Chapter - 1

Introduction

1.1. Background

Antennas are essential front end entities of modern wireless communication systems. Today's wireless communication systems utilize planar antennas those are popular over other types of radiators especially in personal communication devices for wireless access. The reason for popularity of planar antennas is essentially credited to their being economical, low profile and easier integration with portable and personal communication devices. The advantages of planar antenna do accompany some drawbacks too, e.g. narrow bandwidth, poor radiation efficiency, and low power handling capacity. The limitations of patch antennas that need to be addressed in present communication system are their intrinsic narrow-band behavior and the polarization purity (Pozar 1995). A signal transmitted by any radio base station cannot maintain its polarization state as it transverses towards the mobile terminal device due to channel properties. Thus, the polarization purity of antennas installed in terminal devices cannot be represented as a very strong design constraint (Collins 1979). Even with aid of statistical analysis, it is hard to predict the polarization state of signal received on an antenna (Salah 1987) which implies antenna should not be designed on pure polarization assumptions for the reception. High cross-polarization levels of an antenna do not deteriorate the radio-link performances such as in cellular or satellite communications and they certainly represent an obvious choice for polarization diversity applications (Lee 1972). The pretension of satisfying broader bandwidth requirements is demolished by a constraint that compel to keep the antenna dimensions as compact as possible. In earlier generation of communication systems, the task was usually accomplished by techniques that rely on introducing slots or using reactive loads, but in current and future generation systems, subscriber expectation from service providers is extensive and thus, novel solutions should be explored.

Microstrip antennas are used in Satellite Communications for Domestic direct broadcast TV, vehicle-based antennas, the global system for mobile communication (GSM), and GPS. Smart weapon systems use microstrip antennas because of their thin profile. Initially microstrip antennas were designed for defence applications but soon it got release in commercial domain. Radar altimeters use small arrays of microstrip radiators. Patch antennas have been used on communication links between ships and satellites. Other related applications include antennas for communication and navigation, altimeters, blind landing systems, telephone and satellite communications. There are many applications in wireless communication that uses patch antenna for more than one distinct band of frequencies.

To ensure wider number of services operating around different carrier frequencies, possibility of a multi-frequency operation is expected in a communication link. Broad-band and multi-frequency operation depend on the excitation of two or more resonances those are excited near each other in the case of broad-band antennas while resonate far apart in the case of multi-frequency operation. Among the geometries of patch antennas that show multiple resonances (James 1989; Wang, 2001; Sabban 1983; Yang, 2001; Tunski 2001), polygonal patch shapes are interesting subject of research. The patch dimensions, the number of edges, slope of edges etc. represent suitable degrees of freedom for an antenna designer to explore and excite multiple resonances in order to achieve broadband or multi resonant character for the antenna (Bilotti 2001; Billoti 2003a; Billoti 2003b).

Computational electromagnetic using supercomputing capabilities can model complex electromagnetic wave interactions, in both the frequency and time domains. Innovative antenna designs to perform complex and stringent functions always remain a challenge (Balanis 1992). Kolundzija et al. (Kolundzija 2000) proposed an automated meshing of polygonal surfaces to segment a polygonal model into convex quadrilaterals to analyze efficiently as per electromagnetic theory. Sorokosz et al. (Sorokosz 2012) confirms that a circular patch can be approximated with an appropriately designed polygon, when model analysis is performed. In the last two decades, many commercial simulation softwares e.g. computer simulation technologies (CST) Microwave Studio (MWS), Ansoft HFSS etc. have supported the rapid advancement of patch antenna research. They have become fundamental tools in design and simulation of planar antennas. Method of moments (MoM) uses integral equations that are obtained for the fields produced by unknown currents to satisfy the excitation and boundary conditions. The full wave (FW) method or the finite-difference time-domain (FDTD) method converts Maxwell's equations into difference equations. The finite element method (FEM) solves Maxwell's equation in the form of the vector wave equation by the Rayleigh–Ritz variational method (Lee 2012). Yikai et al. (Yikai 2013) reviewed characteristic modes for radiation problems from antenna design to feeding design and found that with the help of many unique and attractive features of control managements, physical understandings to the radiating problems can be much clearer, computation burdens in antenna optimization procedure can be greatly alleviated, and designs with favorite features such as compact and low profile can often be obtained. CST MWS Suite allows virtual prototyping phase of one's design, minimizing unexpected surprises one may get, once a physical prototype is constructed and measured in the laboratory.

Various techniques are available for fabrication of microstrip patch antenna but a commonly popular economical fabrication technique such as wet-etching method will be more suitable in case one of the objectives is technology-transfer to industry in near-future. Photolithography technique can be used to transfer the mask image on electroplated copper on printed circuit board (PCB) board using negative photo resist and then it is developed in a developer solution. The unexposed unwanted features were etched out in a etching chemical solution.

Polygonal with odd number of edges as in case of pentagon geometries may be of a symmetrical shape as that of a regular hexagon with even number of edges or they can be asymmetric too. The resonant frequencies of a regular patch depends on the geometry of the conductor, after substrate thickness and permittivity are decided. The resonances along the frequency axis may be dominated by exploiting suitable degrees of freedom (Billoti 2003b). Polygonal Patch geometries can be triangular or rectangular as per conventional definition of word polygon but in general conception, polygon refers to geometries with edges greater than or equal to five (Garg 2001). The text in the thesis will follow this general conception.

1.2. Literature Survey

Economic printed monopole antenna with low power operation, wide impedance bandwidth and ease of manufacture are required for modern communication systems. Various stripline fed printed monopole antenna designed such as circular, triangular, square and hexagonal have been presented (Kumar 2002), but regular designs such as triangle, rectangle and square have relatively less bandwidth (Agrawall 1998). Hexagonal is popular geometry used to design a stripline fed monopole antenna (Zhao 2016) (Li 2014) (Tripathi 2014) (Dastranj 2017) (Shaalan 2010) (Yadav 2017) and investigated in detail by Ray et al. (Ray 2010a) (Ray 2010b) (Ray 2010c). The literature on microstrip patch antenna is dispersed over thousands of research articles in classical journals. Lee et al. (Lee 2012) reviewed methods to develop patch antenna in 2012 to find that all the techniques reported to broaden the operating bands of patch antennas results in increased volume, which alleviate the low profile merit of microstrip patch antennas. The quest of wideband, efficient, and low profile patch antennas designs is still considered to be one of the holy grails in antenna research community (Lee

2012). Bilotti et al. (Bilotti 2010) have presented polygonal patch design with broader operating band to work with portable gadgets of the new generation mobile systems. It has been shown that integration of wireless functionalities like, multi-frequency operation, and accommodation of a camera in regular universal mobile telecommunication system (UMTS) antennas, without changing the shape and increasing the space occupancy is possible (Bilotti 2010). For UMTS & wireless local area network (WLAN) wireless applications, Manzini et al. (Manzini 2004) proposed an economical antenna with broadband/multi-frequency operation modes based on polygonal shapes.

Selection of dielectric substrate for patch antenna is one of the significant aspects of the antenna design. Many researchers have exploited different dielectric substrates with different permitivities for patch antenna in different applications. Griguer et al. investigated 3D Metamaterial for the Enhancement of Patch Antenna Radiation that has shown an improvement on the directivity (Griguer 2009). A planar (2D) antenna array comprised of planar polygon slot antenna elements utilizes a metamaterial inspired reactive coupling element on a Liquid Crystal Polymer (LCP) substrate of a 16-element planar X-band bidirectional antenna array for beamforming applications (Chieh 2013). A star-shaped fractal design of rectangular patch antenna side lobe level is reduced with the introduction of slots. The measured gain increases from 5.479 dB to 11 dB and bandwidth from 550 MHz to 5 GHz after design exploits the air gap present between the substrate and the ground plane to improve effective permittivity (Jilani 2013).

Microstrip patch antennas can be fed radio frequency (RF) energy by a variety of techniques. These techniques can be classified into two categories- contact feed and non-contact feed. The most popular contact feeding techniques are the microstrip line feed and coaxial probe feed while popular non contact feeding technique are aperture coupling feed and proximity coupling feed. Balanis compares the properties of all four types of feeding schemes which is summarised in Table 1 (Balanis 2016). Printed monopole antenna with tapered feed line was used for super wideband (2.5-80 GHz) applications (Manohar 2014). Coaxial or Probe-fed triangular patch integrated with a pair of monopoles exhibits multi-band characteristics and high gain, when a reflector ground plane was placed below the patch (Jhamb 2011).

Table 1.1. Comparison between different feeding technique (Balanis 2016)

Characteristics	Microstrip Line Feed	Coaxial Feed	Aperture coupled Feed	Proximity coupled Feed
Spurious feed radiation	More	More	Less	Minimum
Reliability	Better	Poor	Good	Good
Ease of fabrication	Easy	Soldering and drilling needed	Alignment Required	Alignment Required
Impedance Matching	Easy	Easy	Easy	Easy
Bandwidth (achieved with impedance matching)	2-5%	2-5%	2-5%	13%

Distinct geometries of patch antenna like triangular, rectangular, pentagon, hexagon, etc. are well explored by many researchers. Any antenna design suitable to operate in different impedance bandwidth can be realized by changing the dielectric constant of substrate, patch dimension and metal thickness of the conductor strip. When a thick substrate is used, the bandwidth of patch antenna with probe feed is narrowed by inductance introduced by probe or coaxial feed (Balanis 2016). A L-shaped probe was utilized to feed a circular patch antenna to produce conical radiation pattern as reported by Guo et al. The probe horizontal part with the patch conductor behaves as an open circuited stub and compensates the probe inductance by the vertical part, using the L-probe feeding (Guo 2004). The transmission line model (TLM) was utilized by Vishwakarma to theoretically evaluate the series and shunt inductance introduced by the probe and the shorting pin. It was found that the resonant frequencies' ratio is extremely dependent on the location of shorting pin (Vishwakarma 2009). Mousskhani et al. proposed a new broadband transmission line model for rectangular microstip antennas by combining circuit models with different modes (Mousskhani 2008). A compact probe-fed microstrip patch antennas with folded patch feed techniques for UWB applications was proposed and analyzed using equivalent transmission line model to achieve an impedance bandwidth of 92% in the frequency range of 3.94–10.65 GHz (Malekpoor 2015).

Hexagonal structure is preferred over other geometries since it generates wider band but with higher order modes (Ray 2010) (Zhou 2011) (Ghaderi 2011). The hexagonal geometry can be further exploited to generate lower modes and achieve a wider or an ultra-wide-band. Different ground structures and defects such as rectangular ground, stepped ground or different shapes of slot within the ground plane have been explored to design a UWB antenna (Bekasiewicz 2016) (Alsath 2015) (Kumar 2014). Modern radio frequency S-band communication systems such as Wi-Fi, 5G, 4G (TD-LTE), WiMAX, Internet of Things (IoT) require broad impedance bandwidth in order to fulfill stringent requirements (Balanis 2016) (Alibakhshikenari 2018) (Alibakhshi-Kenari 2016). Consequently, many wideband S-band antennas has been studied, explored and reported (Hong 2005) (Li 2014) (Joshi 2018a). But wideband patch antennas have low boresight gain over the operating band due to the presence of higher order radiating modes. A low profile patch antenna with a gain less than 3 dB was reported (Hong 2005). Antenna performance in terms of axial ratio (less than 3 dB), improvement in bandwidth with aperture coupled equilateral triangular shaped microstrip patch antenna was observed (Sharma 2008). Luis Brás et al. developed pentagonal patch-excited sectorized antenna for localization systems for an operating band of 2.4–2.5 GHz with approximately semispherical radiation pattern (Bras 2012). The shape of rectangular aperture is translated to an irregular octagonal aperture to achieve broader impedance bandwidth from 2.8 GHz – 4.9 GHz (Gunavathi 2009). The antenna, firmware and application and comparison of the performance of the Hive5 with a wireless sensor network (WSN) of four nodes under the same fingerprinting algorithm, an artificial neural network (ANN) are also discussed (Bra 2013).

Circular, rectangular, and triangular microstrip antenna with a rectangular ring on a thick substrate with low dielectric constant, were explored at lower frequencies of microwave range for modern wireless communication systems (Kumar 2002). The stub-loaded coplanar waveguide-fed hexagonal shaped microstrip antenna with similarly shaped slotted ground plane was proposed in (Deshmukh 2015) that yielded impedance bandwidths of 108% and 115% centered at 3.7 GHz and 3.64 GHz, respectively. The introduction of hexagonal slot in a hexagonal patch antenna design, to improve gain characteristics was studied and analyzed in (Joshi 2015c). The coplanar waveguide-fed regular hexagonal slot antenna was fabricated that demonstrated a bandwidth of 55.39% at the center frequency of 2.2 GHz, covering wireless communication bands including GSM1800, GSM1900, IMT2000, and WLAN (Sari-kha 2006). The perturbed hexagonal dual-band patch antenna with a circular slot and vertical slits for wearable applications operating in the GSM-900 and 1800 bands was presented in (Sundarsingh 2014). Choo et al. (Choo 2005) investigated radio frequency identification (RFID) reader antenna for operation in the ultra high frequency (UHF) band and a new helix antenna called the multi-layered polygonal helix antenna (MPHA) was proposed. To overcome the null-reading problem of dipole-type RFID tag applications a triple-feed RFID tag antenna can be employed that possesses a near-3D omni-directional radiation pattern, with a gain deviation of less than or equal to 3.0 dB (Lin 2009). Polygonal helix antennas were investigated to find critical design parameters i.e. the number and the shape of the polygonal layers to control the gain and the radiation pattern of the antenna (Choo 2005). Mandal et al. proposed an antenna that consist of a rectangular radiating patch with a star shaped slot and a plus shaped conductor backed plane, that provided a fractional bandwidth of 122% (5.25 to 21.61 GHz) (Mandal 2015) respectively. A shape of six armed star polygonal patch antenna with slot was suggested to achieve reconfigurable antenna structure. A tapered monopole antenna investigated in view of UWB wireless body area network (WBAN) applications yields a larger bandwidth (Verbiest 2006). The design of compact multimode patch antennas for multiple input and multiple output (MIMO) applications uses the short-circuited ring patch antennas for high system spectral efficiency (Herscovici 2008). Kanth et al. (Kanth 2009) presented dual band fractal antenna for a new resonant frequencies of 1.176 GHz and 2.487 GHz allotted to Indian Navigational Satellite Systems. A triangular shaped corner truncated short circuited antenna was designed and simulated for operating in two bands viz Band I (2.5 GHz–2.7 GHz) and Band II (3.4–3.7 GHz) (Singh 2010). A rectangular patch antenna and a circular patch antenna were compared using the simulation results obtained from CST MWS for X-Band applications (Nayna 2014). A hexagonal microstrip antenna was designed that operates for S-Band i.e., 2-4 GHz (Suganya 2015). Babar et al. discussed that the use of U-Slot, truncated corners and Electromagnetic Band Gap structures to achieve dual band (circular polarized at 3.65 GHz band) antenna with enhanced performance. Dual band characteristic was achieved using U Slot in the conducting patch, CP in the lower band was attained using truncated corners and lastly EBG structures were deployed and evident improvement was noticed among certain aspects of the antenna (Babar 2015). Chandran et al. optimized gain and bandwidth using genetic algorithm with iteration of 20 of a rectangular microstrip patch antenna by implementing a combination of different kinds of slots on the patch surface and ground plane has been simulated using Ansys

HFSS. The gain has an improvement of about 18.6% and almost 100% for bandwidth after optimization (Chandran 2014). In the last three decades, research has been devoted to improve the performance of any antenna by varying critical parameters.

By perturbing sides of a rectangular patch geometry, a convex polygonal radiator can be developed to obtain Broadband behavior (Billoti 2003b). Alu et al. (Alu 2003) indicated a proper perturbation of patch shape may improve antenna performance. Broadband or a multi frequency behavior was also exhibited by Alu et al. using polygonal patch antenna design. It is possible to configure the radiation pattern of a Hexagonal Fractal Antenna using the control algorithms making it steerable in real time environment (Saidatul 2007). A printed hexagon antenna with band-notch function presents nearly omnidirectional radiation patterns and impedance matching over the UWB frequency spectrum excluding the WLAN sub band (Dong 2008). A relatively compact UWB antenna was designed to exhibit a band-notch function and to eliminate interference signals from WLAN systems such as IEEE 802.11a and high performance radio LAN (HIPERLAN) (Naser-Moghadasi 2010).

Economic and compact microstrip patch antennas for wireless services such as wireless local area network (WLAN) are omnipresent in our daily life. A stacked patch antenna was proposed earlier to achieve monopole like radiation pattern with a gain of 6 dBi for broadband WLAN band from 5.15 to 5.9 GHz at higher order mode (TM_{03}) (Liang 2016). Compact patch antenna with shorted parasitic patch with a gain between 5.3 and 7.3 dBi across the operating band for dual band 2.4 and 5 GHz WLAN operation was presented by Chang et al. which can be implemented in ceiling-mount access points (Chang 2008). A V-shaped slot was introduced by Wong et al. along with shorting pins in a triangular patch antenna for indoor WLAN communications. Multiple modes present in the operating bandwidth (4.82 to 6.67 GHz) resulted in wideband characteristics with a gain of 5 dBi and omnidirectional radiation pattern (Wong 2016). Parasitic elements were used to design a slot-coupled WLAN antenna operating at 4.095 -5.845 GHz for the outdoor access points (Yeom 2014). Parasitic patches and chocks were used to achieve the gain of 8 dBi.

Ground plane geometry plays a vital role in design of polygonal patch antenna. which Choi et al. (Choi 2014) presented the use of the triangular element based surface mesh to solve for the impedance profile of power and ground planes enables effective discretization of multi-dimensional and irregular geometries extended to multiple plane pairs and the modeling of apertures located on any layer. Ground modified double-sided printed compact ultra wide band (UWB) antenna with triangular shaped slots on the top edge increases the impedance bandwidth (Azim 2011).

Hexagonal monopole antennas fed at the edge and the vertex are widely explored at lower frequencies for modern wireless communication systems (Kumar 2002). Deshmukh et al. (Deshmukh 2015) proposed a hexagonal shape microstrip antenna with co-planar waveguide feed, backed by hexagonal slot ground. The two variations in which patch were rotated by 30° were investigated which yields impedance bandwidth of 100% and 108% respectively. A X-Band hexagonal shaped microstrip patch antenna that has a bandwidth from 9.21 GHz to 9.38 GHz was discussed by Das et al. The return loss was improved and resonant frequency was shifted by introducing slots on the sides of the patch (Das 2015). Hexagonal slots were introduced by Datta et al. to reduce the patch size by about 80.22% has been simulated using Method of Moment based software IE3D (Datta 2013). Agrawal et al. designed and presented a hexagonal shaped antenna with second iteration fractal for ultra wideband (UWB) application (2.64-6.96 GHz). The ground slot and slit variation were also simulated with a gain of 2.84 dBi at 3.8 GHz and a maximum gain of 5.2 dBi at 6.5 GHz (Agrawal 2012).

Printed antennas can be useful as a communicating element, sensor or energy collector. Reig et al. (Reig 2014) reviewed printed antennas for sensor applications and discussed the utility of the inherent characteristics of printed antennas for smart sensor systems. Strain, gas concentration, bioactivity and other magnitudes can be measured as a change in a printed antenna parameter, such as input impedance or resonant frequency. Mansoul et al. (Mansoul 2014) simulated and measured a selective frequency-reconfigurable monopole antenna for cognitive radio applications with a reconfigurable integrated filter in the ground plane. The antenna can be operated either in a wideband mode or in one of four sub-bands, which allows using it for sensing the wide band. Modern radars and other systems of commercial and military interests are desired to have re-configurability. Producing high power reconfigurable antennas for these systems is a big challenge (Nawaz 2013). A coupling patch with three shorting legs over the monopole is introduced to reduce the lowest frequencies of operation, and a circular top-loading disk located on the top of the coupling patch further extends the lowest frequencies of operation. The antenna is simple in structure and has wideband impedance bandwidth with stable radiation characteristics over the entire frequency band. It can be widely used in indoor distributed antenna systems with its outstanding characteristics (Zhou 2014). Rhee et al. (Rhee 2014) simulated and measured frequency-reconfigurable antenna for broadband airborne applications using modified biconical unipole antenna. The antenna is reconfigured using a p-i-n diode switch and do not cover the entire operating band at the same time. It can be used as a high-power antenna designed to withstand up to 18 W for aircraft applications.

Rütschlin et al. (Rutschlin 2013) reviewed the reconfigurable antennas that they are consequential devices to design. Design complexity needs to be considered, although hybrid electromagnetic (EM) -circuit co-simulations allow the actual switch along with behavior their packaging effects to be taken into account. The design optimization of any reconfigurable antenna must consider its performance in all possible operating modes generated by the geometry of the antenna. Perruisseau et al. presented an antenna exhibiting a wide bandwidth including a rejection band where dynamic control was demonstrated through

PIN diodes based 4-states implementation that was adaptable in terms of location of the rejection frequencies (Perruisseau-Carrier 2010). Kim et al. (Kim 2012) designed a broadband millimeter wave antenna with high gain. A guard ring resonator was introduced to the conventional patch antenna structure to suppress the propagation of the surface wave and extend the bandwidth of the antenna, while the dual resonator structure increased the antenna gain. Harrabi et al. (Harrabi 2013) designed and implemented a broadband antenna operating in X-band with a footprint of $0.7\ \lambda_0 \times 0.7\ \lambda_0$ compatible with an antenna array that radiated in the upper level with a maximum directivity of 5.1 dBi. A wearable dual-band patch antenna provides two paths for currents, making it viable for dual resonances. The effect of patch dimension, slot radius, and slit length on the antenna performance is investigated by performing a comprehensive parametric study (Sundarsingh 2014). Performance of Flexible wearable antennas for global positioning system (GPS) reception was evaluated on different garment-based substrates. A corner-truncated square patch antenna achieves desired circular polarization (CP) performance if the effects of the printing film are included in the antenna design (Heikkinen 2006). Thakare et al. suggested fractal-based antenna geometry helps to reduce size of antenna as well as backscattering radar cross section as compared to conventional antenna geometry. Backscattered radar cross section (RCS) reduction is a function of the dielectric thickness. A superstrate loading on the metallic patch can be used for frequency tuning, bandwidth enhancement and RCS reduction (Thakare 2010). Fractal antennas with high permittivity ceramic layers such as titanium dioxide (TiO2) are excellent design to be mounted in compact gadget for wireless communications (Medeiros 2012).

A co-planar waveguide (CPW)-fed hexagonal fractal antenna for UWB was proposed with acceptable radiation characteristics for communication applications (Neyestanak 2010). Tang et al. (Tang 2004) observed wideband behavior similar to the Sierpinski gasket antenna by designing a fractal antenna based on hexagon (Tang 2004). Ma et al. (Ma 2010) proposed a

CPW-fed triple-band quasi-fractal monopole antenna using Sierpinski triangle for WLAN wireless interoperability for microwave access (WiMAX) applications. By adjusting the circumradius of hexagon and the size of multistep in the ground, a triple-band is obtained with omni-directional radiation characteristics. A comparative performance analysis of two microstrip fractal patch antennas, one based on Square Minkowski Island while the other on Triangular Koch Loop was executed. The analysis concluded that Triangular and Square Koch Loop based antenna exhibit different performance characteristics on miniaturization using fractal procedure (Moraes 2011). Fractal antenna array was reviewed and fractal geometry was explored to obtain a dual band frequency selective surface (FSS) (Werner 2003). Fractal Antenna was analyzed to find that as the fractal iteration increases, perimeter of patch increases and effective area of antenna decreases while the radiator exhibits wideband characteristics (Dalsania 2012). A general procedure for the construction of fractal multiband antennas has been presented along with results for a pentagonal design (Tang 2003). Resonant frequencies increases with an increase in the fractal iteration of the pentagon used to construct the multiband antenna. Fractal geometry reduces the size of conventional patch antenna by shifting the first resonant frequency towards lower range. The self similarity in the fractal geometry of antenna allows multi resonant properties to an antenna. The 3D-self-similarity fractal antennas have acceptable resonant resistance and constant input impedance at the high frequency bands. It is suitable for designing compact antennas with multiple resonances (Elkamchouchi 2007).

A star shaped fractal antenna design and its performance up to five iterations has been discussed in detail in one of chapters of reference (Balanis 2016). The maximum gain of a star shaped circular microstrip fractal antenna designed for commercial and military wireless applications was 5.5 dB at 2.37 GHz (Kumar 2008). Benazir et al. has applied the concept of fractal to circular patch with star triangular antenna to achieve multiband and broadband for super wideband application. It has been shown that maximum bandwidth is achieved at the higher level of iteration that cover the entire frequency band from 1 to 30 GHz (Benazir 2014). Kumar et al. has designed, fabricated and tested a star shaped circular multiband fractal antenna resonating for military as well as communication applications at multiple frequencies and concluded that fractal geometry of conventional antenna reduces the size of antenna by shifting the first resonating frequency toward lower side and the self similarity in the geometry of antenna gives multiband resonances. It exhibits multiple resonances at 0.845 GHz, 1.47 GHz, 2.47 GHz, 3.05 GHz. It was observed that the maximum gain of the antenna is 5.5 dB at 2.47 GHz (Kumar 2008). A star shaped fractal design of rectangular patch antenna was proposed to improve gain from 5.479 to 11 dB and attain an improvement in bandwidth from 550 MHz to 5 GHz by introduction of fractal geometry. The antenna achieved the bandwidth of 9 to 14 GHz covering X-Band and Ku-Band. The antenna was proposed for various applications in radar, motion detectors, amateur radio operation, communication system and aerospace (Jilani 2013). Waladi et al. (Waladi 2013) investigated a star-triangular fractal monopole antenna for super-wideband (1 to 30 GHz) applications to conclude that by increasing the number of iterations and optimizing antenna parameters, a good impedance matching and improvement in bandwidth is observed.

Economical and compact UWB antennas are always in demand for wireless broadband communication systems and networks. High data rate, wireless connectivity, longer range applications and compactness have become essential requirements for trending generation of UWB wireless communication systems (Adamuik 2012) (Schantz 2015). In order to cater these requirements, antennas with large impedance bandwidth and low power dissipation are required (Wiesbeck 2009). The solution for such a requirement can be a planar monopole antenna (Nikolaou 2017). UWB monopole antennas are recently explored as required for internet of things (Bekasiewicz 2016) and automotive communications (Alsath 2015).

Compact UWB antenna designs pose quite a challenge at lower microwave frequencies, since the operating wavelength increases at lower frequencies (Li 2017). Microstrip-fed hexagonal slot antenna with monopole radiation characteristics for UWB application was earlier proposed in (Ghaderi 2011). The challenge to achieve UWB at lower frequencies is solved by exciting multiple modes.

A UWB multiple input, multiple output (MIMO) antenna with different characteristics modes was designed with diverse radiation pattern and high isolation (Zhao 2018). Different modes can excite desired diverse radiation patterns. The diverse mode can be combined to achieve wide band or ultra wideband antenna. Various UWB antennas have been designed using microstrip line feed (Toktas 2017) (Yang 2017) and CPW feed (Tanyer- Tigrek 2010). A CPW fed hexagonal fractal antenna with slot for super wideband applications has been investigated (Singhal 2016). Probe-fed patch antenna using folded patch feed, U shaped slot, E-shaped edges for UWB applications has been designed and analyzed using equivalent circuit model (Malekpoor 2015).

Demand of economic UWB antenna with high gain and stable radiation pattern are increasing for recent high data rate wireless communication systems (Addaci 2016). UWB monopole antenna such as triangular, rectangular, hexagonal and elliptical (Ray 2008), have unstable boresight gain over the entire radiation bandwidth, the beam squints at boresight due to presence of higher modes at higher frequencies within operating bandwidth (Thajudeen 2014). Especially, hexagon and its configurations are used for designing UWB monopole antennas for enhanced bandwidth (Tripathi 2014) (Ghaderi 2011), but generally hexagon excites higher modes (Ghaderi 2011) (Joshi 2018a) and provides low gain at them (Ray 2013), consequently provides non-uniform and non-directional radiation pattern. It is necessary to recognize a method to generate directional radiation pattern in UWB monopole antenna with hexagonal patch for stable and consistent radiation pattern. Peak Gain of the

UWB monopole antenna may be enhanced through various techniques such as frequency selective surface (FSS) (Tahir 2017) (Tahir 2016) (Krishna 2015) (Krishna 2014), artificial magnetic conductor (AMC) (Dewan 2017) (Hosseinipanah 2010) (Park 2013) (Yeo 2012) (Zhang 2012), by adding parasitic element (Zhang 2012), etching polygonal slot on antenna (Joshi 2015), using superstrates (Haraz 2012) and surface mounted horn (Ranga 2010), out of which boresight gain can be enhance by using parasitic element (Zhang 2012). Using superstrates and parasitic elements tremendously increases the volume and area of the antenna respectively.

Boresight gain of planar antennas can be enhanced by the introduction of additional structure in the ground plane as demonstrated in (Thajudeen 2014) but the technique increases the antenna dimensions. The antenna designed in (Thajudeen 2014) has an average boresight gain of 3.4 dB within operating band and overall dimension of 81.7 × 103.12 mm2. The gain of a planar antenna can also be enhanced by enlarging the electrical size using the shunt inductive effect of shorting pins (Zhang 2016), but involves tedious job of identifying accurate location for shorting pins. Another way of increasing the gain of a patch antenna is introduction of slots in ground plane. High gain planar antenna can also be designed by introducing six triangular slots in the ground plane, which results in a defected ground structure (Mandal 2013). Rectangular slot in the ground plane is etched to achieve high gain in patch antenna (Kanaujia 2016). Defects in ground plane such as introduction of different geometries of the slot or modification of the ground plane geometry can significantly enhance the gain of the patch antenna at higher frequencies within the antenna operating band. Ray and Tiwari proposed a stripline and vertex fed hexagonal monopole antenna that exhibited wideband characteristics with an average peak gain of 5.11 dBi, but with overall dimensions of 150 × 150 mm2 (Ray 2010). A vertex-fed hexagonal and hexagonal flower fractal antenna was earlier proposed for multiband applications (Bahuguna 2013) (Bahuguna 2013).

Various feeding methods such as probe feed, inset feed or strip line feed, coupled feed and coplanar waveguide (CPW) feed are available for antenna designs but strip line and CPW feeds are popularly used to excite a UWB antenna in order to achieve impedance matching and to avoid spurious radiation due to feeding apparatus (Toktas 2017).Due to requirement of large ground plane size for CPW fed antenna, asymmetry in CPW and stripline has been introduced in order to achieve impedance matching over the entire UWB band (Liu 2014). Asymmetry in the direct fed such as modification of the probe diameter and modified feeding are used for bandwidth enhancement (Emadeddin 2018) (Liu 2011). Due to limitation of CPW fed antennas for overall compact structure, efficient direct probe feeding becomes a suitable choice. But, direct-fed UWB monopole antenna using a coaxial probe or connector is a challenge for antenna researchers. A compact probe-fed microstrip patch antennas with folded patch feed techniques for ultra wideband (UWB) applications was proposed and analyzed using equivalent transmission line model to achieve an impedance bandwidth of 92% in the frequency range of 3.94–10.65 GHz (Malekpoor 2015). Lim (Lim 2005) fabricated a grounded co-planar waveguide (GCPW) fed hexagonal antenna over an economical FR-4 printed circuit board that exhibited excellent impedance bandwidth over the UWB frequency range. Omar et al. (Omar 2012) fabricated an easy-to-design UWB antenna operating in the federal for communication commission (FCC) band that again employs a CPW to feed a triangular monopole antenna. By addition of small fractal elements to a polygon-shape CPW-fed monopole radiator, coverage of standard UWB bandwidth (3.1–10.6 GHz) was achieved with antenna dimensions only of 25 × 25 mm2 only (Fallahi 2013). Antenna feed plays a significant role in exciting higher order mode and modification of the feed such as using larger diameter probe may permit antenna to generate higher order mode (Emadeddin 2018). Even with a modified connector feed, design of a probe-fed UWB planar antenna is still a challenge for antenna research community.

According to the literature survey done it is found that the advances in patch antennas of last three decade have been impressive, while key challenges such as wideband and high gain still attracts researchers due to subscriber demand. Antenna size reduction or miniaturization (Khan 2015) (Fallahpour 2018) (Gao 2018), operating band enhancement (Chu 2016), achieving re-configurability (Oliveri 2015), reflector (Dahri 2017) etc. continues to be the big challenge while designing polygonal patch antenna for wireless communication systems.

1.3. Research Motivation

Literature survey concludes that although many researchers have explored polygonal geometries through their work but a systematic approach to understand the effect of polygonal geometry over antenna performance has not been undertaken in past and still is an interesting subject of research. The main limits of polygonal patch antennas in present communication system are both the intrinsic narrow-band behavior and the polarization purity. The objective is to cater the today's bandwidth requirement by keeping the antenna compact.

Every novel patch antenna that should be designed, developed and characterized should achieve some of the common patch antenna features such as compact antenna size, operating band enhancement, gain-enhancements etc. The ground plane defects and fractal geometries are helpful in reducing the size of antenna by shifting resonant frequency to lower side and thus should be explored. A printed circuit board with FR-4 as a dielectric will be an economic approach for designing the polygonal patch antenna. Recent studies point towards use coaxial-feed as one of the approaches that may yield multiband or broadband antenna characteristics which may be further exploited to achieve super wide-band characteristics. Literature review reports various attempts to address polygonal patch antenna(s) and to explore it more.

Multi-frequency operation for different carrier frequencies for various services is used in a wireless communication system. Multiple resonances are closely spaced in case of broadband operation, while in case of multi frequency operation posses distant spaced multiple resonance. Geometries of patch antennas that show multiple resonances (James 1989) (Wang 2001) (Sabban 1983) (Yang, 2001) (Tunski, 2001), polygonal patch shapes are interesting subject of research.

Based on the literature review and interaction with the experts and researchers during scientific conferences (Joshi 2014a) (Joshi 2014b) (Joshi 2015a) (Joshi 2015b) (Joshi 2015d), it was found that probe fed polygonal patch antenna is not much explored.

1.4. Objective and Scope of the Thesis

The main objectives of the proposed work i.e. "Implementation of Performance enhancement techniques on a probe fed hexagonal planar antenna" to be carried out are as follows:

1. To investigate and compare planar polygonal(s) geometries with conventional circular and rectangular geometry for better antenna performance.

2. To identify a suitable combination of patch geometry and easy to handle antenna feed configuration.

3. To investigate impedance matching techniques over planar polygonal antennas with suitable feed.

4. To investigate techniques to improve antenna performance either in terms of its bandwidth or gain.

5. To implement performance enhancement techniques over a polygonal antenna for suitable application.

The research focuses on bandwidth and gain enhancement of polygonal patch antenna by taking into account the interest of researchers in academia and industry through reported literature to understand various aspects of development of polygonal patch antennas in a more systematic manner. The research focuses on design of polygonal patch antenna which can operate between 1 to 20 GHz and not on bands determined for 5G due to limitation of resources. The outcome of the research can be applied principally over 5G antennas whenever resources are available.

1.5. Outline of the Thesis

The research work presented in this thesis is organized as follows

Chapter 1 elaborate the problems and issues caused by probe, antenna bandwidth with pure mode and leads towards the solution. The motivation to carry out research in the area of planar antenna(s), objectives and scope of the thesis is also covered in this thesis.

Chapter 2 of the thesis describes the planar antenna theory. The selection of hexagon out of various patch geometries and suitable feeding technique to excite it, is elaborated in detail. The effect of the probe on bandwidth, perturbation of hexagon are also discussed.

Chapter 3 of the thesis demonstrates the reduced ground plane effects on planar antenna. This chapter discuss how the ground plane reduction excites or suppresses antenna mode(s) by compensating impedance mismatch due to direct feeding through patch to ground capacitance.

Chapter 4 of the thesis discusses the effect of the parallel plate capacitor (PPC) on return loss and impedance through results obtained from the measurement. This chapter of the thesis proposes a technique to improve the radiation bandwidth in probe fed hexagonal patch by introducing artificial magnetic conductor (AMC) array and PPC for applications like Wi-Fi.

Chapter 5 discusses the ground plane reduction technique as demonstrated in chapter 2 to transform a dipole antenna to monopole antenna with a C-Band and Ultra Wideband Characteristics (UWB).

Chapter 6 concludes the observations based on the solutions to the issues raised in the objectives in chapter 1 of the thesis. Further possibilities of research are discussed as the future scope in one of the sections of the chapter.