1.
INTRODUCTION

1.1 Introduction

In the present scenario of modern life style, there is an immense demand of compact communication devices that provide fast wireless communication. This demand has necessitated rapid advancement in modern high speed wireless communication technologies as well as radar and navigation system which continue to bring more challenges for design and development of compact broadband antennas. The growing challenges of designing compact broadband antennas have become vital and interesting area of research for many scientists and researchers. The broadband antenna is a key element of any high speed wireless communication system. It has the property of providing higher data rate because of its wider operating frequency range. According to Shannon's channel capacity theorem, the data rate increases linearly with increase in channel bandwidth while similar increase of capacity requires exponential increase in signal to noise ratio (SNR).

$$C = BW \times log_2(1 + SNR) \tag{1.1}$$

where *C* is the channel capacity (bit/second), *BW* is the bandwidth (Hz), and *SNR* is the signal to noise ratio. Further, according to equation (1.2) given below, the time delay 'τ' required for signal transmission is reduced when channel bandwidth is increases.

$$\tau = \frac{1}{BW} \tag{1.2}$$

The antenna that can provide acceptable and stable performance over wider range of frequencies is known as broadband antenna. Initially, its requirement was noticed for military aircraft because of the problems associated with integration of different antennas along with increasing number of electromagnetic systems and equipment required for different electromagnetic applications. Also, proper positioning of multiple antennas was a very serious issue. Due to these issues, the necessity of a single broadband antenna which could serve multiple applications and frequencies was recognized. Several broadband antennas [Jordan *et al.* (1964)] have been designed and developed in this regard. The broadband antennas designed and fabricated during initial developmental stages are bulky and have three-dimensional structure. The frequency independent antenna (FIA) [Rumsey (1957)] discovered by V. H. Rumsey is a broadband antenna that can be designed for theoretically infinite bandwidth. Many unconventional antenna structures were developed with the concept of FIA which include log-periodic, spiral, and sinous antennas. Since the development of microstrip patch antenna (MPA) many planar antennas got attention because of their inherent properties. The MPA has a limitation that it offers narrow bandwidth [Pozar (1992)]. This limitation of narrow bandwidth has been overcome by planar antennas having partial ground plane and different shapes of patch. The bandwidth enhancement and size miniaturization are still ongoing issues for research on planar antennas. The planar antennas having low-profile can be made compact and can provide many advantages that allow their use in many modern wireless communication systems.

Since the release of report on ultrawideband (UWB) Technology by Federal Communication Commission (FCC) the UWB antenna has become very prominent for variety of commercial and military applications. According to FCC's first report [FCC (2002)], the unlicensed commercial frequency spectrum having bandwidth of 7.5 GHz from 3.1−10.6 GHz with power spectral density (PSD) limited to -43.1 dBm/MHz is allocated for UWB communications. This technology utilizes signal having bandwidth of greater than 500 MHz or fractional bandwidth of more than 20 % with respect to -10 dB reflection coefficient points. This indicates that the broadband antenna which can operate over aforesaid frequency range with good frequency and time domain performance, also known as UWB antenna is required for UWB communications. However, UWB system is typically useful for short-range and mainly indoor communication environment that is characterized by dense multipath propagation and consequently suffers from multipath fading [Kaiser *et al.* (2009)]. The UWB technology combined with multiple-input-multiple-output (MIMO) antennas is a feasible means to achieve enhanced data rates and reduced multipath fading [Kaiser *et al.* (2009)]. MIMO is an antenna technology intended for enhanced quality wireless communications in which multiple antennas are used at both transmitter and receiver sides. The antennas arranged in MIMO system utilize the principle of diversity technique in which multiple versions of same signal that are affected by different signal path reflections, diffractions and scattering arrive at the receiver. Therefore, the probability that all signal versions will be affected at the same time is considerably reduced and therefore, diversity technique helps to improve the quality of wireless communication [Kaiser *et al.* (2009)]. However, the UWB-MIMO technology provides enormous bandwidth and hence rich diversity and data rate. Moreover, in near future even more bandwidth will be required. Therefore, broadband antennas offering wider bandwidth as compared with UWB antennas which form part of MIMO system will be utilized for further enhancing the data rate and quality of modern wireless communication technology.

This chapter presents the brief introduction on broadband antennas along with their types, applications and bandwidth enhancement techniques: dielectric loading and curved boundaries with multiple segments.

1.2 Broadband Antennas

One of the key elements of any wireless communication system is the antenna, also known as aerial. It is defined as "a means for radiating or receiving electromagnetic waves" [IEEE Std. 145 (2013)]. In other words, antennas can be thought of as eyes and ears for electromagnetic waves in space or transducers that convert electromagnetic energy into electrical energy and vice versa. With the advancement of technology, many antennas have been designed which can be operated over specified frequency ranges according to their applications.

In terms of frequency range, there is no unique definition of broadband antenna because desired characteristics of antenna required over specified range of frequencies vary markedly with applications [Dyson (1962)]. Therefore, the term "broadband" is nebulous term. However, such antennas, which retain certain desired characteristics in terms of radiation pattern, polarization or impedance matching over an octave or more (that is, two-to-one (2:1)) frequency range can be referred to as "broadband antennas" [Jordan *et al.* (1964)]. In this thesis, special attention is given to impedance matching corresponding to -10 dB reflection coefficient (S_{11}) or voltage standing wave ratio (VSWR) value of 2. This signifies that the broadband antennas considered here can provide $S_{11} \leq$ -10 dB or VSWR $\leq$ 2 for bandwidth of 2:1 or more. For broadband antennas, the terminology used for specifying the bandwidth is percentage or ratio. These are defined respectively as follows:

$$B_P = 2 \times \frac{f_h - f_l}{(f_h + f_l)} \times 100\,\% \tag{1.3}$$

$$B_R = R{:}1 = {f_h}/{f_l} : 1 \tag{1.4}$$

where B_P and B_R are percentage and ratio bandwidth respectively, f_h and f_l are respectively the higher and lower cut-off frequencies of the band, and R is the ratio f_h/f_l

Reflection coefficient 'S_{11}' and VSWR are figures of merit in antenna system that explain the impedance matching between antenna and transmission line. These terms are defined at the input port of antenna where antenna is connected to the transmission line. Reflection coefficient is the ratio of reflected and incident fields which explains what function of incident electromagnetic (EM) field is reflected due to impedance discontinuity at the junction of antenna and transmission line.

$$S_{11} = \frac{E_R}{E_T} \tag{1.5}$$

$$S_{11}\,(in\,dB) = 20 \times log(|S_{11}|) \tag{1.6}$$

where E_R and E_T are reflected and incident electric field strengths respectively, and S_{11} is the voltage reflection coefficient. Input impedance mismatch characteristic can also be represented in terms of VSWR:

$$|S_{11}| = \frac{VSWR - 1}{VSWR + 1} \tag{1.7}$$

OR

$$VSWR = \frac{1+|S_{11}|}{1-|S_{11}|} \tag{1.8}$$

VSWR can be defined as the ratio of maximum to minimum electric field amplitudes of standing wave in transmission line connected to antenna. When input impedance of antenna is not matched to impedance of transmission line, the antenna causes reflected wave which creates standing wave along the transmission line. In case of perfect matching, VSWR = 1.0, i.e., S_{11} = 0 or $-\infty$ dB, which means ideally no reflection or in other words, maximum power transfer takes place from the transmission line to the antenna.

Some of the earliest conventional broadband antennas developed before and during World War II are long-wire types, rhombic and waveguide antennas with relatively constant impedance while their radiation pattern changes radically with operating frequency over useful frequency band. The fishbone and comb antennas have relatively acceptable impedance and radiation characteristics over 2:1 frequency range. Probably discone antenna was the first successful broadband antenna with bandwidth of 4:1 and some of its modified forms have good impedance and radiation characteristics over 5:1. Owing to the bandwidth of 4 or 5 is to 1, these antennas are also known as very wideband antennas. Helical, monofilar helical and Archimedes antennas have bandwidth of more than 4:1 with desirable impedance and pattern properties. The other category of broadband antennas is aperture type, such as open-ended waveguide, slot, horn, reflector and lens, but they also have limitations in stable pattern. After World War II, breakthrough in broadband antenna evolution was achieved by Rumsey. This breakthrough gave rise to frequency independent antenna (FIA), which has theoretically infinite bandwidth in terms of both impedance and radiation pattern. In this category of antennas, many structures were developed that can operate over 40:1 bandwidth or more. This category of antennas includes self-complementary antenna (SCA), log-periodic antenna (LPA), equiangular (or logarithmic spiral) antenna, sinous antenna and their different versions.

The most useful and advantageous antenna for modern communication systems is planar antenna. Microstrip patch antenna (MPA) developed in seventies was narrowband which limited its utility for broadband systems. This limit was mitigated with the aid of many bandwidth enhancement techniques. Since last two decades various planar antennas are developed which are compact as well as broadband in nature thereby enhancing their efficacy for different electromagnetic (EM) applications.

1.3 Classification of Broadband Antennas

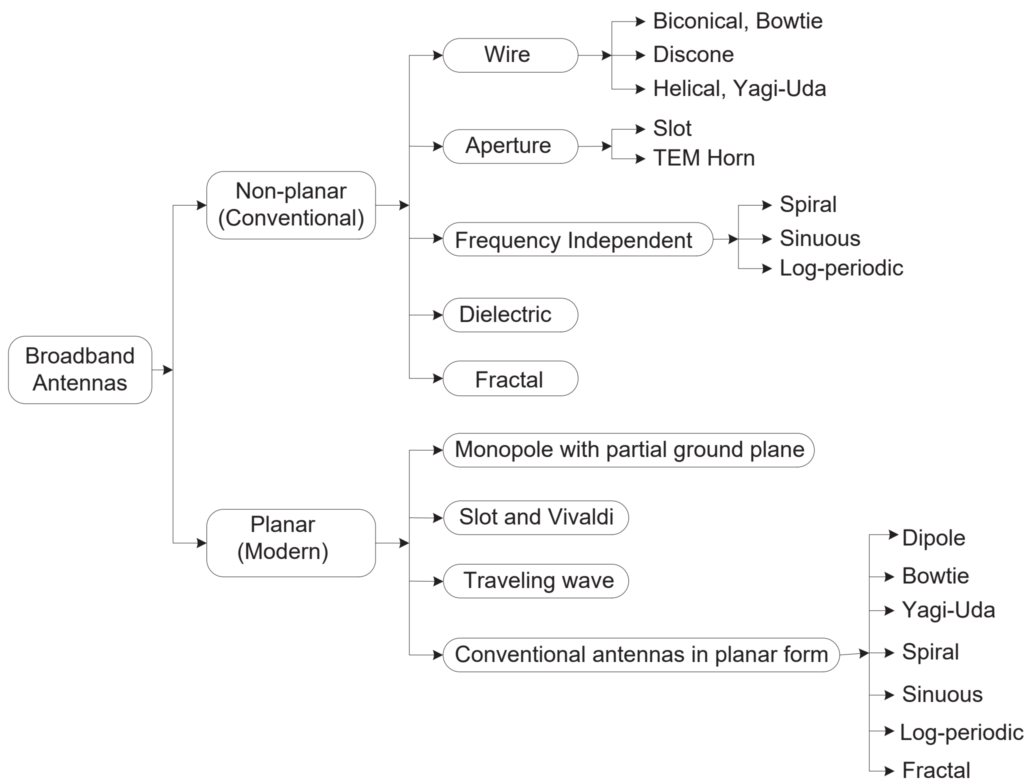

Figure 1.1: Classification of broadband antennas.

On the basis of non-planar and planar geometries, broadband antennas can be classified into two categories: non-planar and planar. The non-planar antennas are considered in the present thesis as conventional antennas, which came into existence before the development of MPA whereas planar antennas which can be designed using printed circuit board (PCB) technology are mentioned as modern antennas. The classification of broadband antennas is provided in Figure 1.1.

The preliminary and simplest form of non-planar antenna is metallic wire or rod. In 1887, Hertz performed an experiment on transmission and reception of radio waves. An infinitesimally small dipole of length, $L<<\lambda$ with a uniform current distribution is known as Hertzian dipole [Balanis (2008)]. The wire dipole and monopole are the most important and fundamental antennas that operate at their resonating frequencies. As the name suggests, the dipole antenna has two poles or two terminals through which EM energy transmission or radiation takes place. Commonly used dipole antenna is half-wave dipole having symmetrical terminals of length equal to $\lambda/2$ at corresponding operating frequency and provides omnidirectional radiation pattern. It is used as a reference antenna for many antenna measurements.

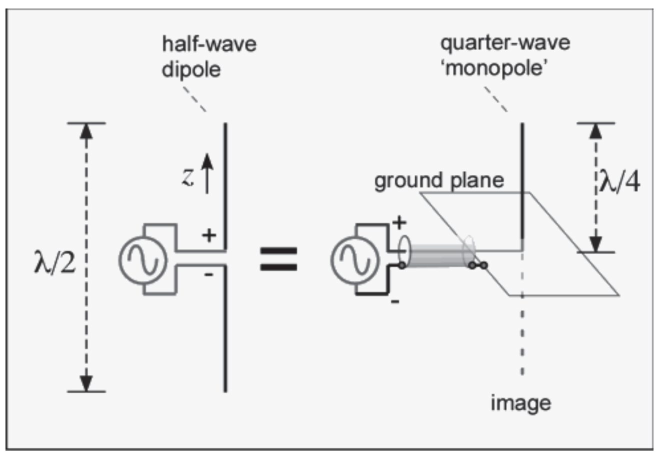

Figure 1.2: Dipole and monopole antennas [https://i.stack.imgur/NEjeM.gif].

A monopole antenna is a modified form of dipole antenna. It has single radiating terminal of length equal to $\lambda/4$ (half of dipole length) on ground plane which creates a virtual monopole below ground plane. This configuration of monopole antenna on perfect ground plane can be treated as dipole antenna [Balanis (2008)]. Figure 1.2 shows the half-wave dipole and its corresponding monopole antenna.

Bandwidth of these wire dipole and monopole antennas can be increased by increasing the radius of wire or in other words, the volume it occupies [Gandy (2006)]. With this standard rule, the dipole and monopole antennas are modified in innumerable ways for obtaining broad bandwidth. Some of these modified antennas are named as biconical, bowtie and discone antennas. These modified dipole and monopole antennas provide wide impedance bandwidth with omni-directional radiation patterns. Other non-planar broadband antennas made of metallic wire are helical antenna and Yagi-Uda antenna. Apart from wire geometry, other forms of geometry which radiate through aperture are known as aperture antennas. Slot and TEM horn antennas can be taken as examples of aperture antennas. The antennas designed using self-complementary concept can provide constant impedance independent of their frequency of operation. The frequency independent antenna (FIA) is a class of antennas whose geometry is completely defined by angles. The antenna characteristics - shape specified by angles, self-complementary, self-scaling and self-similarity properties when combined together give rise to many profound antenna geometries, which can truly or closely parallel frequency independent concepts. Some of these antenna geometries are spiral, sinuous and log-periodic. The fractal antenna is also a type of antenna whose geometry is identical to a self-similar structure. Its geometry is suitably designed to provide multiple bands or broad bandwidth [Cohen (1997)]. Apart from the antennas having specially designed geometry, the dielectric antenna with conventional geometry has its own advantages. The dielectric antenna generally known as dielectric resonator antenna (DRA) is made up of dielectric (ceramic) material having low-loss and relatively high permittivity. Due to the material properties, compact DRA can provide wide bandwidth. The non-planar broadband antennas are advantageous for high power and/or long distance communication applications due to their greater power handling capability. However, non-planar antennas are bulky and large in size. Therefore, these antennas are not suitable for most of the handheld mobile devices.

The planar antennas designed through PCB technology are widely used in wireless communication due to their inherent advantages such as their planar structure, low cost to fabricate, low profile, light weight, easy integration with other planar circuits. Various non-planar and planar broadband antennas are shown in Figure 1.3.

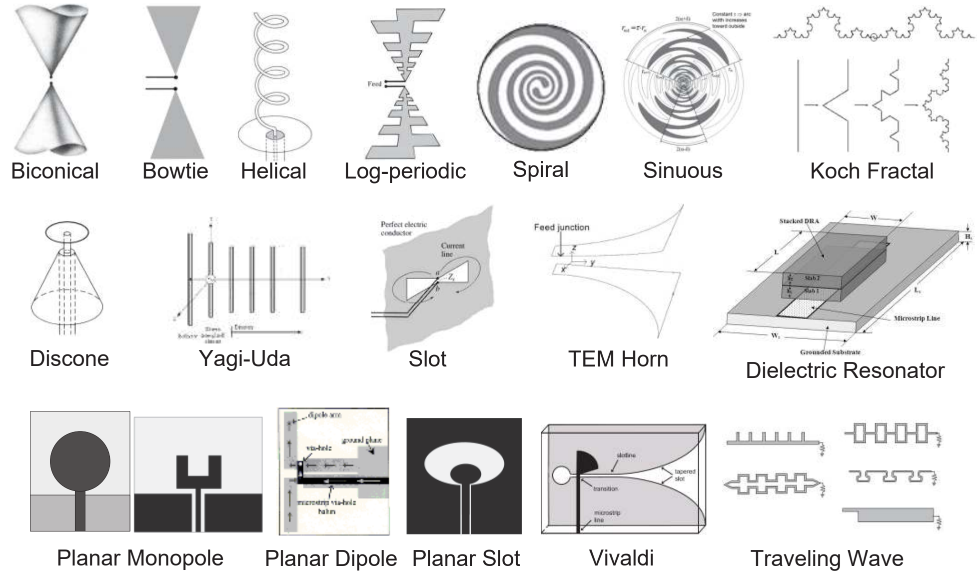

Figure 1.3: Geometries of various non-planar and planar broadband antennas.

The microstrip patch antenna (MPA) is a particular type of antenna under the general category of planar antennas. The MPA was first proposed by Deschamps in 1953 and practically developed by Howell and Munson in 1970's [Garg *et al*. (2001)]. Microstrip patches of various classical shapes were successfully used during initial stages of the development of modern wireless communication systems. One of the major disadvantages of MPAs is their very narrow frequency bandwidth. Due to the bandwidth limitation of MPAs, antenna researchers and engineers are still trying to design and develop other broadband planar antennas so that these can be used in modern wireless communication systems. Many types of broadband planar antennas have been developed for use in modern communication systems. The planar broadband antennas [Allen (2007)] that gained much attention in recent years are: monopole antenna with partial ground plane, slot antenna, and Vivaldi antenna. In order to derive the benefits of basic non-planar broadband antennas using planar geometries, the conventional antennas were developed in planar form. Broadband planar dipole, bow-tie, Yagi-Uda, traveling wave, spiral, sinuous, log-periodic, fractal antennas are some of the conventional broadband antennas available in planar form.

1.3.1 *Broadband Antennas under Non-planar or Conventional Category*

1.3.1.1 Frequency Independent Antenna

Frequency independent antenna discovered by Rumsey in 1957 is one which shows theoretically infinite bandwidth but practically broad bandwidth. According to him "if all the dimensions of a lossless antenna are increased by a factor of 'k', the pattern and impedance remain fixed when operating wavelength is also increased by a factor of k. In other words, the performance of a lossless antenna is independent of frequency, if its dimensions measured in wavelength are held constant. It follows that if the shape of antenna is such that it could be specified entirely by angles, its performance would be independent of frequency" [Rumsey (1957)]. Infinite biconical and infinite bow-tie antennas fulfill this property, though they were designed before the concept of FIA was reported. However, design of an antenna having infinite size is impractical. Therefore, truncation of antenna structure is required that makes it of finite size and therefore limits its frequency independent behavior thereby making the antenna of broad bandwidth but not of infinite bandwidth. Once the concept of FIA was properly understood many antenna structures were developed which are broadly categorized into three types: spiral, log-periodic, and sinuous antennas as depicted in Figure 1.4.

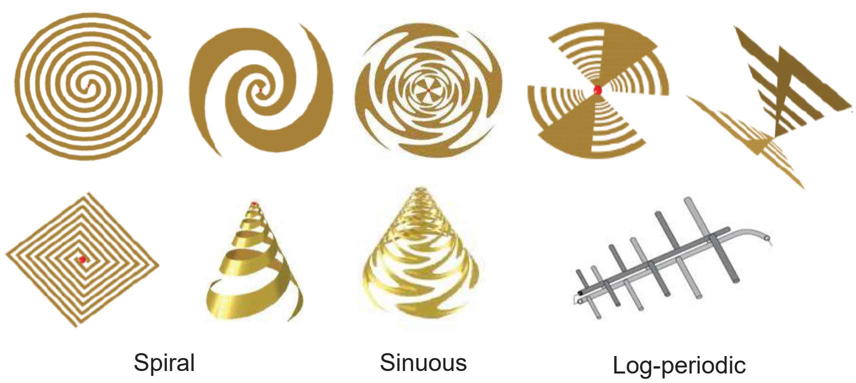

Figure 1.4: Geometries of different frequency independent antennas [http://www.antennamagus.com/images/Newsletter4-0].

Spiral antenna [Turner (1958) and Dyson (1959)a] was first introduced by Turner in 1954 and fabricated by Dyson in 1958. Its conducting arms are spiraled which can be defined by angles only and fed at the center. The spiral antenna is designed in such a manner that radius of spiral winding increases linearly or logarithmically and the respective antennas are called equiangular spiral or logarithmic spiral. Spiral antenna can be of circular, square or star shape. Another category of FIAs is log-periodic antenna (LPA). The LPA is designed in such a way that its impedance and radiation characteristics vary periodically with logarithmic of frequency [DuHamel *et al*. (1957)]. Its concept was given by DuHamel and Isbell in 1957. A typical LPA has multiple elements of increasing sizes. Its bandwidth and therefore lower and higher cutoff frequencies are decided by longest and shortest elements respectively. In 1987, DuHamel conceived an element called the sinuous antenna [DuHamel (1987)] which is similar in size, bandwidth and gain as spiral, but provides two orthogonal senses of polarization. Sinuous structure is a specific type of log-periodic structure that can be characterized by different shapes of curves or turns with continuous winding structure. The outer-most radius of the antenna structure fixes lower cutoff frequency while shortest radius fixes higher cutoff frequency. Among various FIAs, the LPA is found to be more advantageous [Sammeta and Filipovic (2014)a]. The LPA is mainly available in two forms: log-periodic dipole array (LPDA) designed using multiple dipoles while toothed log-periodic antenna (TLPA) designed using metallic sheets.

1.3.1.1.1 Trapezoidal Toothed Log-periodic Antenna (TTLPA)

Circular- and trapezoidal-shaped TLPAs were considered during initial stages of development [DuHamel and Ore (1958)]. Trapezoidal toothed log-periodic antenna (TTLPA) shown in Figure 1.5 is one of the antenna structures described in the present thesis. This antenna is named log-periodic because it is designed in such a way that its impedance and radiation characteristics vary periodically with logarithmic of frequency. Its shape cannot be completely defined by angles but by self-similar, self-scaling and/or self-complementary properties. A typical TTLPA has multiple elements (also known as teeth) of increasing sizes which can be constructed using a metallic sheet.

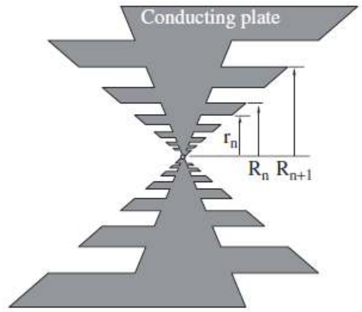

Figure 1.5: Geometry of trapezoidal toothed log-periodic antenna [Balanis (2008)].

Its bandwidth and therefore lower and higher cutoff frequencies are decided by longest and shortest elements respectively, where each element is quarter-wavelength long at corresponding design frequency. Length, width and spacing of each element are calculated by the design equations given below.

$$\tau = \frac{f_n}{f_{n+1}} = \frac{R_{n+1}}{R_n} \tag{1.9}$$

$$\sigma = \frac{r_n}{R_n} \tag{1.10}$$

where τ is geometric ratio, σ is the spacing factor, f_n and f_{n+1} are respectively the design frequencies of elements of lengths R_n and R_{n+1}, and r_n is the distance of corresponding element (representing length R_n) from the center. For the proposed antenna $f_{n+1}>f_n$ and $R_n>R_{n+1}$.

Equation (1.9) can be written in logarithmic form as

$$log(\tau) = log(f_n) - log(f_{n+1}) = log(R_{n+1}) - log(R_n) \tag{1.11}$$

According to Equation (1.11), $log(f_n) - log(f_{n+1})$ for n = 1, 2, 3..., n is same as $log(\tau)$. It clearly explains that the property of LPA is similar for each logarithmic period of frequency. As operating frequency increases the active region moves towards smaller elements. Active region is part of antenna responsible for effective radiation at the operating frequency. The two-arm TTLPA generates bidirectional radiation pattern with linear polarization because it is balanced type and its input impedance is approximately equal to 188.5 **Ω**. Therefore, it requires balanced feed with appropriate input impedance for proper excitation. However, the non-planar antenna fed through balanced feed is fragile, but the power handling capability of non-planar metallic antenna is better than microstrip patch antenna (MPA) which makes this type of antenna suitable for applications where antenna system is fixed (immobile) and power transmission requirement is high. The LPA can be used as primary feed for parabolic reflector used in radar, an element of the array antenna at base stations for wireless communication, ultra high frequency (UHF) terrestrial television (TV), in high frequency (HF) communications for electromagnetic compatibility (EMC) measurement and many other applications where wide bandwidth is required. The drawback concerning poor mechanical properties can be addressed using proper plastic or wooden material as support structure for the antenna and its feed which doesn't affect the performance of antenna significantly.

1.3.1.1.2 Dielectric Loading for Bandwidth Enhancement/ Size Miniaturization

Metal TTLPA can be designed to achieve a very wide bandwidth. Its lower cutoff frequency and bandwidth are decided by dimensions and number of elements used. To further increase its bandwidth towards lower frequency side the longest element and hence aperture size has to be increased. Therefore, the challenge is faced when bandwidth of the antenna is to be increased through the improvement of lower frequency response without increasing overall aperture size. For such purpose, different techniques including stub loading [Pirai *et al.* (2009)], meander line [Elsheakh *et al.* (2014)], and fractal Koch curves [Karim *et al*. (2010)] were reported which are suitable for planar log-periodic dipole array (LPDA). Another technique is dielectric loading in which the elements of wire LPDA are loaded with cylindrical hat cover filled with dielectric [Jardon-Aguilar *et al.* (2011)]. These reported techniques are not suited for non-planar TTLPAs. The dielectric slabs of identical shape can be used to load TTLPA so that bandwidth enhancement/ size miniaturization can be achieved without increasing aperture size of antenna. The Dielectric loading can either result in size miniaturization of the antenna or reduction in its lower cut-off frequency due to increase in effective length l_{eff} of the antenna in terms of wavelength which is expressed as

$$l_{eff} = l \times \sqrt{\varepsilon_{reff}} \tag{1.12}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} \tag{1.13}$$

$$l_{eff} \propto \lambda_{eff} \propto \frac{1}{f_{lc}} \tag{1.14}$$

$$\lambda_{eff} = \frac{\lambda}{\sqrt{\varepsilon_{eff}}} = \frac{c}{f_{lc} \times \sqrt{\varepsilon_{eff}}} \tag{1.15}$$

where ε_r is relative permittivity of dielectric material, l is actual length of the antenna, ε_{reff}, λ_{eff}, f_{lc} are effective relative permittivity, effective wavelength and lower cut-off frequency pertaining to the proposed antenna respectively and c is the speed of light = 3×10^8 m/s.

1.3.2 *Broadband Antennas under Planar Category*

All the antennas printed on dielectric substrate using printed circuit board (PCB) technique are considered as planar/patch antennas or modern antennas due to their wide variety of applications in modern communication systems. Monopole antenna with partial ground plane and quasi-self-complementary antenna (QSCA) studied in the present thesis are considered as planar broadband antennas.

1.3.2.1 Monopole Antenna with Partial Ground Plane

The monopole antenna is quarter wavelength long at the design frequency. It is derived from half-wavelength dipole antennas by substituting the bottom arm of the dipole antenna with a large metallic ground plane while positioning the top arm perpendicular to the ground plane. According to the image theory, reflections from the large conducting ground plane create a “virtual monopole” underneath the ground, as shown by the dotted lines in Figure 1.2. The planar monopole antenna (PMA) having radiating patch and/or slot of different shapes and partial ground plane yields broad impedance bandwidth and omni-directional radiation pattern when properly excited. The full (complete) ground plane of PMA is the main limiting factor for obtaining wide impedance bandwidth. This limitation has been nicely mitigated using truncated/partial ground plane. The geometries of circular patch antenna with full and partial ground planes are shown in Figure 1.6.

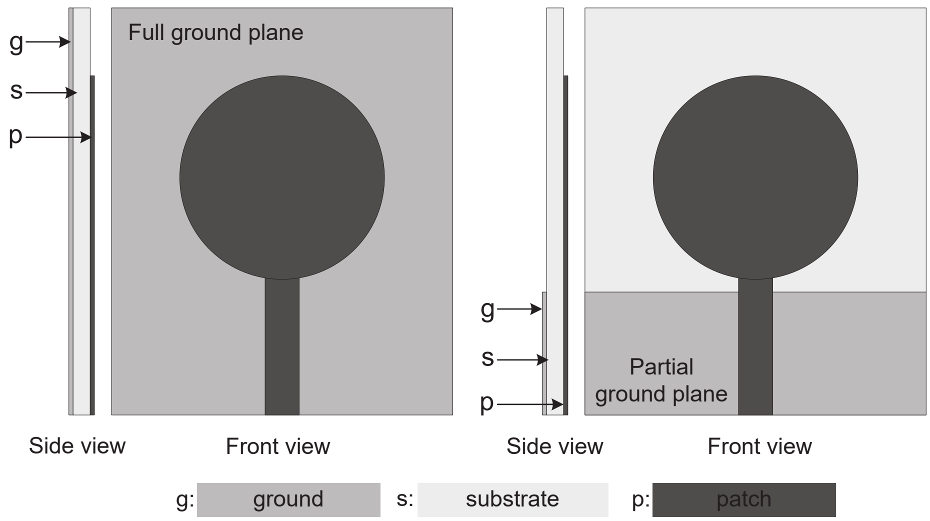

Figure 1.6: Circular patch antenna with full and partial ground planes.

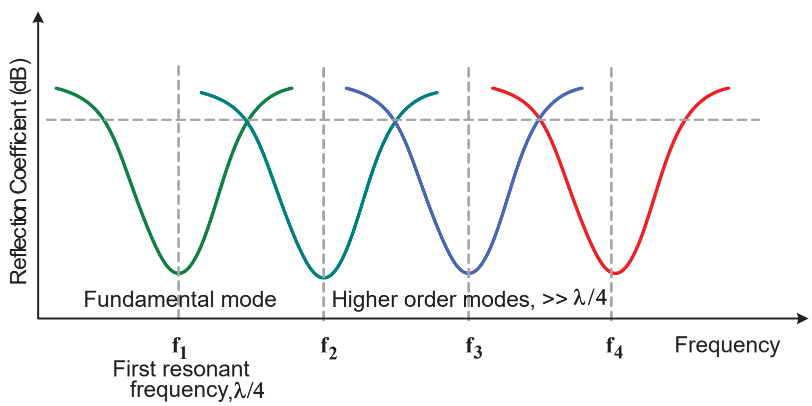

Figure 1.7: Principle of overlapping resonant modes of the planar monopole antenna [Allen (2007)].

The PMA can be properly excited through 50 Ω microstrip line without the need of balun, which is as required for dipole, balanced spiral, log-periodic and sinuous antennas. The broad bandwidth achieved using PMA is due to reduced quality factor ‘Q’ and overlapping closely spaced resonating modes having proper impedance matching as shown in Figure 1.7. The fundamental mode exists when the operating wavelength is larger than antenna size (applicable for first resonant frequency) and the higher order modes exist when operating wavelength becomes smaller than antenna size (applicable for higher frequencies) [Allen (2007)]. The

PMA became very useful due to its inherent properties such as its planar structure, compact size, easy mountability on planar surfaces, simple low-cost manufacturing, and near omnidirectional radiation pattern. The PMA is a potential candidate for UWB communication and there are many improvements on PMA have been done since the work on UWB antennas was initiated.

1.3.2.2 Quasi-Self-Complementary Antenna (QSCA)

Self-complementary antenna (SCA) [Mushiake (1992)] introduced by Mushiake is another kind of broadband antenna, which operates on different concept. It shows constant impedance regardless of frequency and shape of structure. The SCA discovered by Mushiake has metallic and slot parts, which are complementary to each other and the product of their impedances is a real constant. Some self-complementary structures are depicted in Figure 1.8. Due to the constant resistance, the SCA provides wide impedance bandwidth when excited through properly matched feed line. It can ideally provide infinite impedance bandwidth when designed on infinitely large ground plane. Its self-complementary structure is designed in such a way that input impedance (≈ 188.5 Ω) becomes constant regardless of frequencies used.

$$Z_1 Z_2 = \left(\frac{\eta}{2}\right)^2 \tag{1.16}$$

where Z_1 and Z_2 are the input impedances of patch structure and complementary slot respectively, and η is the intrinsic impedance of free space (≈ 120π Ω). For self complementary structures, Z_1 and Z_2 must be same (= Z). Therefore the input impedance of SCA is obtained by solving equation (1.16) as follows:

$$Z^2 = \left(\frac{\eta}{2}\right)^2 \tag{1.17}$$

Therefore

$$Z = 60\pi \approx 188.5\ \Omega \tag{1.18}$$

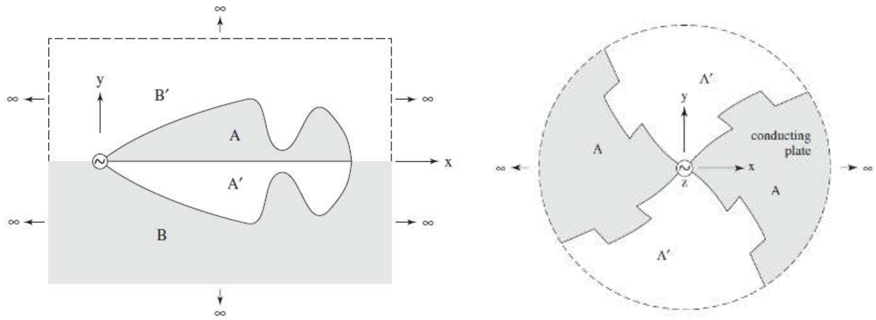

Figure 1.8: Self-complementary structures [Balanis (2008)].

But the practical antenna would provide limited bandwidth because of the finite antenna size and requirement of impedance matching circuit. However, in order to achieve desired bandwidth and integration of antenna with 50 Ω coaxial cable, an appropriate impedance matching circuit is required for impedance transformation from 188.5 to 50 Ω. These issues are resolved with the development of a quasi-self-complementary antenna (QSCA) having compact size and in-built impedance matching circuit [Guo *et al.* (2008)]. The development of QSCA has grown the family of SCAs to a higher level. The geometries of different QSCAs reported in the literature are shown in Figure 1.9.

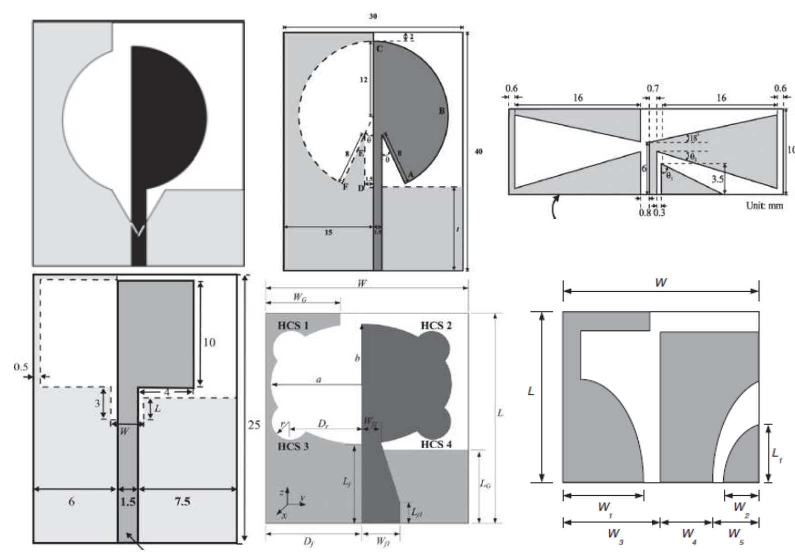

Figure 1.9: Geometries of different quasi-self-complementary antennas (QSCAs).

A QSCA consists of a radiating patch, complementary slot and inbuilt ground plane on either same or opposite side of substrate. The QSCA is so named because its radiating patch and complementary slot are not fully complementary to each other. It can be easily fed using microstrip line (MS)/ coplanar waveguide (CPW) feed. Very compact, wideband and UWB planar antennas are possible using QSCA. The recent systems which demand compact planar broadband antennas are UWB and UWB MIMO systems. UWB technology requires broadband antennas having bandwidth of 7.5 GHz (3.1−10.6 GHz). UWB system is a fast growing technology for pulse based high speed communication, microwave imaging, and precision radar systems. The UWB systems have the advantages of low power consumption, low cost, capability to provide high data rate, low interference, and ease of installation, which are essential for short range communication. The MIMO technology used with UWB systems further improves the performance of fast wireless communication services.

1.3.2.3 *Curved Boundary and Multiple Segments for Bandwidth Enhancement/ Size Miniaturization*

Many bandwidth enhancement/ size miniaturization techniques for planar monopole antennas (PMAs) are available in the literature. Some of the antennas utilizing different techniques are CPW-fed patch with modified ground plane [Deng *et al.* (2009)], CPW-fed slot antenna [Chen (2003)], MS-fed patch with modified partial ground plane [Lin *et al.* (2008)], asymmetrical coplanar strip (ACS)-fed patch [Liu *et al.* (2014)], coplanar stripline (CPS)-fed patch [Roshna *et al.* (2014)], complementary split ring resonator (CSRR) loaded patch [Rani *et al.* (2014)], metamaterial based antenna [Pandey *et al.* (2014)], fractal shaped patch [Kumar *et al.* (2011)], leaf-shaped patch [Fakharian *et al.* (2014)], and MS-fed flower slot antenna [Tang *et al.* (2014)]. One of the promising techniques for bandwidth enhancement and size miniaturization can be the use of natural shape patches having curved boundaries and multiple segments for planar antennas. The first resonance or lower-cutoff frequency, f_l of this type of antenna is inversely proportional to the perimeter of the patch as given below.

$$f_l \propto \frac{1}{p} \tag{1.19}$$

where f_l is lower cutoff frequency and p is perimeter of patch.

Increase in perimeter of the patch shifts the first resonance or lower cutoff frequency of the antenna towards lower frequency without changing the outer diameter of the patch. In addition, distinct sub-sections of the patch boundary can resonate at higher frequencies which will further increase the bandwidth of the patch antenna. This concept, which is utilized in the study of some antennas presented in the present thesis helps in making the antenna wider in bandwidth and compact in size.

1.4 Motivation and Challenges for Design and Development of Compact Broadband Antennas

It can be easily observed from the 'Introduction' section of the present chapter that the broadband antenna is a key element of any high speed wireless communication system. Meanwhile, the technological growth in the areas of fast wireless communication as well as, radar and navigation systems requires compact broadband antennas to be designed and developed. This aspect makes the researchers, scientists/engineers to rethink about further enhancement of bandwidth and size miniaturization of suitable antennas. In literature, many techniques are reported for bandwidth enhancement and size miniaturization of both non-planar and planar antennas. Still, there is a scope for making both non-planar and planar antennas compact in size and broader in bandwidth. This scope has motivated the author to design, develop and test some broadband antennas for present thesis work.

It is mentioned in the 'Broadband Antenna' section that the FIA having dimensions ranging from zero to infinity can theoretically provide infinite bandwidth. However, zero and infinite size antennas are impractical. Therefore, truncation of practical antennas is necessary. This truncation limits the bandwidth from lower to upper frequency and makes the antenna a broadband antenna instead of infinite bandwidth antenna. One of the FIAs is TTLPA having two similar arms, its bandwidth and therefore lower and upper operating frequencies are limited due to the use of longest and smallest elements. The scope for designing proper feed system that excites the arms of balanced TTLPA using coaxial cable over wide bandwidth still exists. This problem can be solved using a balun, which is a transition device between balanced antenna and unbalanced coaxial cable. In this regard, a broadband balun is required which does not degrade the bandwidth of antenna. The problem is aggravated further when bandwidth enhancement towards lower frequency is desired without increasing the antenna size. To overcome this issue, various end-loading, meandered line and fractal curve techniques were proposed for LPDA, though these are not suitable for TTLPA made of metallic sheets.

The problem of bandwidth enhancement for planar antennas without increasing their size remains one of the research issues. The lower operating frequency of PMA is inversely proportional to the circumference of radiating patch. Since the release of unlicensed UWB spectrum, many techniques have been reported for design of compact PMAs suitable for UWB. Still there is a scope for further enhancement of antenna bandwidth covering UWB along with Bluethooth spectrum using natural shape radiating patch. There are overlapping narrowband communication spectrums: Worldwide Interoperability for Microwave Access (WiMAX) (3.3–3.6 GHz), Wireless Local Area Network (WLAN) IEEE802.11a (5.15–5.35 GHz and 5.725–5.825 GHz), High Performance Radio LAN (HiperLAN) (5.15–5.35 GHz and 5.47–5.725 GHz), and international telecommunication union (ITU)-8 GHz (7.725–8.500 GHz) that interfere with UWB spectrum. Therefore, the necessity to suppress these overlapping spectrums gives researchers opportunity to devise suitable band rejection techniques. Apart from interference with overlapping communication spectrums, the UWB technology also suffers from multipath fading which can be mitigated with the aid of MIMO technology. These problems can be overcome through improvement of isolation between MIMO antennas over wide bandwidth. Although many UWB MIMO antennas using different isolation techniques are proposed recently, there is still scope for designing compact broadband MIMO antennas providing band rejection characteristics without using additional isolation techniques. The challenge is advanced further when a single radiating patch has to be utilized as broadband MIMO antenna.

In accordance with the discussed motivations and challenges for design and development of compact broadband antennas, several novel ideas are put forward by the author and efforts are made to overcome aforesaid problems.

1.5 Objective and Scope of the Present Thesis

The objective of the present thesis is to solve aforesaid problems in the design and development of some compact and broadband non-planar TTLPA and planar monopole antennas (PMAs) for wireless communication, radar and navigation as well as UWB and MIMO applications.

For the excitation of TTLPA, the tapered microstrip line-to-coplanar stripline transition, also known as balun is designed and developed by the author. The bandwidth enhancement of TTLPA towards lower frequency side is achieved using dielectric loading on upper side of metallic arms without changing the cross-sectional aperture of the antenna.

The bandwidth enhancement of the PMAs towards lower and higher frequency sides was achieved by the author using multiple sections and increased circumference of the radiating patch respectively. For such purpose, radiating elements of natural shapes like flower and leaf shapes having curved boundaries and distinct segments are utilized. Further, the band rejection of overlapping spectrums is achieved using slit and slot on radiating patches. By utilizing the concept of QSCA, broadband MIMO antenna is designed and developed by the author, which does not require additional isolation technique. The idea of shared radiator by multiple elements of the antenna is used by the author to design and develop compact broadband MIMO antenna.

In the process of design and development of compact broadband antennas with the proposed ideas, simulation and experimental studies are carried out. The simulation studies are performed using Ansys' high frequency structure simulator (HFSS) and/or computer simulation technology microwave studio (CST MWS) softwares. The works carried out by the author are presented in different chapters of the thesis as given below.

In chapter 2, the research work reported in the literature related to problems mentioned earlier including bandwidth enhancement and size miniaturization of LPAs and PMAs along with UWB and UWB MIMO antennas is extensively reviewed.

In chapter 3, trapezoidal toothed log-periodic antenna (TTLPA) under the non-planar broadband antenna category is considered. Its excitation using balun and bandwidth enhancement technique is described. The TTLPA along with tapered MS-to-coplanar stripline transition (balun) for antenna excitation is studied and the effect of transition on the performance of TTLPA is also discussed. Further, dielectric loaded trapezoidal toothed log-periodic antenna (DLTTLPA) is investigated to show the bandwidth enhancement and size miniaturization property of dielectric loading.

In chapter 4, planar monopole antenna (PMA) under the planar broadband antenna category is considered. The flower-shaped patch as a modified version of circular patch is described. The bandwidth enhancement of proposed antenna over conventional circular patch is discussed. Further, the proposed flower-shaped patch antenna is excited using CPW and microstrip line (MS) feeds and their input and radiation characteristics are compared.

In chapter 5, castor leaf-shaped quasi-self-complementary antenna (QSCA) and its two-element MIMO configuration without and with dual band-rejection characteristics are investigated. First, two castor leaf-shaped QSCAs: one with sharp corners and another with smooth corners are designed and their performance are compared. After that, MIMO antenna consisting of two identical smooth-corner castor leaf-shaped QSCAs arranged in mirror image configuration is studied. Further, the MIMO antenna with resonators for dual band-rejection is studied. The input, radiation and diversity performances of both MIMO antennas without and with resonators are investigated.

In chapter 6, two-port MIMO antenna using shared radiator is investigated. The evolution of this antenna with each step for obtaining proper isolation over wide bandwidth is discussed. Further, the input, radiation and diversity performances of the MIMO antenna are presented.

In chapter 7, the brief summary of all investigations and observations carried out in the thesis is presented. The major findings along with concluding remarks of the antennas investigated by the author are outlined. Further, the scope for the future works related to this thesis is discussed.

At the end, all the references cited in the present thesis are listed which shows that the research work carried out in the present thesis is made possible due to the information gathered from these references.