2.
Literature Review

2.1 Introduction

Broadband antenna plays a vital role in the field of wireless and mobile communication systems where high data rate and/or multiple wireless services are required as discussed in previous chapter. This necessitates design and development of broadband and compact devices and components for present and future generations of wireless communication systems that demand broadband and compact antennas. In addition, broadband antennas are used in radar and navigation systems. Owing to this demand, research in the area of broadband antennas, which are suitable for various types of communication as well as radar and navigation systems continue to grow. Many broadband antennas are reported in open literature and each of them has its own merits and demerits for specific applications. Thus, to have a clear insight on work done in the past on broadband antennas, literature survey is carried out so that objectives of present thesis can be accomplished. This chapter presents a brief survey of the studies done on various categories of broadband antennas of both non-planar and planar category. Further, detailed literature survey on trapezoidal toothed log-periodic antenna (TTLPA), planar monopole antenna (PMA) and quasi-self-complementary antenna (QSCA) is carried out in different sections of the present chapter.

2.2 Literature Survey on Broadband Antennas

The discovery of broadband antennas was made in the last decade of nineteenth century. In 1898, Lodge [Lodge (1898)] introduced the biconical, spherical, square plate and triangular dipoles. He also introduced the conical monopole antenna with earth as ground plane. The rediscovery on Lodge's principle related to biconical and conical monopole antennas was carried out by Carter [Carter (1939)]. He incorporated a tapered transition for these antennas which improved the design of broadband antennas. Schelkunoff studied biconical antenna in 1941 and explained the importance of size and shape [Schelkunoff (1941)]. In 1941, Lindenblad's element and turnstile array were developed for television transmission to support wide band of frequencies [Lindenblad (1941)]. The biconical antenna was bulky and therefore, need was felt to modify it. Discone antenna studied by Kandoian [Kandoian (1945)] is a modified form of biconical antenna in which one of the cones of biconical antenna was replaced by a circular disk and second cone was made hollow. Further reduction of weight was achieved through the use of wires for making the discone structure. In 1952, Brown and Woodward published an article containing extensive experimental studies on biconical and bowtie antennas. Each section of bowtie antenna studied by them is a planar version (of triangular geometry) of the section of biconical antenna and provides similar characteristics but the planar geometry of bowtie is attractive due to its less volume and weight [Brown and Woodward (1952)]. Meanwhile, other antennas like helical [Kraus (1948)], coaxial and rectangular horn antennas [Brillouin (1948)] were developed during 1940s.

Rumsey's concept [Rumsey (1957)] of frequency independent antennas (FIAs) when combined with self-complementary concept [Deschamps (1959)] of constant input impedance and logarithmic periodicity [Duhamel and Isbell (1957)] during 1950s and 1960s advanced the development of broadband antennas. The combination of these concepts established many distinct antenna structures: equiangular spiral [Dyson (1959)a], conical spiral [Dyson (1959)b], LPDA [Isbell (1960)], toothed log-periodic antenna (circular and trapezoidal) [Duhamel and Ore (1958)], and their variations which provide bandwidth of more than 10:1. In 1982, Kanda explained the effect of resistive loading of TEM horn [Kanda (1982)]. The basic TEM horn consists of two linear or exponential tapered metal plates, which are arranged in V-shape and provide very wide bandwidth. In 1987, Duhamel got a patent on sinuous antenna [Duhamel (1987)]. The sinuous antenna belongs to family of FIAs and provides wide bandwidth with two orthogonal senses of polarization but its geometry is more complex than other FIAs. During 1990s many monopole disk antennas of different shapes excited through coaxial cable and placed vertically above large ground plane were developed that provide very wide bandwidth [Agrawall *et al.* (1998)]. Further improvement of the impedance bandwidth of a vertical monopole antenna has been achieved using trident feed structures [Wong *et al.* (2005)]. The antennas discussed till now are non-planar and made of metal sheets which are not suitable for compact handheld devices.

Apart from non-planar metal antennas, planar antennas designed on metal-coated dielectric substrate are best suited for compact handheld devices due to their planar structure, low cost, low profile, light weight, easy integration with other planar circuits. However, older versions of microstrip patch antennas (MPAs) had narrow bandwidth. The concept of MPAs was first proposed by Deschamps [Deschamps (1953)] and practically developed by Howell [Howell (1972)] and Munson [Munson (1974)]. Since 1970, development of MPAs accelerated using a variety of bandwidth enhancement techniques including the use of multilayer substrate [Hall *et al.* (1979)], parasitic elements [Wood (1980)], thicker substrates of low dielectric constant [Derneryd and Karlsson (1981)], and stacked configuration [Bhatnagar *et al.* (1986)]. Later on, different bandwidth enhancement techniques employing microstrip line-fed L-strip patch [Mak *et al.* (1999)], L-shaped probe [Mak *et al.* (2000)], shorting strip [Ammann and Chen (2003)], and many more were proposed. The printed circuit board (PCB) technology leads the design and development of many other broadband antennas. A wideband arrayble planar circular dipole antenna element was proposed by Thomas *et al.* in 1994. The circular patches of the dipole antenna were placed on the opposite sides of the substrate [Thomas and Wolfson (1994)]. A patent on a coplanar waveguide (CPW) fed planar monopole antenna with wide impedance bandwidth was granted in 1999 to Zollinger [Zollinger (1999)]. In 2000, Barnes pioneered planar UWB magnetic slot antenna which has two leaf-shaped slots interconnected along the axis and fed at the center [Barnes (2000)].

After the release of UWB in 2002 for unlicensed commercial use, the design and development of compact planar broadband antenna for UWB applications picked up. In the series of broadband antennas studied for UWB applications, Schantz proposed planar dipole antenna having elliptical radiating patch [Schantz (2002)] and electrically small bottom-fed planar elliptical dipole providing bandwidth of approximately 3:1 [Schantz (2003)]. Further, the planar elliptical dipole antenna fed through microstrip line (MS) was investigated by Zhang *et al.* [Zhang *et al.* (2006)]. In addition to planar dipole, many non-planar antennas were also converted to planar form using PCB technology. In 2008, wideband periodic endfire array having bandwidth of 54.1 % was developed using bowtie dipoles on opposite sides of substrate [Qu *et al.* (2008)]. Many LPAs were also designed in planar form; in 2006 uniplanar log-periodic slot antenna fed through CPW was proposed which is a compact low-profile wideband antenna [Chen *et al.* (2006)]. This log-periodic slot antenna was modified for unidirectional radiation pattern using cavity-backed system [Ouyang *et al.* (2011)]. One of the recently developed LPA with increased bandwidth was explained in reference [Sammeta and Filipovic (2014)a]. Increased bandwidth was obtained using a ring on the outer periphery of four-arm circular toothed log-periodic antenna. They also developed sinuous antenna with improved efficiency using lens-loaded cavity backed four-arm sinuous antenna [Sammeta and Filipovic (2014)].The spiral antenna providing wide bandwidth was also designed on opposite side of substrate and fed using CPW feed [Huang and Lv (2014)].

Another type of very attractive compact planar broadband antenna is wide slot excited by stub attached to feed line. A slot antenna comprised of circular slot and circular tuning stub was realized which provided a bandwidth of 110 % [Denidni and Habib (2006)]. In 2008, Krishna *et al.* presented a compact slot antenna using Koch fractal slot which is excited by microstrip line fed rectangular stub [Krishna *et al.* (2009)]. The fractal geometry can be applied to most of the antennas because it can provide multiple bands and/or broadband through tuning [Cohen (2005)]. In reference [Emadian and Ahmadi-Shokouh (2015)], one of the smallest slot antennas providing a bandwidth from 2.5 to more than 23 GHz along with dual band-notched characteristic was presented. Recently, another type of slot antenna also known as notch antenna was also discovered. It has an open slot (slit) of triangular shape [Gopikrishna *et al.* (2008)], L shape [Gong *et al.* (2014)] or rectangular shape [Zhang and Li (2015)] which is excited by microstrip line. Vivaldi antenna is also a notch antenna having tapered slot. The Vivaldi antenna with exponential tapered slot was first proposed by Gibson in 1979. It was described as a class of aperiodic continuously scaled antenna structures with theoretically unlimited instantaneous frequency bandwidth [Gibson (1979)]. Recent developments on Vivaldi antenna are discussed in reference [Pandey (2016)].

Other than planar dipole and various types of slot antennas, planar monopole antennas (PMAs) have been studied since the release of UWB due to its promising candidature for UWB applications. In 2005, simplest forms of PMAs were investigated by Liang and his group using circular patch and finite ground plane in which microstrip line (MS) [Liang *et al.* (2005)a] and CPW feed [Liang *et al.* (2005)b] were used for excitation. Few years later, the quasi-self-complementary antenna (QSCA) was proposed. In reference [Guo *et al.* (2008)], semi-circular patch fed through CPW and complementary slot on same side of substrate was discussed whereas in reference [Guo *et al.* (2009)], semi-circular patch attached to microstrip line feed and complementary slot on opposite side of substrate was reported. In past few years, UWB MIMO technology became popular due to some demerits of UWB systems. Various PMA, QSCA and slot antennas were proposed for UWB MIMO systems. Due to the suitability of PMAs for UWB systems and QSCAs to maintain high isolation among multiple ports of UWB MIMO systems, detailed survey of PMAs and QSCAs of different shapes of radiating elements is discussed in sections 2.4 and 2.5 of this chapter.

2.3 Trapezoidal Toothed Log-periodic Antenna (TTLPA)

TTLPA is a type of LPA with trapezoidal-shaped radiating elements. The concept of LPA was originated by Duhamel in 1957. According to him LPA has "antenna structure for which the input impedance and radiation patterns vary periodically with the logarithm of frequency". Duhamel and Isbell proposed many log-periodic structures using three principles: angle concept, self-complementary concept, and logarithmic periodicity concept. They constructed circular toothed log-periodic antenna and experimentally obtained that the designed antenna provides linearly polarized bidirectional patterns with equal and constant principal plane beamwidth over bandwidth of greater than 10:1 [Duhamel and Isbell

(1957)]. The design procedure, construction and experimental results for TTLPA were first explained in 1958. A variety of TTLPAs in sheet and wire forms for linearly polarized omnidirectional, bidirectional and directional patterns as well as circularly polarized bidirectional and unidirectional patterns [Duhamel and Ore (1958)] were also studied. Further, theoretical and experimental studies along with design procedure for the array of wire TTLPA were carried out to achieve higher gain [Duhamel and Berry (1958)]. The high gain antennas such as reflector and lens operating over wide range of frequencies are very much suitable in communication and ECM fields as well as search applications but their primary feed limits the antenna bandwidth. In reference [Duhamel and Ore (1959)], TTLPA is described as primary feed for reflector and lens antennas operating over 600 MHz − 6 GHz. The unidirectional wire TTLPA was further proposed as a suitable candidate for high frequency (HF) point-to-point communications [Duhamel and Berry (1959)]. In 1960, Bell *et al.* performed near-field measurement on a triangular-toothed log-periodic antenna. The measurement reveals that two waves exist on the antenna structure: transmission line wave travels from apex to active region which excites the teeth, and radiated wave is produced by the excited teeth, which account for the far-field pattern [Bell *et al.* (1960)]. In the same year, Isbell introduced log-periodic dipole array, (LPDA) using coplanar dipole array which can provide unidirectional patterns of constant beamwidth with almost constant input impedance over any desired bandwidth [Isbell (1960)]. Later on, Carrel did extensive study on LPDA using mathematical analysis and explained step-by-step procedure for design of LPDA [Carrel (1961)]. In addition, Berry and Ore proposed log-periodic monopole array to reduce its maximum height to one-fourth of a wavelength at its lower operating frequency instead of half wavelength [Berry and Ore (1961)]. After that, Jackson and Wheeler developed a log-periodic-slotted cylinder antenna with slot having shape of TTLPA that exhibits uniform pattern over wide frequency range compared to single axial slot [Jackson and Wheeler (1962)]. Further, in 1964, Greiser developed log-periodic folded slot, dipole and monopole arrays [Greiser (1964)]. The K-band TTLPA was designed that operate over the frequency range

2.5−15 GHz [Barbano (1966)]. The dimension of each element is one-fourth of a wavelength at corresponding operating frequency. Therefore, antenna size becomes larger at lower frequency. Often, the size reduction was necessitated where space is limited. In 1970, Kuo proposed reduced-size LPDA by folding the larger dipole elements and by loading each dipole with rectangular stub [Kuo (1970)]. Further, size reduction was achieved by bending each element towards apex as described in reference [Keen (1974)].

One of the disadvantages of microstrip patch antennas (MPAs), which were designed on dielectric substrate, is their narrow bandwidth. In 1980, microstrip patch array was designed in log-periodic arrangement to get wide bandwidth [Hall (1980)]. Toothed log-periodic antenna (TLPA) was also realized as mixtenna for millimeter and submillimeter wavelengths [Siegel (1986)]. Few years later, a dual linearly-polarized narrow slot antenna utilizing trapezoidal-toothed slot outline element was developed for broadband applications [Tammen and Mayes (1991)]. In 1992, study on log-periodic microstrip patch antenna was carried out using full-wave spectral domain method [Wu (1992)]. In the same year, Mushiake discussed many two- and three-dimensional TTLPAs using self-complementary concept [Mushiake (1992)]. Meanwhile, during 90's circular TLPA was utilized to build heterodyne receiver for use at submillimeter-wave-to-far-infrared frequencies [Gearhart *et al.* (1993)]. In 1999, Kang *et al.* utilized TTLPA to develop Josephson junction array (JJA). They fabricated the JJA integrated with a TTLPA using high temperature superconducting thin film and found that the antenna enhances the exchange of electromagnetic energy between Josephson junction and free space effectively [Kang *et al.* (1999)]. Further in 2002, the triangular TLPA was utilized as feed for integration with a cryogenic amplifier [Engargiola (2002)]. The feed consists of four triangular toothed log-periodic arms, together forming a pyramid and another metallic pyramid located at the center holds low-noise amplifiers and cryogenics. The numerical analysis for the radiation pattern of the developed feed was done by Ericsson *et al.* [Ericsson *et al.* (2003)]. TLPA was also utilized as a THz emitter using LTG-GaAs finger-photomixer integrated LPA [Mendis *et al.* (2004)]. Hertel and Smith investigated two-arm conical log-periodic antennas with different shapes of teeth structure using finite-difference-time-domain (FDTD) method [Hertel and Smith (2003)].

Due to the demand of compact wideband antennas, the size reduction of original LPA was essential. In [Klemp *et al.* (2004)a] two miniaturization techniques: radial modulation and azimuthal expansion were proposed for TLPA. Further in reference [Klemp *et al.* (2004)b], four-arm LPAs with different shapes of teeth along with miniaturization technique were proposed for broadband polarization diversity reception. In 2005, Ergül and Gürel presented non-planar TTLPA using simulation [Ergül and Gürel (2005)]. The TTLPA in dual polarized configuration was again utilized as a feed for reflector so that reflector becomes useful for applications in VHF/UHF/microwave communication systems, radio astronomy, spectrum monitoring etc. [Joardar and Bhattacharya (2006)]. The size miniaturization of LPA was further studied using Koch-shaped dipole [Anagnostou *et al.* (2008)], meander lines [Gheetan and Anagnostou (2008)] and fractal tree dipoles loaded with rectangular patches [Wang *et al.* (2008)]. In 2009, Q-band toothed LPA with monolithically integrated μ-coaxial impedance transformer/feeder was proposed [Satio *et al.* (2009)]. In the same year, analytical model was proposed for calculation of resonance frequencies and bandwidth of TLPA [Scheuring *et al.* (2009)]. Later on, toothed TLPA with band-rejection capability was developed [Mruk *et al.* (2010)]. Band-rejection was achieved through removal of resonant teeth, integration of dual-band filter and combination of both. In 2011, a log-periodic dipole antenna using cylindrical hat cover at the end of each dipole was proposed to achieve size reduction [Jardon-Aguilar *et al.* (2011)]. Thereafter, with the advancement of UWB-MIMO technology, a conformal four-arm TLPA with feed network integrated on a single conical MID [Orlob *et al.* (2012)] was proposed. Soon after, LPA was investigated with dielectric resonators [Kumari and Behera (2013)]. In 2014, four-arm dual circularly polarized TLPA with increased bandwidth was developed by Sammeta and Filipovic. Increased bandwidth with miniaturization factor greater than 2 was obtained using an outer annular ring [Sammeta and Filipovic (2014)a]. Further in

2015, LPA with miniaturized size using square fractal geometry was proposed for UWB services [Amini *et al.* (2015)]. In the same year, TTLPA was utilized for RF energy harvesting [Simon *et al.* (2015)]. Recently, Lorho *et al.* discussed impedance and radiation properties of UWB dual-polarized antennas including toothed LPA having enhanced bandwidth [Lorho *et al.* (2016)].

2.4 Planar Monopole Antenna (PMA)

As discussed in section 2.2, discovery of planar antenna deigned on PCB started in 70's and microstrip patch antenna (MPA) designed during initial phase was of narrow bandwidth. After that, many bandwidth enhancement techniques were proposed. Some of these techniques are already discussed in section 2.2. The PMA consists of a quarter-wavelength patch and a supporting ground plane, both printed on same or opposite sides of substrate depending on the chosen feed line: CPW or microstrip line (MS). Probably the Tab monopole was the first PMA with size smaller than a quarter-wavelength and bandwidth more than 50 % [Johnson and Rahmat-Samii (1997)]. Thereafter, Zollinger published a patent explaining CPW fed broadband planar monopole antenna [Zollinger (1999)]. Later on, a CPW-fed staircase bow-tie monopole antenna with improved bandwidth of 77.1 % was proposed [Lee *et al.* (2002)]. Further in 2003, two truncated square monopoles were proposed for diversity application with bandwidth of about 2.3−7.7 GHz [Wong *et al.* (2003)]. Since 2004, many compact and simplest PMAs were designed. Suh *et al.* described a planar inverted cone antenna (PICA) which provided impedance bandwidth of more than 10:1 [Suh *et al.* (2004)]. It is composed of a single flat element vertically mounted on a ground plane. Further, Sierpinski fractal monopole antenna was made uniplanar by exciting the patch through CPW instead of vertical arrangement of patch and ground [Kitlinski and Kieda (2004)]. The CPW feed was again utilized to excite hexagonal radiating patch covering whole UWB (3.1−10.6 GHz) [Kwon and Kim (2004)]. The circular disk monopole antenna fed through microstrip line with partial ground plane was one of the simplest broadband PMA for UWB till 2004 [Liang *et al.* (2004)]. Circular disk monopole antenna was again studied using CPW instead of microstrip line (MS) for excitation [Liang *et al.* (2005)a]. Liang again studied the circular-ring monopole antenna fed through microstrip line (MS) to show that both circular disk and circular ring monopole exhibit almost same performance [Liang *et al.* (2005)b]. Further, PMAs with different basic geometrical shapes of patch including rectangular [John and Ammann (2005)], elliptical [Huang and Hsia (2005)], triangular [Lin *et al.* (2005)], [Liu and Kao (2005)], and U-shapes [Kim *et al.* (2005)a] were proposed for UWB applications. Later on, incorporation of different provisions including U-shaped slot [Choi *et al.* (2005)] and parasitic patches [Kim *et al.* (2005)b] were made in PMA to achieve band-rejection.

The shape of the patch boundary near the ground plane plays a very important role in impedance matching for broadband PMAs. Most of the PMAs developed in 2006 were designed by taking this aspect into account. Meanwhile, PMAs with band-rejection characteristic for UWB applications continued to attract the attention of researchers. In this regard, Cho *et al.* utilized staircase shape for patch boundary, curved structure for ground plane, and U-shaped slot for WLAN band rejection [Cho *et al.* (2006)]. Su and Wong utilized semi-circular disk patch and ground plane along with a pair of thin slits on ground plane for WLAN band-rejection [Su and Wong (2006)]. Kim and Park utilized three steps on the boundary of semielliptical patch and curved ground plane. The WLAN band-rejection was achieved using combination of an elliptical slot on patch and a parasitic strip opposite to slot [Kim and Park (2006)]. Further, Kim *et al.* used curved boundary for both patch and ground plane and the slot type split ring resonator (SRR) for band-rejection [Kim *et al.* (2006)]. Qu *et al.* presented rectangular patch and ground plane with rounded corners and a slot type resonator on feed line for band-rejection [Qu *et al.* (2006)]. Eldek proposed a tab monopole having tapered transition near feed line and ground plane with staircase geometry [Eldek (2006)]. In addition Chang *et al.* proposed a tulip-shaped monopole, which provided enormous bandwidth covering frequencies from 2.55 to 40 GHz [Chang *et al.* (2006)]. This research continued with innovative monopole geometries. In 2007, Ling *et al.* studied the effect of edge curve of monopole on impedance bandwidth and proposed a binomial-curved monopole [Ling *et al.* (2007)]. Hong *et al.* used arc-shaped edge monopole and ground plane with two bevel slots on upper corners and two semicircular slots on bottom edge along with a T-shaped stub inside elliptical slot placed on radiating element for band-rejection [Hong *et al.* (2007)]. Jacob *et al.* presented a different kind of PMA having multiple branches on top of strip monopole [Jacob *et al.* (2007)]. Further, Luo *et al.* proposed dual band-notched planar antenna using a pair of annular rings with a tuning stub inside the ring, where one annular ring was embedded in the feed line [Luo *et al.* (2007)]. In 2008, Ray presented the detailed study on different aspects of printed monopole antenna [Ray (2008)]. Naghshvarian-Jahromi introduced a PMA with wide bandwidth using Penta-Gasket-Koch slots [Naghshvarian-Jahromi (2008)]. Ahmed and Sebak presented a PMA having steps on top of monopole and a circular slot and a thin arc-shaped slot on the patch for band notch [Ahmed and Sebak (2008)]. In reference [Lin and Chuang (2008)], triangular monopole antenna with ridged ground plane was proposed for UWB applications. After that, PMAs were designed with improved performance in terms of size miniaturization, bandwidth enhancement, and radiation pattern stability. An elliptical monopole antenna with hexagonal ground plane along with wedges on sides of both patch and ground plane providing improved radiation pattern was proposed for universal mobile communication system (UMTS) and UWB systems [Thomas and Sreenivasan (2009)]. Deng *et al.* proposed a PMA with enhanced bandwidth of 17.7 GHz (2.3−20 GHz). It is composed of rectangular monopole antenna notched at bottom, a T-shaped CPW ground in the notch, and CPW ground out of the notch [Deng *et al.* (2009)]. Further, Elsheakh *et al.* utilized metallo electromagnetic band gap (MEBG) structure for bandwidth enhancement as well as size reduction of semicircular patch supported by semicircular ground plane [Elsheakh *et al.* (2009)a]. His group again used spiral artificial magnetic conductor (SAMC) with semicircular monopole antenna [Elsheakh *et al.* (2009)b]. The proposed SAMC improved the performance of the antenna in terms of gain, bandwidth and cross-polarization properties and made the antenna compact also. Thereafter, Li *et al.* proposed a spade-shaped monopole antenna with triple band-notch characteristics [Li *et al.* (2009)]. Triple band-notch was obtained by employing a pair of hook-shaped defected ground structure

(DGS) on ground, an Ω-shaped slot on patch and a parasitic octagonal-shaped ring on back side of patch. Subsequently, need was felt for design and development of UWB PMA with multiple band-notch characteristics so that interfering frequency bands can be suppressed without filters. Kim *et al.* proposed many types of microstrip resonators, such as open-circuited line resonator, short-circuited line resonator, closed-loop resonator and open-loop resonator [Kim *et al.* (2010)]. These resonators could be integrated with PMA to suppress the interfering bands. Thomas and Sreenivasan proposed a PMA with single band-notch capability by utilizing a small patch on opposite side of main patch and connected with main patch through a conducting via [Thomas and Sreenivasan (2010)]. Wu *et al.* utilized an open-loop resonator at the centre of fork-shaped antenna for WLAN band rejection from UWB [Wu *et al.* (2010)]. Zhang *et al.* proposed a segmented circular patch where the segmentation provides band-notch [Zhang *et al.* (2010)a]. Further, dual band-notch characteristic was achieved using an M-shaped slot on circular patch and another W-shaped slot on ground plane opposite to feed line [Sun *et al.* (2010)]. In reference [Abdollahvand *et al.* (2010)], dual band-rejection characteristic was achieved using Γ-shaped stub in radiating patch and modified G-shaped DGS on feed line. Again, Zhang *et al.* proposed a planar monopole UWB antenna, which was composed of annular ring patch with C-shaped slot on patch and complementary split ring resonator (CSRR) on ground plane for dual band-rejection [Zhang *et al.* (2010)b]. In this series, a triple band-notch characteristic was obtained using multiple semicircular ring slots and an L-shaped slot on radiating patch [Trang *et al.* (2010)]. Furthermore, very compact PMAs were developed employing different techniques. In reference [Zaker and Abdolali (2010)], staircase geometry on patch and a rectangular notch opposite to feed line on ground plane were utilized to obtain antenna size of 11×16 mm^2. In reference [Soltani *et al.* (2010)], asymmetric coplanar strip (ACS) fed half rectangular patch with staircase geometry was used to design the antenna having size of 12×21 mm^2. Later on, a modified pythagorean tree fractal attached with a T-shaped patch was proposed for UWB applications [Pourahmadazar *et al.* (2011)]. Similarly, in reference [Kumar *et al.* (2011)] a wheel-shaped fractal antenna was proposed.

Koohestani *et al.* developed a PMA, which consists of a dome-topped, bowl-shaped patch with a truncated tapered ground including a notch below feed line [Koohestani *et al.* (2011)]. After that, antennas in which patch and feed line are offset from center of substrate were also designed. In reference [Azim *et al.* (2011)], a rectangular patch with truncated ground having triangular-shaped slots on its top edge was proposed. Chen *et al.* proposed a PMA by embedding a semi-elliptically fractal-complementary slot into asymmetrical ground plane for super wideband applications [Chen *et al.* (2011)]. Afterwards, Yazdi and Komjani utilized a pair of arc-shaped parasitic elements around a circular patch for WLAN band-notched UWB applications [Yazdi and Komjani (2011)a]. They also utilized mushroom-like EBG structure on sides of feed line for band-rejection [Yazdi and Komjani (2011)b]. Further, Mishra *et al.* proposed a fork-shaped antenna for Bluetooth and UWB applications with WLAN band-rejection characteristics [Mishra *et al.* (2011)]. The band-notch was obtained using a pair of L-shaped slots on sides of ground plane. The research on PMAs for UWB with band-notch characteristics got a new dimension quickly through the utilization of resonant structures. Xu *et al.* used two spiral EBG structures with stepped rectangular patch for dual band-notch, where the spiral EBG is more compact than conventional mushroom-type EBG [Xu *et al.* (2012)]. Sung proposed a short-circuited folded stepped impedance resonator (SIR) for band-rejection and used it with circular PMA so that UWB with dual band-notch characteristic can be achieved [Sung (2012)]. Li *et al.* utilized interdigital capacitance loading loop resonators (IDCLLR) with circular PMA for suppression of narrow interfering WLAN bands [Li *et al.* (2012)]. These resonators have the property to resonate over very narrow band of frequencies. Meanwhile, Mehranpour *et al.* proposed a very compact PMA of size 10×16 mm^2 with dual band-notch function using a pair of L-shaped slits and an E-shaped slot on square patch and ground plane having protruded V-shaped strip [Mehranpour *et al.* (2012)]. Nguyen *et al.* proposed a compact PMA with triple band-notch function. UWB was achieved using beveled patch and ground plane whereas triple band-notch was achieved using three open-ended quarter-wavelength slots [Nguyen *et al.* (2012)]. In addition, Lu and Yen proposed an arc-shaped PMA with a rectangular parasitic patch for UWB applications [Lu and Yen (2012)]. Later on, a compact UWB PMA was designed using rectangular patch with etched half-elliptical slot and a pair of open-circuited stubs attached to ground plane [Xu *et al.* (2013)]. Zhang *et al.* proposed a broadband circularly polarized PMA using vertically long rectangular patch, a vertical stub attached to ground near patch, and a horizontal slit on ground plane attached to feed line gap [Zhang *et al.* (2013)]. Further, Wong *et al.* proposed a via-fed tapered monopole filter-antenna, which is compact, high in-band selectivity and insensitive to ground plane size [Wong *et al.* (2013)]. Furthermore, Sung proposed a modified H-shaped resonator for triple band-notch function which was used with a circular UWB PMA [Sung (2013)]. Afterwards, two rectangular UWB PMAs were arranged orthogonal to each other for UWB MIMO application [Liu *et al.* (2013)]. A vertical stub attached to ground plane was used for isolation improvement. Tang and Lin developed UWB MIMO antenna with dual band-notch characteristic [Tang and Lin (2014)]. In this antenna, two rectangular monopoles are placed side-by-side over a truncated ground plane and multiple strips are connected to patch through via for isolation improvement and band-rejection. Further, Kiem *et al.* proposed 4×4 UWB MIMO antenna using circular patches in orthogonal arrangement [Kiem *et al.* (2014)]. Bandstop filter was utilized for isolation enhancement and mushroom-like EBG structure for WLAN band-rejection. Thereafter, a single pentagonal patch with dual-polarization was proposed for UWB MIMO applications [Mao and Chu (2014)] while high isolation was achieved using a T-shaped slot etched on radiating patch, a stub attached to ground plane and a pair of slits etched on ground plane. Cai *et al.* proposed a compact wideband PMA with triple band-notch characteristics [Cai *et al.* (2014)]. The antenna is composed of rectangular monopole antenna having a rectangular slot and multiple spiral slots on feed line for triple band-notch characteristics. The PMAs with extremely wide bandwidth were also proposed. In reference [Ebadzadeh *et al.* (2014)], a circular patch with an arc-shaped slot and a pair of stepped slits fed through tapered microstrip line having elliptical ground plane was proposed for the frequency range 2.2−28.4 GHz with two notched bands. Further, in reference [Manohar *el at.* (2014)], a PMA with feed region employing exponential curve and tapered microstrip line was proposed for super wideband applications. The proposed antenna operates over the frequency range 2.5−80 GHz.

In 2015, the PMAs providing UWB were described for different applications. Bahrami *et al.* studied an implantable UWB antenna of size 12×12 mm^2 for neural recording system [Bahrami *et al.* (2015)] due to its advantages of low-power consumption, low cost, small size, and high data rate capability. Saghlatoon *et al.* designed an inkjet-printed wideband PMA on cardboard for RF energy harvesting applications [Saghlatoon *et al.* (2015)]. The antenna operates over frequency range of 600−1500 MHz, where several strong radio signals are available for ambient RF energy harvesting. Further, a compact monopole antenna was proposed for automotive communications and its diversity performance was studied [Alsath and Kanagasabai (2015)]. The patch of antenna consists of a half-circular and half-square ring structures whereas the ground plane was curved and defected by slots and a stub attached to ground plane for obtaining reduced lower frequency. Subsequently, Huang *et al.* designed a compact UWB MIMO antenna with triple band-notch function using curved monopoles placed in orthogonal arrangement [Huang *et al.* (2015)]. The triple notched bands were obtained using complementary split ring resonator (CSRR) slots on patch and a pair of C-shaped parasitic elements arranged along feed line. In addition, a compact UWB antenna was also proposed using planar patterned metamaterial structure [Islam *et al.* (2015)]. Recently in 2016, a compact UWB MIMO antenna was proposed which is composed of two identical stepped monopoles arranged side-by-side with a comb-line structure attached to ground plane for impedance matching and isolation improvements [Malekpour and Honarvar (2016)]. Zhao *et al.* proposed design concept of broadband PMA with improved pattern uniformity using ground-cooperative radiating structure [Zhao *et al.* (2016)]. They explained that "a properly designed metal ground can serve as a cooperative lower frequency radiator for reducing the antenna dimensions, broadening impedance bandwidth, and achieving almost uniform omnidirectional patterns over a wide frequency band". Further, Tang *et al.* designed a PMA with improved realized gain performance over UWB [Tang *et al.* (2016)]. The improved performance was achieved using an arc-shaped slot on standard elliptical monopole and a UWB multimode-resonator filter attached to feed line.

2.5 Quasi-Self-Complementary Antenna (QSCA)

QSCA is an advanced planar version of self-complementary antenna (SCA). The SCA is known to provide constant impedance independent of source frequency and shape of antenna structure. This remarkable property leads the antenna to achieve extremely broad bandwidth. The discovery and concept of utilizing such structures originated in 1948 [Mushiake (1948)]. In the same year, he studied rotationally and axially symmetric two-terminal self-complementary planar antennas [Mushiake (1949)]. This work was further extended to four-and multi-terminal self-complementary planar antennas with star, ring and other connections [Mushiake (1959)]. Few years later in 1963, a three-dimensional two terminal self-complementary antenna was described [Mushiake and Saito (1963)]. Probably after a gap of about fifteen years, self-complementary planar structure was further upgraded using checkerboard type structure [Inagaki *et al.* (1979)]. After the concepts of single element self-complementary structure was properly understood, study on multiple elements arranged in co-planar, side-by side, and compound form using stacked configurations was carried out in 1982 [Mushiake (1982)]. Later on, he studied mutual impedance between loaded uni-pole notch type SCA elements in 1996 [Mushiake and Kasahara (1996)]. In 2004, Mushiake summarized all his previous findings related to SCAs [Mushiake (2004)]. It also has been mentioned that the self-complementary structures can ideally offer infinite impedance bandwidth when designed on infinite large ground plane and excited through proper feed. However, these SCAs are not suitable for compact communication systems due to their large metallic structure.

The family of SCAs was advanced with the development of quasi-self-complementary antennas (QSCAs), which can be designed on PCB with inbuilt appropriate feed. In 2003, probably the first QSCA was proposed by Wong *et al.*

for WLAN application [Wong *et al.* (2003)]. It consisted of a T-shaped patch and a separate rectangular patch having similar T-shaped slit on same side of substrate of size 6×21 mm^2. The 50 Ω coaxial cable was used to directly excite the antenna and bandwidth of about 1.5 GHz was obtained. Similar type of QSCA with triangular patch and complementary slot excited using 50 Ω coaxial cable was proposed by Chen *et al.* in 2007 [Chen *et al.* (2007)]. This antenna operated over the frequency range 2.38 to more than 12 GHz (VSWR ≤ 1.25) and the size of the antenna was 75×75 mm^2. These QSCAs were directly excited through 50 Ω coaxial cable whereas the input impedance of SCA was about 188.5 Ω. Therefore, the antenna might suffer from impedance mismatch. This issue was mitigated by using impedance matching network built on same antenna substrate. In 2008, a novel QSCA having semicircular patch and complementary slot excited using CPW was proposed [Guo *et al.* (2008)]. This antenna achieved an ultra-wide bandwidth from 1.3 to more than 12 GHz with antenna size of 51.5×40 mm^2. Guo *et al.* further realized the microstrip line fed semicircular QSCA where patch and slot along with triangular notch were designed on opposite sides of substrate [Guo *et al.* (2009)]. The antenna achieved ultra-wide bandwidth from 2.86 to 10.7 GHz with antenna size of 16×25 mm^2. Again Guo *et al.* proposed a very compact (size of 19×16 mm^2) novel QSCA comprising of tapered radiating slot with Γ-shaped self-complementary structure for UWB application [Guo *et al.* (2010)]. Later on, Huang and Su proposed microstrip line fed quarter circular QSCAs of size 28.5×26 mm^2 for WLAN band-notched UWB applications. In reference [Huang and Su (2011)], band-notch was obtained using a parasitic arc-shaped strip placed opposite to quarter circular patch whereas in reference [Huang and Su (2012)], a parasitic fan-shaped patch was placed inside the quarter circular slot and in reference [Lin *et al.* (2011)], an inverted L-shaped slit was embedded on quarter circular patch. In 2012, again a similar compact microstrip line (MS) fed QSCA of size 25×15 mm^2 having rectangular self-complementary structure was proposed for UWB applications [Huang and Chen (2012)]. In the same year, Lin proposed CPW-fed bowtie QSCA with size of 10×35 mm^2 for UWB applications [Lin (2012)]. Lin *et al.* further developed microstrip line fed QSCAs for WLAN application with obtuse pie-shaped [Lin *et al.* (2013)] and rectangular [Lin *et al.* (2014)] self-complementary structures. In 2014, a very compact QSCA of size 19.7×19 mm^2 was proposed for UWB applications using half-elliptical patch along with two half-circular patches. After these discoveries, the QSCA was proposed for UWB-MIMO applications because it provides high isolation between the ports of MIMO antennas. Two element MIMO antenna using microstrip line fed half-circular QSCAs along with rectangular slit on ground plane arranged side-by-side was proposed by Liu *et al.*. The slit was used in reference [Liu *et al.* (2014)a] for improved isolation whereas in reference [Liu *et al.* (2014)b] and [Yu *et al.* (2014)], four element MIMO was proposed without any other isolation improvement technique. Recently, a dual polarized two- and four-element MIMO antennas with band notch characteristics using quasi-self-complementary structure was proposed [Zhu *et al.* (2016)].

2.6 Summary

It has been observed through the review on the historical development of broadband antennas that advances in antenna have allowed the reduction in its size and improvement in its bandwidth. Both the non-planar and planar antennas are important depending on the suitability for various applications including wireless communication and radar as well as navigation applications. The TTLPA is one of the established antennas for broadband applications where the antenna is fixed in its position and bidirectional radiation pattern is required. The bidirectional radiation pattern can be obtained through balanced TTLPA having two symmetrical arms, which require an appropriate balun with proper impedance transformer. Furthermore, many bandwidth enhancement and size reduction techniques were proposed for log-periodic dipole array (LPDA) but these are not compatible with metallic sheet TTLPA. Therefore, research on bandwidth enhancement and/or size miniaturization techniques for TTLPA need to be investigated further.

At the same time, planar antennas are prominent for mobile handheld communication devices. It is also observed through review on PMAs that the shape of patch and partial ground plane near feed region plays an important role for obtaining broad impedance bandwidth as well as lower cutoff frequency. Many PMAs were designed and developed using basic geometries as well as curved structures but little amount of work has been done on PMAs using geometries of natural structures such as flowers, leaves, and trees. Further, it is observed through survey of recent literature that PMAs are being utilized for UWB MIMO antennas with band-notch characteristics. In addition, the QSCA is a good candidate for the design and development of compact MIMO antennas but still scope exists to do further research work on compact broadband MIMO antennas using natural-shaped structures and co-radiators.

Keeping in view the aforesaid aim and scope to do further research work on broadband TTLPAs, PMAs, and QSCAs, the author has done simulation and experimental studies on different non-planar and planar antennas which are discussed in following chapters of the thesis.