% was achieved [70]. A reconfigurable cross dipole fed with coaxial baluns and a switchable feeding network was proposed to realize quad polarization diversity. The feed network consisted of power divider, a single pole double throw (SPDT) switch and a

90° delay line was utilized to feed the four port crossed dipole. The reconfigurable cross dipole having the vertical and horizontal polarization integrated with the switchable feed network reconfigured the antenna with $\pm 45^\circ$ linear polarizations, LH/RH CPs. More than 35% operating bandwidth was achieved for all four polarization modes [71]. Further a magneto-electric dipole antenna consisted of three pairs of horizontal rectangular patches, a Γ -shaped feed, a metallic cavity and four PIN diodes was used to design a reconfigurable antenna with tri-polarization states. Three horizontal patches were connected or disconnected by switching the diode states between ON and OFF to excite the LP, LHCP and RHCP waves. An effective overlapped bandwidth of 39% was achieved for both $S_{11} \leq -10$ dB and $AR \leq 3$ dB [72].

In 2019, a quad-polarization reconfigurable antenna with omnidirectional radiation pattern was presented. The antenna consisted of a circular loop with four arc dipoles for horizontal polarization, top loaded monopole for vertical polarization and a broadband feeding network. Further, the left hand circular polarization and right hand circular polarization was achieved by simultaneously exciting the circular loop and top loaded monopole antenna in different phases using the additional $\lambda/2$ phase shifter with feeding network. An overlapped operating bandwidth of 26% was realized for both $S_{11} \leq -10$ dB and $AR \leq 3$ dB [73]. Further, a tri-polarization reconfigurable antenna based on the crossed dipoles and parasitic elements was presented. The presented antenna utilized two crossed dipoles fed by $3/4_\lambda$ squared ring to provide 90° phase shift, two feeding patches etched on the top and bottom side of the substrate and three sets of the parasitic elements. To enable the polarization reconfigurability four PIN diodes were embedded between each cross dipole and the feeding element. By controlling the states of the PIN diodes three polarization mode of LP, LHCP and RHCP was realized with an operating bandwidth of 48.6% for sub-6 GHz 5G application [74]. A cross H-shaped slot coupled reconfigurable antenna with mushroom-type metamaterial loading was designed having penta-polarization

modes using the characteristics mode analysis (CMA). By controlling the states of the PIN diodes on the dual port feeding network, the amplitude and phase difference between the two ports were dynamically controlled to realize the HP, VP, 45°-LP, LHCP and RHCP. An overlapped operating bandwidth of 28% was achieved for all modes [75]. A switchable feed network was utilized to operate the antenna in single fed and dual fed mode to realize four polarization modes. At single-fed mode the switchable feed structure provided required excitation for slant +45° linear polarization or -45° linear polarization and at dual-fed mode it worked as the switchable phase shifting power divider to produce left-hand or right-hand circular polarization. The antenna had the operating bandwidth of 230 and 260 MHz at CP and LP states, respectively [76]. Further, an odd number of dipoles with trapezoidal-shaped arms printed on both side of the substrate was adopted as the radiator to generate the smaller number of multilinear polarizations. Three different antennas with five, seven, and nine reconfigurable polarizations were designed and discussed. An overlapped bandwidth of 20.6%, 17.6% and 15.9% was achieved for five, seven, and nine LPs, respectively [77]. A polarization conversion partially reflecting surface (PRS) was utilized to reconfigure the polarization among HLP, VLP and 45° LP. Unlike the previous work [68], the proposed reconfigurable PRS surface worked as active polarizer and provided higher gain simultaneously. The designed polarization conversion PRS provided a stable reflection and polarization conversion for all polarization modes [78]. Further, a slot loaded circular patch antenna operating in TM_{31} mode was modified to achieve $\pm 45^\circ$ polarization states. Initially, two vertical slots were loaded to the edges of the circular patch to redistribute the antenna surface current to realize the stable broadside radiation with high directivity. Secondly, two horizontal and four fan shaped slots were introduced to reconstruct the circular patch for $\pm 45^\circ$ polarization. By optimizing the connection of fan shaped slots with the vertical and horizontal slots with PIN diodes three types of polarization states HP, VP and 45° LP with 5.7% operating bandwidth were realized [79].

1.3.3 Antenna with Hybrid Reconfigurability

It has been evident from the literature review of previous sections that several techniques have been proposed to design the antenna with single tunable characteristics. However, antenna with hybrid reconfigurability functions where any two of the three antenna characteristics (frequency, polarization and pattern) or all the three characteristics can be adjusted simultaneously are getting more attention in the rapidly growing communication environment to enhance the signal quality and for efficient use of the frequency spectrum. Multiple-parameter reconfigurability is much more complex because all the antenna parameters are interdependent and are sensitive to each other. Thus they offer a great challenge to design an antenna with multiple reconfigurable characteristics together. However, several efforts have been acknowledged to design the hybrid reconfigurable antennas with frequency and pattern reconfigurability, frequency and polarization reconfigurability and pattern and polarization reconfigurability. This section presents the previous work done on the pattern and polarization reconfigurable antennas, which is associated with the scope of this thesis.

In 2012, a microstrip antenna with pattern and polarization diversity was proposed. The antenna was fed through a four-way power divider made by three Wilkinson power dividers and interconnected with copper switches to realize the reconfigurability. The antenna could work in two modes. In mode 1, the radiating elements were excited in same amplitude and phase, a conical beam radiation pattern with linear polarization was achieved while in second mode, antenna was excited in equal amplitude and 90° phase difference to realize the circularly polarized broadside pattern [80]. A microstrip fed truncated monopole antenna with the ability to reconfigure its polarization in x-direction and y-direction and switching its omnidirectional pattern in XZ plane and YZ plane. This was achieved by using the two switchable monopoles arranged side by side with a common ground and activated alternatively to achieve the required pattern with switchable polarization. Thus

the antenna had the switchable omnidirectional pattern with the reconfigurable polarization in the two orthogonal planes [81]. Followed by, Chao Gu *et. al.* proposed a smart antenna with electronic beam-switching and reconfigurable polarizations. The antenna utilized a square patch antenna with polarization reconfigurability as the driven element and several printed dipole antennas with PIN diodes were used as a parasitic element for beam switching. By controlling the states of the PIN diodes three types of polarization including two orthogonal and one diagonal and switched pattern in different directions covering the azimuth plane from 0° to 360° was achieved [82]. Further, a compact patch array antenna with dual circular polarization and 2-D beam switching was developed. The array element consisted of a square driven patch with four truncated corners, connected with the driven patch through PIN diodes for polarization switching, a parasitic patch and three switchable feeding probes embedded with a single-pole triple-throw switch. Due to the spatial relative position of the three probes, individual excitation at three probes could generate 90° or 180° phase difference. Further, a 2×2 array was designed to reconfigure the pattern among nine different beams with dual circular polarization for each beam by selecting the different combination of the feed probes at each array element [83]. A stacked annular ring microstrip antenna element with the ability to reconfigure its polarization among $+45^\circ$, -45° , $+135^\circ$ and -135° was used to design a 2×2 array antenna to switch its pattern between broadside with $+45^\circ$ and -45° polarization and conical beam with horizontal and vertical polarization, respectively. Each radiating element of array operated in same polarization, a broadside pattern with narrow beam-width was generated and when the array element operated with polarization direction pointed inward or outward, resulting the microstrip antenna operated in TM_{01} mode generating conical beam radiation pattern with vertical polarization. Moreover, when the elements were arranged in sequential rotation polarization directions, a conical pattern with horizontal polarization was generated [84]. Further, a metal patch, feed part, four switches and four diagonal metal walls were utilized

to change the current distribution of the antenna to realize a pattern and polarization reconfigurability. The antenna had the ability to produce six radiation pattern modes and three polarization modes including one LP narrow beamwidth mode, one LP wide beamwidth mode, four LP directional beam and two CP wide beamwidth mode [85].

Further in 2021, a slot-fed electronically reconfigurable polarizer was realized based on the theory that a combination of linearly polarized antenna and a metal strip inclined at certain angle could generate circularly polarized radiation. The proposed polarizer was consisted of two cross dipoles printed on the top and bottom side of the substrate and excited through a microstrip coupled slot antenna. By controlling the states of the PIN diodes embedded in the middle of the dipole switching between two circular polarizations was realized. Based on the antenna element a 2×2 array with sequential rotation technique was developed to realize the broadside beam and a quasi-difference beam while operating the antenna in LHCP and RHCP polarization states [86]. A compound reconfigurable antenna with pattern and polarization diversities was designed using the reconfigurable metasurface antenna. The proposed antenna consisted of 3×3 square metasurface, a ring-shaped pixel structure, a square microstrip patch and a simple feeding network. Three different polarization was generated by exciting the two orthogonal degenerate modes due to the combined effect of the microstrip patch and 3×3 square metasurface while the pattern switching was achieved by loading the switchable annular pixel structure around the metasurface. The antenna had the ability to realize steerable beam directions of $\pm 40^\circ$ with horizontal polarization, $\pm 20^\circ$ with vertical polarization and $\pm 25^\circ$ with circular polarization [87]. In the same year, a dual polarized reconfigurable antenna with beam steering capability was proposed based on the reconfigurable parasitic layer approach. The proposed technique was based on the use of a pair of cross shaped parasitic strips interacting with the currents in the orthogonal direction generated from two orthogonal ports. The antenna could realize three main lobe directions of 0° , $+25^\circ$ and -25° for dual polarization [88].

Further, a metasurface antenna with multi-polarization and pattern reconfigurability was proposed. The proposed antenna consisted of two parts, including a loop antenna fed by feed network layer and a metasurface antenna excited by aperture coupling. Polarization and pattern reconfigurability were achieved by loading the PIN diodes on the feeding network and rotating the metasurface layer individually. An omnidirectional pattern with vertical and horizontal polarization was realized when the loop antenna was excited, while a directional pattern with left hand circular polarization and right hand circular polarization was realized when the metasurface antenna was excited [89]. A 3-D antenna array with pattern reconfigurability and multi-polarization ability was proposed by utilizing four vertically placed reconfigurable endfire dipole-pair and four-patch switchable feed networks. Based on the switchable operating dipoles and appropriate pathways on the feed network, the proposed antenna achieved 12-different operating modes including broadside patterns and backfire patterns with independent LHCP/RHCP, $\pm 45^\circ$ LP in the elevation plane and four endfire patterns with vertical polarization in azimuth plane [90].

A literature review on the hybrid reconfigurable antenna is carried out based on which Chapter 3 and Chapter 4 of the thesis are presented.

1.4 Objective and Scope of the Thesis

In today's scenario the demand of reconfigurable antennas has been greatly increased. Although many research techniques have already been explored to achieve various single or multiple reconfigurability functions in an antenna, yet there are still numerous drawbacks and some challenges, which need to be addressed to fulfil the current communication system requirements. Some of the major and current contributions are discussed in the literature review section. Many antenna designs require the placement of active components on the radiation layer to reconfigure the antenna characteristics, which degrades the antenna radiation performance [91]. Some of the design concepts required the

external matching network to maintain the good impedance matching while antenna is switching from one state to other. Due to such additional circuits the antenna suffers from large profile and encounter extra losses in the circuits. Other concerns that still need to address include: realization of hybrid reconfigurability functions using the single antenna structure while maintaining a stable performance across different states. Based on the literature review on hybrid reconfigurable antennas, it is observed that very limited work is done on the reconfigurable antenna with polarization and pattern reconfigurability. Besides, up to now, no work has been reported on the antenna with pattern reconfigurability and quad polarization diversity of HP, VP, LHCP, and RHCP. This thesis aims to build a new design methodology to address the discussed limiting aspect and fill the research gap in the literature. Hence the key problems that are deeply investigated in this thesis and their corresponding proposed solutions are summarized as follows:

1. *Design of a beam steering antenna*: The first objective of this thesis is to design a beam steering antenna for WLAN applications. In WLAN applications, the wireless access point should be able to cover the wide communication area. Widebeam antennas can be used in the wireless access point to cover the wide coverage area, but widebeam antennas suffer from low gain, which degrades the communication performance of the system. To avoid this, an antenna with switchable single and multiple beams can be a possible solution to cover a wide communication area. Therefore, in this thesis design of a compact, planar, electronically reconfigurable microstrip antenna array with beam steering capability is discussed.
2. *Integration of multiple reconfigurability with circular polarization agility and 1-D beam switching*: The reconfigurable antenna discussed in the early section of this thesis is a single parameter tunable antenna with all the switching components and biasing circuits placed on the radiation layer. The placement of switching components and biasing circuits on the radiation layer deteriorates the antenna

radiation performance [91]. A reconfigurable antenna with multiple parameter reconfigurability is more desirable for modern communication systems. Thus in the later section of the thesis, a circular polarization reconfigurable antennas array with 1-D beam switching containing a separate layer of the feed network, switching components and biasing circuits are discussed.

3. *Realization of multiple reconfigurability with quad polarization agility and 2-D beam switching*: The final goal is to realize a quad polarization reconfigurable antenna array and 2-D beam switching using a simple, low loss feeding network and a 2x2 stacked antenna configuration is addressed.

1.5 Thesis overview

This thesis is organised in five chapters as follows:

Chapter 1 presents the brief introduction on the reconfigurable antenna. A brief overview of reconfigurable antenna including background, classification, different techniques for implementing reconfigurability, their potential applications and advantages of implementing reconfigurable antennas are discussed. Further the current state-of-the-art review of various techniques for realizing the pattern reconfigurable antennas, polarization reconfigurable antennas and hybrid reconfigurable antennas are also discussed. Based on the review, some research gaps are identified and motivated to work on the area of single and hybrid reconfigurable antennas designed in this thesis. The objective and scope of the present thesis is also highlighted in this section.

Chapter 2 discusses about the design and implementation of 1×2 reconfigurable beam steering array antenna for WLAN applications (5.15-5.35 GHz) by utilizing a designed reconfigurable phase shifting feed network implemented using PIN diodes to provide the tunable phase difference between the array elements. The proposed antenna provides a satisfactory performance using a compact and planar structure.

Chapter 3 demonstrates the design of a circular polarization (CP) agile and beam switchable reconfigurable cavity-backed 1×2 array antenna by utilizing a previously designed phase shift feed network in chapter 2 and further integrated with four switchable feed probes for polarization reconfigurability. The proposed antenna provides switchable left hand circular polarization (LHCP) and right hand circular polarization (RHCP) along with the switchable beam for each polarization state.

Chapter 4 presents a design of a multifunctional quad-polarized 2×2 array antenna with 2-dimensional beam switching for 5G-sub 6 GHz application by utilizing a previously designed phase shift feed network in chapter 2 and further integrated with three switchable probes for each array element for quad polarization reconfigurability. The proposed antenna provides switchable vertical polarization (VP), horizontal polarization (HP), left hand circular polarization (LHCP) and right hand circular polarization (RHCP) along with the 2-D beam switching for each polarization state.

Finally, the **chapter 5** briefly summarized the concluding remarks and the investigations of all the previous chapters. The future scope related to the present research work is also emphasized in this chapter.

The overview of the present thesis is illustrated chapter wise in Fig. 1.6.

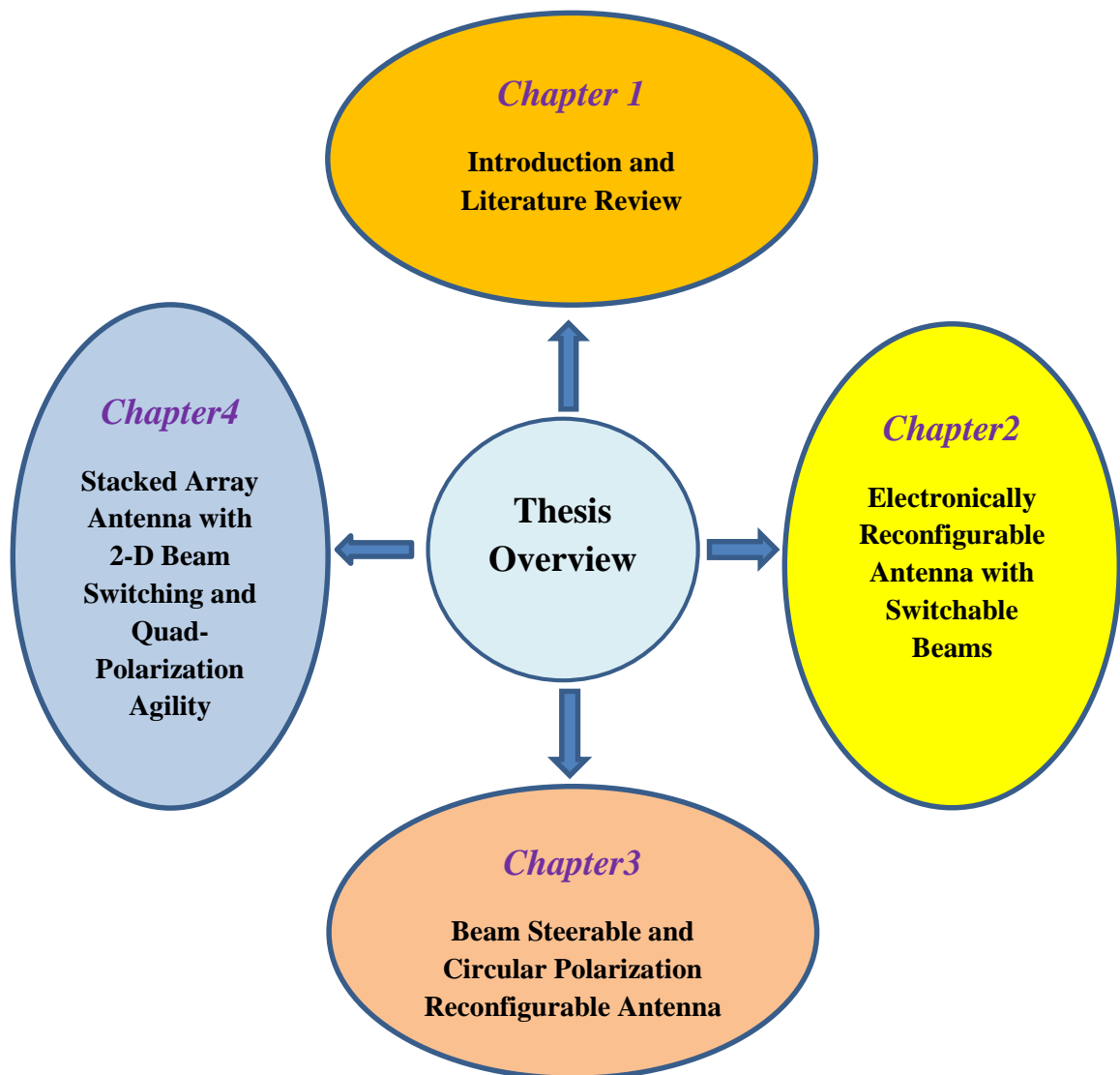


Figure 1.6: Overview of the present thesis work.