CHAPTER 1

INTRODUCTION

1.1 RATIONALE

Microstrip patch antennas mainly draw the attention for low-power transmitting and receiving applications. These antennas consist of a metal patch (rectangular, square, or some other shape) on a thin layer of dielectric/ferrite (called a substrate) on a ground plane. Microstrip antennas have matured considerably during the past three decades, and many of their limitations have been overcome (Garg et al., 2001). As the size of communication devices is decreasing day by day, the demand of miniaturized patch antennas is growing. Many methods of reducing size of antennas have been developed in past two decades. The recent trend in this direction is to use the fractal geometry (Gianvittorio and Rahmat-Samii, 2002). The design of an antenna for a specific resonant frequency requires calculation of optimal value of various dimensions. This is a hard task for fractal antennas because the accurate mathematical formulas leading to exact solution do not exist for the analysis and design of these antennas. The use of bio-inspired computing techniques is gaining momentum in antenna design and analysis due to rapid growth in the computational processing power (Pomenka and Raida, 2006) and the main techniques are Artificial Neural Network (ANN), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO), and Swine Influenza Model based Optimization (SIMBO) etc. In the area of antenna design, the ANNs are employed to model the relationship between the physical and electromagnetic parameters. The trained ANNs are effectively used for the analysis and design of various types of antennas. The bio-inspired optimization techniques have been used by the researchers to calculate optimal parameters of various patch antennas and for the size optimization of antennas (Pattnaik et al., 2003; Kerkhoff et al., 2004). Also the hybrids of ANN and optimization techniques are proposed as effective algorithms for
many applications especially when the expressions for relating the input and output variables are not available (Khuntia et al., 2005; Dubrovka and Vasylenko, 2008). The presented research has addressed these recent topics by designing the miniaturized fractal antennas using the bio-inspired computing techniques for various low power applications and thus, providing cost effective and efficient solutions.

1.2 ANTENNAS FOR COMMUNICATION APPLICATIONS

The antennas are the most important part of the wireless communication systems. The resonant behavior of the antenna has a large effect on the communication system’s performance. Most of the wireless communication applications like Bluetooth, Wireless-Fidelity (Wi-Fi), etc. work in Industrial, Scientific, and Medical (ISM) bands. The ISM bands cover frequency ranges 902-928 MHz, 2400-2484 MHz and 5725-5850 MHz which can be used without end-user licenses. The advantage of being in the category of unlicensed bands is that there is a great scope for the development of consumer and professional products which is considered to be an important step towards the development of wireless computing, mobile internetworking or multimedia applications. These bands have various types of applications like Bluetooth, Radio Frequency Identification (RFID), Wi-Fi, Wireless Local Area Network (WLAN) and Worldwide Interoperability for Microwave Access (Wimax) (Krishna et al., 2008). There are two types of approaches to design a system operating at multiple frequencies: the conventional technique using multiple single-band antennas, each intended for only one of the multiple discrete frequency bands, or a single multi-band antenna designed to handle all discrete frequency bands, e.g. a fractal antenna. Another important aspect of antenna design for communication applications is to develop miniaturized antennas i.e. antennas with reduced dimensions. The miniaturization of antennas helps in designing compact wireless communication devices (Yang, 2005). The bandwidth of conventional microstrip antennas is very small so the bandwidth enhancement techniques are also very essential in antenna design. There are several methods of increasing bandwidth and
the use of fractal geometry is a latest trend to achieve this (Chen et al., 2009). The design of antennas suitable for Multi Input Multi Output (MIMO) systems is also attracting the attention of antenna designers because this technology enhances the data transmission capacity and reduces multipath fading effects (Choukiker et al., 2014). The design of wearable antennas which are flexible enough that these can be bent, crumpled, and folded is also another recent trend. These antennas are generally stitched as the part of clothes and are used for many applications such as military, health monitoring activities, telemedicine, sports, and tracking etc. (Velan et al, 2015). The main challenge in designing wearable antennas is to find appropriate fabrics and polymers which can be employed as flexible substrate materials. The other important challenges are design of antennas having high gain (Jilani et al., 2013) and circular polarization (Tseng and Han, 2010).

1.3 ANTENNAS FOR MEDICAL APPLICATIONS

Antennas for medical applications have widely been investigated and reported in the recent past. The recent applications are typically in the field of information transmission such as RFID / wearable or implantable antennas, in diagnosis such as Magnetic Resonance Imaging (MRI) and microwave computed tomography / radiometry and also wireless telemedicine / mobile health system. Applications are also reported in thermal therapy (hyperthermia, coagulation, etc.) and microwave knife (Ito et al., 2007). Most modern Implantable Medical Devices (IMD) help in establishing a communication link between the implant and external devices behaving as a telemetry system. This communication link can be used to temporarily or permanently program the operating parameters of the IMD, to retrieve both real time and stored physiological data, and to enquire about the IMD system status and therapy history. Several techniques aiming at creating a physical channel have been developed for IMD telemetry, namely static magnetic field coupling, reflected impedance coupling and Radio-Frequency (RF) propagation. Recently, RF transmissions have received increased attentions because of its higher data rates and ability to
communicate over longer distances between the IMD and the external device (Sánchez-Fernández et al., 2010). For medical data telemetry, the Medical Implant Communication Service (MICS) band (402-405 MHz) was established by the Federal Communications Commission (FCC) in 1999 and the ISM frequency bands are also available. However, most of the transceivers make use of the MICS and 2400 MHz ISM bands (Hood and Topsakal, 2007). Hence, by providing communication of the sensor with the external equipment, antennas find major role in medical systems. Small size and high radiation efficiency are the main challenges faced by the antenna designer for medical applications. Other than these some other issues like impedance matching, low-power requirements, and biocompatibility with the body’s physiology, directivity, lobe control etc. are also considered while designing antennas (Conway and Scanlon, 2009; Soontornpipit et al., 2004).

1.4 LIMITATIONS OF EXISTING ANTENNA SYSTEMS

The limitations of existing antennas used in medical and communication applications are as follows:-

- Moderate gain
- Limited directivity
- Large size
- Limited bandwidth
- Not very suitable for MIMO applications due to lack of reconfigurability
- Non availability of accurate & efficient tools for fractal antenna design
- Hybridization of fractal geometries with other techniques has not been investigated
1.5 MOTIVATION

Antennas are used in almost all electronic devices used for wireless communication. These communications include direct person to person communications, communication through base station/Satellite, wireless networks like WLAN etc. and entertainment communications. The quality and efficiency of these communications largely depend on the efficient antenna design. Also the size of communication devices is decreasing day-by-day which dictates a very small space for fitting antennas. Therefore miniaturized antennas are a need of the day. Another requirement is the design of wide-band antennas because most of the communications transfer data with complex signals composed of voice, data, images and video. The fractal antennas have the capability of miniaturized, multiband and wideband performance. Also the bio-inspired optimization algorithms have the potential to provide the better quality results with reduced computation cost. So the motivation of the presented research work is to use fractal geometry concept for providing solutions to the requirement of multiband, miniaturized and enhanced gain antennas for medical and communication applications and to use the bio-inspired computing techniques to obtain the optimized fractal antennas to address the issues of antenna requirements.

1.6 RESEARCH OBJECTIVES

The approved research objectives are:

- Design of fractal antennas suitable for medical and communication applications.
- Parameter optimization of the fractal antennas using ANN.
- Development of hybrid bio-inspired computing techniques for optimization of fractal antenna design.
- Fabrication and experimental testing of the designed antennas.
1.7 MEANING OF FRACTAL ANTENNAS

Use of fractal geometry for the design of small size patch antennas is a recent development in the direction of size reduction and multi-band performance. The definition of ‘Fractal’ was given by Benoit Mandelbrot in 1975. According to Mandelbrot, fractal geometry is a way of classifying structures whose dimensions are fractional numbers (Tang and Wahid, 2002). The fractal geometries are uneven shapes which can be separated into sub-parts and every sub-part is (at least approximately) a small copy of the overall shape. The examples of mathematical fractal geometries are Sierpinski’s gasket, Von Koch’s snowflake, Cantor’s comb, the Lorenz attractor, the Mandelbrot set, etc. The real world examples of fractal shapes include the mountains, clouds, turbulences, and coastlines which cannot be represented by Euclidian shapes (Werner and Ganguly, 2003). Fig. 1.1 shows a fractal geometry named as Sierpinski gasket fractal geometry.

![Sierpinski Gasket Fractal Geometry](image)

The antennas which use fractal geometry as radiating structure are known as fractal antennas. These antennas use self-similar and space filling properties of the fractal geometries to design antennas which have more electrical length fitted into small area. The fractal antennas are of small size and therefore expected to have many important applications in wireless communication. The advantages of fractal antennas (Song et al., 2006) include
Miniaturization and space-filling
Multiband performance
Efficiency and effectiveness
Improved directivity
Improved gain

1.8 EXTRACTS OF LITERATURE SURVEY ON FRACTAL ANTENNAS

Literature survey on the fractal antennas has been carried out by referring to many National & International journals and conference proceedings such as the Journals and Transactions of IEEE (Antennas and Propagation, Antenna and Wireless Propagation, Microwave Theory and Techniques etc.), Journal of Progress in Electromagnetics Research, Microwave and Optical Technology Letters, Journal of IETE, Proceeding of various International and National conferences, and various books. The extracts of most pertinent observations are:

1. Puente et al. (1996) introduced the Sierpinski gasket based monopole fractal antenna having multiband performance. The radiating structure of the antenna is made on a dielectric substrate and fixed perpendicularly on a ground plane. The experimental and computed results are presented to show a multiband behavior over five bands for this fractal Sierpinski antenna. This behaviour is due to the self-similarity characteristics of fractal geometry of antenna.

2. Puente-Baliarda et al. (1998) discussed in detail the operation of a multiband fractal antenna based on Sierpinski triangle. The described fractal antenna has shown a notable degree of similarity at five bands, the same number of scales over which the fractal structure appears similar. The bands are also spaced by a log-period of two, the same spacing that relates the five scales on the fractal shape. Thus, it is concluded that the geometrical self-similarity properties of
the fractal structure have been translated into its electromagnetic behaviour. Due to its mainly triangular shape, the antenna is compared to the well-known single-band bow-tie antenna.

3. Werner et al. (1999) described the theory and basics needed for analyzing and designing the arrays of fractal antennas. They also introduced various types of fractal arrays and outlined many essential features of these arrays which include the multi-band behaviour, methods of implementing structures with small side-lobe level, efficient designs to thinning, and the capability to design speedy beam-forming algorithms by using the features of fractal geometry.

4. Best (2002) analyzed the radiation patterns of the Sierpinski gasket fractal antenna and found that the self-similar features of return loss characteristics are not observed in radiation pattern characteristics. He proposed a modified Parany gasket antenna and established that the radiation pattern features of this antenna is quite similar to Sierpinski gasket antenna.

5. Gianvittorio and Rahmat-Samii (2002) outlined the size reduction properties of fractal geometries and proposed its use for designing wire and patch antennas. They also described that although mathematically fractal geometry has infinite iterations, but for fractal antennas first few iterations are sufficient. They also used the compact fractal antennas to develop the phased arrays.

6. Tang and Wahid (2002) proposed a fractal antenna using the hexagon as base shape and found that the multi-band characteristics can be achieved using this shape. First three iterations are analyzed and it is found that the resonant frequencies of adjacent bands have ratios equal to three which is two in case of Sierpinski triangular fractal antenna. This large value of resonant frequency isolation results in increased advantage of flexibility in implementing multi-band applications.
7. Best (2003) considered different wired fractal monopole antennas and compared their resonant properties. The fractal geometries analyzed are Hilbert, Minkowski, Koch, Tee, and some Meander-line geometries. The efficiency, radiation resistance, and quality factor of antennas are the parameters which are evaluated. It is established that these antennas have similar behavior for the same area and same wire diameter.

8. Werner and Ganguly (2003) presented a comprehensive overview of the research in the area of fractal antenna engineering. The various topics considered are the design methodologies for fractal antenna elements, application of fractals to the design of antenna arrays, and frequency-selective surfaces with fractal screen elements. The Iterated Function System (IFS) used for designing fractal shapes are described. The hybrid of GA and IFS is also explained for designing the fractal wire antennas.

9. Dehkhoda and Tavakoli (2004) described a crown square microstrip fractal antenna and demonstrated that the size is reduced compared to a nearly square antenna at the first resonant frequency. At higher resonant frequencies, crown square antenna has a larger Voltage Standing Wave Ratio (VSWR) bandwidth. The antenna is considered up to second iteration as the further iterations do not have much effect on the resonant properties.

10. Anguera et al. (2004) presented a multiband fractal antenna designed using the modified Sierpinski fractal shape and two parasitic patches. Multilayer arrangement is used to implement the antenna showing dual band behavior and broad bandwidth. The radiation pattern shapes are almost similar in both bands. An electrical circuit model is proposed to demonstrate the enhancement of input impedance.

11. Rahim et al. (2005) described a square patch fractal antenna based on Sierpinski carpet geometry. The antenna is excited using the transmission line feeding technique. The return loss and the radiation pattern parameters are
used to study the behavior of the antenna. The multiband operation is observed from simulation and experimental results. The radiation pattern has shown that the proposed fractal geometry has performance comparable to a dipole antenna.

12. Ding et al. (2006) presented a crown fractal antenna based on circular shape. The antenna is developed up to second iteration and fed using the CPW feed. The resonant parameters of the antenna show that the antenna has ultra wideband (UWB) performance with wideband and omni-directional features. The antenna has very small size dimensions.

13. Huang et al. (2006) designed a fractal antenna with a tuning stub. The antenna has multiband and broadband behavior. A microstrip line is used to excite the antenna. The proposed antenna has reduced size and simple structure. A bandwidth of almost 18% is achieved using the proposed fractal geometry which is a high value for single microstrip antennas.

14. Anguera et al. (2006) proposed a triple band fractal antenna implemented using the combination of a double-band and a single band antenna. The multilayer stacking is used to develop the antenna. All the three bands have high efficiency and broad bandwidths. The antenna has similar radiation pattern shapes in different bands.

15. Song et al. (2006) demonstrated that the Sierpinski gasket geometry based fractal patch antennas can be designed to operate at desired frequencies by varying the fractal designs and iterations. They designed double band fractal antenna with modified Sierpinski gasket shape having a broadband behavior. The perturbation factor of the antenna is varied to get the improved bandwidth. The results of the modified Sierpinski antenna are compared with the standard Sierpinski antenna.
16. Guangguo and Shouzheng (2007) proposed two fractal monopole antennas designed using the hybrid of Koch and Sierpinski gasket fractal geometries. The fractal elements miniaturize the traditional Sierpinski gasket antenna while maintain the multi-band behavior. Micro-electromechanical System (MEMS) switches are used to introduce the frequency reconfigurable characteristics which results in increased flexibility in multi-band operation.

17. A reduced size multiband microstrip antenna is presented by Krishna et al. (2007). The square antenna is taken as base antenna and it has slots based on Sierpinski fractal geometry. The antenna has multilayer structure and is excited electromagnetically by a microstrip line printed on other substrate. The antenna has double resonant band and a size miniaturization of around 77% at fundamental resonant frequency.

18. Hwang (2007) used a vertically cut half Sierpinski triangle to implement a antenna with multiple resonant bands. The half Sierpinski triangle is further modified and slotted ground plane is utilized to attain the broadband characteristics. The antenna is excited using co-axial probe feeding technique and has nearly omni-directional pattern.

19. Kumar et al. (2007) presented a rectangular antenna with two sides having fractal geometry. The antenna is implemented using a single substrate with co-axial feeding. The multilayer configuration is also designed and proximity coupling is employed with and without air-gap. The multilayer antenna results in improved bandwidth and reduced size. The proposed multilayered fractal antenna has better cross polarization level which varies with the size of air-gap.

20. Azari and Rowhani (2008) presented new fractal geometry for microstrip antennas based on hexagonal shape. The antenna is developed up to second iteration and has UWB operations. The co-axial feeding is used for exciting
the antenna. The radiation pattern plots show that the antenna has a good value of gain.

21. Naghshvarian-Jahromi (2008) introduced a fractal patch antenna using pentagon shaped Koch geometry. The antenna is fed using microstrip line feed and the performance of the planar structure is compared with the monopole antenna performance. The antenna is also analyzed in time domain. The antenna has sufficient gain for the WLAN and Bluetooth applications.

22. Mishra et al. (2008) developed an updated expression for Sierpinski gasket monopole fractal antenna. The expression determines the resonant frequency of the antenna for given values of fractal iteration number, the length of the outermost triangular shape, and substrate parameters. The expression for the design of antenna for the given value of frequency is also proposed.

23. Yong and Shaobin (2008) proposed a fractal antenna based on the base square shape having multiple resonant bands. A method to control the frequency separations between different bands is also proposed. The microstrip line feeding method is used to improve the matching properties. The antenna covers the Global Positioning System (GPS) and digital multimedia broadcasting applications.

24. Mirzapour and Hassani (2008) proposed a fractal antenna based on a snowflake shape. The antenna has compact size and wide bandwidth of operation. The performance of the antenna with coaxial probe and capacitively coupled feeding is compared. The bandwidth improvement of about 50% is achieved by using an air-filled substrate and capacitive feed. The miniaturization of almost 70% is attained by slot-loading technique as compared to a simple Koch fractal antenna.

miniatuization is attained in comparison to the standard Sierpinski triangular antenna by varying the separation of first two resonant frequencies. The use of proposed antenna for handset applications is explored by studying the effect of hand and head on the performance of antenna.

26. A fractal shaped slot is used for enhancing the bandwidth of a square patch antenna by Chen et al. (2009). A microstrip line is used for feeding the antenna. The dependence of the bandwidth on the iteration order and iteration factor of the fractal geometry is analyzed. The bandwidth improvement results are compared with a traditional square antenna with wide slot and an improvement of around 3.5 times is achieved.

27. Manimegalai et al. (2009) presented a fractal monopolar antenna based on Cantor set geometry. The antenna has multiple resonant bands and covers many applications in 2 GHz to 7 GHz frequency band. The Cantor set geometry helps in size reduction and provides flexibility for controlling the resonant frequencies and their bandwidths.

28. Cao et al. (2009) presented a fractal antenna based on Minkowski geometry. The antenna is implemented for RFID reader applications in 2.4 GHz band and it has a bandwidth of 100 MHz. The dimensions of the proposed fractal antenna are lesser than the traditional patch antenna based on rectangular shape. The small size is helpful in designing miniaturized RFID systems.

29. Gemio et al. (2009) employed the fractal geometry based ground plane to design a multiband antenna. The triangular patch is printed on a substrate and fixed over fractal ground plane in perpendicular direction to design a monopole configuration. The combination of resonances of fractal ground and that of monopolar patch enhance the features of the entire geometry. The antenna is designed to operate over two resonant bands covering WLAN applications of 802.11 standard.
30. Aggarwal and Kartikeyan (2010) presented the design of a fractal patch antenna, which uses a unique fractal geometry known as Pythagoras tree. The antenna is excited using CPW feed and it has been designed for double band resonant behavior at the 2.4 GHz and 3.5 GHz band for a very wide bandwidth features.

31. Kumar and Sreeja (2010) proposed, simulated and tested a fractal patch antenna using modified Sierpinski geometry. The antenna has multiple resonant bands. The wideband features are attained by using a slotted ground plane and the modified Sierpinski structure.

32. Anoop et al. (2010) proposed a patch antenna with fractal geometry having multiple resonant bands. The antenna has compact size, less weight and the fractal geometry resulted in multiband characteristics. The base shape of the fractal antenna is square and the first three iterations are explored to analyze the performance.

33. Jibrael and Hammed (2010) designed a fractal patch antenna with plus shaped fractal geometry. The proposed antenna has small size and multiple frequency operations. The self-similarity and space-filling characteristics are observed to a high level. The designed antenna has four resonant bands between 2 GHz and 12 GHz.

34. Azari (2011) has presented a fractal antenna using an octagonal geometry. The proposed antenna is explored up to second iteration and has super wideband features making antenna suitable over a wide frequency range from 10 GHz to 50 GHz. The antenna has a good value of maximum gain over the whole resonant band.

35. Bayatmaku et al. (2011) presented a patch antenna using an E-shaped fractal geometry. The antenna is excited using a co-axial feed. The different iterations and various combinations of the parameters in every iteration are explored to
find an optimal design suitable for Long Term Evolution (LTE) / Wireless Wide Area Network (WWAN) applications. The antenna performance is analyzed using various parameters like bandwidth, gain, radiation patterns, and return loss.

36. Choukiker et al. (2011) presented an antenna employing fractal geometry in half circle form derived using the Descartes circle theorem. The antenna is excited using a modified CPW feed. The antenna has double band of resonance covering 2.4/5.2 GHz WLAN applications with sufficient bandwidth for these bands. The current distribution characteristics of the antenna are analyzed to understand the resonant behavior.

37. Soh et al. (2011) presented the use of Sierpinski geometry for the design of a planar inverted-F antenna. The antenna is designed using the textile and polyester fabrics so it is suitable for on-body integration. The antenna has dual frequency of operation centered at 2.45 GHz and 5.2 GHz with a good bandwidth. The shape of the radiation pattern is omni-directional with moderate value of gain. The antenna has efficiency of around 70%.

38. Sung (2011) has proposed a wideband fractal slot antenna using Sierpinski fractal geometry. The base shape is square patch antenna with wide square slot. The square slot is modified by Sierpinski structure keeping same outer dimensions. The antenna is excited using a microstrip line feed. The number of resonant bands depends upon the iterations of the Sierpinski square radiating elements. The fractal slot structure also enhances the bandwidth of the slot antenna.

39. Lee et al. (2011) investigated the design of a wearable Minkowski fractal antenna for Very High Frequency (VHF) band. Two different conductive materials are examined to check the suitability for the desired band. An L-shaped folded ground plane is used while feeding the antenna. The proposed flexible antenna achieved an efficiency of 48%, with a size of less than 0.5 m.
40. Pourahmadazar et al. (2011) presented a fractal monopole antenna using Pythagoras tree geometry. The antenna is excited using a modified microstrip line feed and UWB performance. The traditional T-patch is modified by inserting a Pythagoras tree geometry for achieving a wide bandwidth. The proposed antenna has a reduced size and the proposed multi-fractal concept results in flexibility for shifting resonances and bandwidth.

41. Jahromi et al. (2011) enhanced bandwidth and impedance matching of fractal monopole antennas by using the grounded CPW feeding technique. The results of this new feeding method are evaluated against the conventional standing monopole antenna and a significant improvement in magnitude of $S_{11}$ parameters is observed. It is found that the grounded CPW feed results in antennas which show a small cross-polar field and a good radiation pattern.

42. Kumar and Nikam (2012) presented a fractal antenna using modified Appollonian gasket fractal geometry. The antenna is fed using CPW. The fractal geometry in combination with a modified ground plane resulted in UWB operation. The effect of variation of different parameters of antenna is studied. The antenna shows a bandwidth of almost 143% centered at 10.5 GHz with a nearly omni-directional radiation pattern.

43. Oraizi and Hedayati (2012a) used square and Giuseppe Peano fractal shapes to design a microstrip antenna with multiple frequency operation. The antenna is implemented as a double layer structure with radiating patch on the top and ground plane at the bottom. A microstrip line is used in between the two substrate layers to feed the antenna by electromagnetic coupling. The antenna exhibits a circularly polarized behavior.

44. Kumar et al. (2012) presented a monopole fractal antenna based on inscribed triangle circular geometry. The antenna is excited using the CPW feed and has UWB operation. The radiation pattern of the antenna has omni-directional
shape. The parametric study of the antenna is presented to show the effect of different parameters on the antenna behaviour.

45. Oraizi and Hedayati (2012b) also investigated the use of Giuseppe Peano fractal shapes for designing compact microstrip antennas. The boundary of the square patch is modified in the form of Giuseppe Peano curves which result in increased perimeter in almost same surface area which results in size reduction while maintaining the gain. Slotting of the radiating element produces additional size reduction. The broad-band characteristics are obtained by inserting an air-gap between the radiating element and ground plane.

46. Olaode et al. (2012) presented the approach of Meandering i.e. inserting bends for achieving the miniaturization. They proposed analysis of the results of replacing the straight dipole antenna by the Meander fractal curves. The dipole antenna operating in VHF range is selected for the verification. The equivalent circuit is also derived from that of straight line dipole. The meandered dipole antenna up to 6 bends is analyzed and it is found that the antenna with three bends has optimum performance.

47. Li and Mao (2012) modified standard bow-tie antenna by using the Koch-like fractal geometry. The sides of the bow-tie antenna are replaced with fractal curve and the performance is compared with the unmodified bow-tie dipole and triangular Sierpinski antenna. It is found that all the antennas have same resonant bands in low frequency but improved resonant parameters in high frequency bands.

48. Ghatak et al. (2013) presented a Sierpinski fractal antenna with hexagonal boundary. The antenna is analyzed up to second order and UWB performance is achieved with band rejection features. A ‘Y’ shaped slot is inserted to achieve the band rejection characteristics. The antenna is excited using CPW feeding mechanism. The time domain analysis shows that the group delay is very small over whole band.
49. A Sierpinski fractal antenna for THz band is designed by Xu et al. (2013a). The electrical conductivity of the graphene varies with the frequency and this property is used to make the antenna reconfigurable. The slots of Sierpinski geometry are filled by the graphene to achieve the reconfigurable characteristics. The $S_{11}$ and radiation patterns plots of first three iterations are explored to study the behavior of the antenna.

50. Dorostkar et al. (2013) presented a fractal antenna based on circular and hexagonal shapes. The antenna has super wideband operation which is achieved by partial ground plane. GA is used to optimize the parameters. The antenna has good impedance bandwidth and gain which makes it attractive to many wireless applications.

51. Kumar and Choubey (2013) presented a circular pentagonal fractal antenna for UWB operation with a notch band to escape obstruction from the WLAN communications. The CPW feeding is used to excite the proposed antenna. A ring slot on the feeding line is used to insert the notch band at desired frequency. The antenna has omni-directional shape of radiation pattern in H-plane and bidirectional shape in E-plane.

52. Naser-Moghadasi et al. (2013) proposed a CPW fed monopolar antenna with a fractal shaped radiating structure and a T-shaped structure inbuilt into it. The antenna has UWB operation with a notch band between 3.3-4.2 GHz. The UWB characteristics are obtained by using rectangular notches in the ground plane and the notch features are obtained by the T-shaped structure. A bandwidth of around 117% is achieved excluding the notch band.

53. Two triple band antennas are presented by the Varadhan et al. (2013) using tree like fractal geometries. One antenna is designed for RFID reader and other is for RFID tag. A read range up to 87.5 cm is achieved by the tag antenna. The antennas have sufficient bandwidths for these applications. The CPW feed is used for exciting the antennas.
54. Karmakar et al. (2013) presented a monopolar antenna having fractal shaped slots. The antenna has UWB performance which is achieved by slotting the ground plane and impedance steps. The impedance matching is improved by the adjusting the gap between the radiating patch and the ground plane. The antenna has a bandwidth of around 120% with an omni-directional radiation pattern with sufficient gain for UWB applications.

55. A compact fractal antenna using the modified rectangular Sierpinski geometry is proposed by Shrestha et al. (2013). The antenna is designed for ISM band applications. The inset feeding is used to excite the patch and it resulted in good impedance matching. The antenna is developed up to second iteration Sierpinski carpet geometry. A miniaturization of around 32% is achieved with reasonable values of return loss and gain of antenna.

56. Thi et al. (2013) presented a planar Spidron fractal antenna for Ku-band satellite communication. The antenna has double band of resonant frequencies with circular polarization. The antenna is excited using the microstrip line feeding and impedances bandwidth up to 9% is achieved. The 3 dB axial ratio bandwidth of around 3% is obtained for the first band. The proposed antenna has a small operating frequency ratio of 1.15 which is required for satellite communications.

57. Fallahi and Atlasbaf (2013) presented a monopole antenna having UWB performance. The small size fractal shapes are added to the corners of the base polygon radiating structure. The CPW feeding is used to excite the bandwidth and the antenna has a compact size. The antenna is analyzed in time domain by calculating the fidelity factor which is more than 0.92. This means that the antenna is suitable for radar applications.

58. Pakkathillam et al. (2013) presented a tapered slot antenna in which the slot boundary is developed using a fractal shape. The antenna is developed for ultra high frequency RFID reader applications using the variable distance
opposite direction current concept. The antenna has a bandwidth of almost 101 MHz centered at 897 MHz.

59. A multiband antenna for RFID reader applications is proposed by Liu et al. (2013a) in their paper entitled “Dual-Band Microstrip RFID Antenna with Tree-Like Fractal Structure”. The tree-like fractal structure is placed in between the patch and ground plane of an air-filled rectangular microstrip patch antenna to achieve dual band operation. The two resonant bands have impedance bandwidths of almost 4.4% and 3.1%.

60. Liu et al. (2013b) in their paper entitled “Miniatirised Wideband Circularly-Polarised Log-Periodic Koch Fractal Antenna” presented a compact fractal antenna with Koch log-periodic shape. The antenna has a resonant band of 2 GHz to 6 GHz with circular polarization. Two crossed dipoles are employed to achieve circularly polarized behavior and the broadband features are attained by log-periodic dipole antenna.

61. Choukiker and Behera (2014) presented a small size sectoral fractal planar monopole antenna. The shape of the antenna is inspired from Sierpinski gasket shape. The antenna has a wideband of operation covering Wimax, Wi-Fi and WLAN applications. The antenna is excited by the microstrip line feed through a matching network.

62. Dholakiya and Pujara (2013) used a circular shaped fractal slot to design an enhanced bandwidth antenna. The antenna performance is analyzed for different iteration factors and orders. A microstrip line feed is used to excite the antenna and it is designed on FR4 substrate. A bandwidth of around 53% is achieved with reasonable value of gain.

63. A triple band wearable antenna is presented by Jalil et al. (2013) using Koch fractal geometry. The simulation model is developed using the CST software. The denim textile material is used as substrate and two different conducting
materials are used to fabricate two different antennas. The antenna performance is studied under three different conditions. The $S_{11}$ and bandwidth parameters are taken as the performance evaluators.

64. Xu et al. (2013b) used meta-surfaces and meta-resonators to design miniaturized patch antennas. The antennas have circular polarization which is achieved by the employing meta-resonators designed using crossbar fractal tree slot and spiral resonators. The miniaturization is attained by the use of metamaterial reactive impedance surface. The proposed concept is verified by implementing three different antennas.

65. Wang et al. (2013) proposed a fractal antenna based on modified Sierpinski-carpet geometry. The fractal geometry is developed up to third iteration. The antenna has triple resonant band characteristics between 1 GHz to 20 GHz. The lower band covers whole UWB frequency range. The antenna has good radiation pattern with sufficient gain in resonant bands.

66. Jilani et al. (2013) presented a fractal antenna for X band and Ku band applications. The traditional rectangular patch antenna is modified by adding fractal geometry at the corners and sides. The introduction of fractal shapes resulted in improvement in gain and bandwidth of the antenna. The designed antenna has multiband operation and has linear polarization. The microstrip line feeding is used for the excitation.

67. Choukiker et al. (2014) presented the design of a fractal monopole antenna for handheld devices and suitable for MIMO implementation. The antenna shape is a hybrid fractal geometry designed by merging the Minkowski and Koch fractal shapes. The antenna has dual band performance with good bandwidth in both bands.

68. An antenna with fractal slots is proposed by Zarrabi et al. (2014) for double notch application. The antenna is designed on FR4 substrate and has UWB
performance. It operates over 2.1-12 GHz band with two notch frequencies at 3 and 5 GHz. The designed antenna has sufficient gain for wireless applications in this frequency band.

69. Jalali and Sedghi (2014) proposed a small size CPW fed monopole fractal antenna having UWB performance. Slots are created in the ground plane to achieve the UWB performance. The resonant band for the antenna is from 2.95 GHz to 12.81 GHz resulting in impedance bandwidth of around 125%. Also the antenna has omni-directional radiation pattern over whole resonant frequency band.

70. Choi et al. (2014) designed a miniaturized fractal antenna for rectenna system working at a frequency of 2.45 GHz. The rectangular Sierpinski carpet structure is used to reduce the size of the antenna. The RF energy is harvested by the fractal antenna from the environment and the output of the antenna is applied as input to a rectifier circuit to produce the dc output.

71. A circularly polarized patch antenna is designed by Reddy and Sarma (2014a) using the fractal boundary approach. The straight boundary of a square patch is replaced by the asymmetrical pre-fractal curves which lead to the excitation of two perpendicular modes resulting in circular polarization. The fractal sides also result in size reduction of the antenna.

72. Reddy and Sarma (2014b) also presented a triple band Koch fractal boundary and fractal slot microstrip antenna having circular polarization. The four different version of the antenna are explored and the final antenna is proposed to be suitable for WLAN/WiMAX wireless applications. The antenna has good 3-dB axial-ratio bandwidth which is another advantage for modern wireless applications.

73. A quasi self complementary microstrip patch antenna having UWB characteristics is proposed by El-Hameed et al. (2014). The antenna geometry
employs crossbar fractal boundary for achieving miniaturization. The impedance matching is improved by inserting a slot in ground plane and its step-tapering is done to reduce the lower-side value of the resonant frequency band. It has an omni-directional radiation pattern with sufficient gain for UWB applications.

74. Subramaniam et al. (2014) employed Minkowski fractal curve to design flexible antennas. The Minkowski geometry results in miniaturization. The antennas are designed for WLAN applications and have acceptable gain values for these bands. Two different materials Flectron and Zeit are analyzed to implement the wearable antennas and it has been concluded that the Zeit antenna has relatively better results.

75. Li et al. (2014) integrated quasi-Sierpinski fractal dipoles and high-impedance surface to design a reconfigurable fractal antenna. The frequency of the proposed antenna can be shifted between X-band, Ku-band, and Ka-band using two switches. The high-impedance surface is implemented by arranging square patches with square slots in the form of an array and is used as a reflector to attain the improved front-to-back radiation.

76. Raviteja et al. (2014) proposed a CPW fed fractal monopole antenna for RFID reader applications at 900 MHz. The antenna has a circular polarization for a bandwidth of 36 MHz; however, the −10 dB bandwidth of the antenna is 256 MHz. The antenna has a compact design and has a read distance of 1.32 m. Therefore, the proposed antenna is suitable for short-distance RFID reader applications.

77. Kumar et al. (2014) presented a fractal antenna having resonant frequency varying capability. The modified Sierpinski triangle monopole antenna has been designed using the moving feeding technique to obtain different resonant frequencies. A microstrip feed line is used as main feed and a movable
coaxial feed is attached to it. A programmable motorized method is used for experimental verification of the proposed approach.

78. Weng and Hung (2014) proposed an H-fractal having multiband performance. The antenna is fabricated using FR4 substrate and has a good directivity. The antenna has non overlapping structure and can be designed to work at different desired bands. The design of this H-fractal antenna is achieved for 2.4/5.5-GHz WLAN bands with sufficient bandwidth for these applications.

79. A plus based fractal slotted array has been implemented for X-band applications by Chatterjee et al. (2014). An asymmetric iris is used to excite the slots placed in the centre of the broad wall of a waveguide. The empirical formula has been derived for conductance of the fractal unit cell. The parametric study has been done and it is found that the iris width does not affect the array element if its width is more than that of slot.

80. Zhou et al. (2014) presented a tree fractal based antenna array which is fed by an L-shaped microstrip line. Two elements have been used to implement a 1 x 2 array which are coupled by a slot. The antenna element resonates from 1.11 to 1.71 GHz with circular polarization which is maintained in array configuration also. The array results in an improved value of gain.

81. A miniaturized reflectarray element is presented by Costanzo and Venneri (2014) using the Minkowski fractal geometry. The patch dimension is kept unchanged and scaling factor of the fractal is utilized to attain the correct phase tuning. A miniaturization of approximately 30% is attained for achieved X-band operation. The designed reflectarray element has wide-angle scanning potential and can be used for broadband applications.

82. Velan et al. (2015) proposed a wearable fractal monopole antenna having dual band performance. A foam sheet of 2 mm thickness is used as the substrate and an electromagnetic band-gap structure is incorporated into the antenna to
reduce the effect of human body. The behavior of antenna under different conditions is presented and specific absorption rate is also measured to validate the performance.

83. Tripathi et al. (2015a) presented the design of a compact fractal MIMO antenna having UWB performance. The Koch fractal geometry is used for designing the monopole elements which are then placed in orthogonal configurations. Isolation is improved by the use of grounded stubs and WLAN band rejection is attained by C-shaped slots. The proposed antenna has quasi omni-directional radiation pattern.

84. Tripathi et al. (2015b) also proposed a small size UWB fractal antenna. The Sierpinski geometry is employed to achieve the compactness and broad band behavior. The designed antenna has radiation pattern with omni-directional characteristics, constant fidelity factor and very less return loss.

85. A compact fractal antenna with UWB performance is proposed by Singhal et al. (2015). The antenna employs an inner tapered tree-shaped geometry with CPW feed which is used to enhance the bandwidth. The designed antenna operates over the frequency range from 4.3 GHz to 15.5 GHz with nearly omni-directional pattern.

86. Pakkathillam and Kanagasabai (2015) achieved broadband characteristics by using fractal geometry in the form of slots placed along diagonal of the patch antenna. The proposed antenna has circular polarization, high gain, compact size and it is suitable for handheld devices. The antenna performance is studied for different iteration factor and iteration orders.

87. A Spidron fractal dielectric resonator antenna having circular polarization is proposed by Altaf et al. (2015). A C-shaped slot is used to achieve a broad 3 dB axial ratio bandwidth. The coupling between the slot and microstrip line is
used to excite the antenna. The antenna has gain values between 2.2 dBi to 3.16 dBi for the axial ratio bandwidth.

88. Cai et al. (2015) presented a small size antenna designed using fractal metasurface and fractal resonator. A reactive impedance surface based on the Hilbert fractal geometry has been employed to improve the antenna characteristics. The miniaturization and circular polarization is achieved by using ring resonator with splits designed using Wunderlich fractal geometry. The antenna performance is validated experimentally for Wimax band applications.

89. A square antenna employing log-periodic fractal geometry is proposed by Amini et al. (2015) for UWB applications. Two types of squares: squares with ring slot and square without slots are arranged in log-periodic form to achieve the UWB operation. This geometry has resulted in a size reduction of 23 percent with almost constant gain in whole band. The antenna features in time domain are also studied and the experimental measurements are used to validate the simulation results.

1.9 THESIS ORGANIZATION

The presented thesis is organized into the six chapters. Chapter 1 and 2 discuss the genesis and the previous research works, Chapter 3 to 5 are dedicated to the contributions out of the research work. The thesis is concluded in chapter 6 followed by the references. The contents of the chapters are briefly described below.

Chapter-1 deals with the introduction to the thesis and research work. It describes the wireless communication and medical applications of the microstrip antennas along with the limitations of the existing antennas. The motivation for the proposed research work and the approved objectives are discussed in this chapter. A brief introduction to the fractal antennas and the extracts of the important papers on fractal antennas are also provided.
Chapter 2 is dedicated to the bio-inspired computing techniques and their applications in antennas. The working principles of ANN, ANN Ensemble, GA, PSO, and BFO are described and some hybrid bio-inspired computing techniques are also discussed. The literature survey related to the applications of bio-inspired computing optimization techniques in antennas is given in this chapter. The limitations of the existing bio-inspired computing techniques are highlighted. The existing applications of the bio-inspired computing techniques in fractal antennas are also reviewed in this chapter.

Chapter 3 discusses in detail the fractal geometry concepts and fractal antennas. Popular fractal antennas and their features are described. All the designed fractal antennas are introduced in this chapter. The important features like miniaturization & multiband operation of the designed fractal antennas are highlighted and their applications are also discussed.

In chapter 4, the development of ANN models for the design of proposed fractal antennas is explained. The various parameters of the fractal antennas selected for ANN models are described. The ANN models are designed using the feed-forward neural networks namely Multi Layer Perceptron Neural Networks (MLPNN), Radial Basis Function Neural Networks (RBFNN), and General Regression Neural Networks (GRNN). The performance comparison of different ANN models on the basis of different performance measures is also given. The design of ANN ensemble models for fractal antennas is introduced and different techniques of developing ANN ensemble models are also discussed in this chapter.

One of the novel contributions of this thesis is the development of hybrid bio-inspired computing algorithms for the design of fractal antennas. This work is presented in chapter 5. The hybrid algorithms are developed to design the proposed fractal antennas for desired frequencies. The performance comparison of bio-inspired computing algorithms for the design of multiband Sierpinski Gasket fractal antenna is also explained. The development of various hybrid algorithms like GA-ANN hybrid Algorithm, GA-ANN ensemble hybrid Algorithm, PSO-ANN hybrid Algorithm,
BFO-ANN hybrid Algorithm, BFO-ANN ensemble hybrid Algorithm is explained. The use of ANN models as objective functions of optimization algorithms is discussed in this chapter. This chapter also deals with the experimental testing and validation of the developed fractal antennas. The photographs of the fabricated antennas and the experimental results are included. The comparison of the simulated results and experimental results is discussed. The suitability of the designed antennas for different applications is also highlighted in this chapter.

Conclusion drawn from the thesis work with some recommendations for future work has been presented in chapter 6. This chapter is followed by the list of references cited in the thesis.

1.10 SUMMARY

The chapter starts with a note on the foundations of miniaturized microstrip antenna design. The underlying principle of bio-inspired computing techniques for designing antenna parameters is highlighted. The features of antennas for medical and communication applications are described. The limitations of existing antennas are listed and motivation for the present work is discussed. The approved research objectives are also provided. The meaning of fractal antennas and their advantages are discussed. The extracts of important papers on fractal antennas published in last two decades are provided which highlight that the fractal antennas are very suitable for designing miniaturized and multiband antennas. It is observed from the literature survey that the Sierpinski gasket is most popular geometry used for designing fractal antennas. Different modified forms of the standard Sierpinski antenna are also proposed which have better performance than the standard shape in one or more aspects. A number of other geometries are also proposed for fractal antenna design. The co-axial feed is used by most of the researcher, however a good number of papers are also published which employed other forms of excitation. The CPW feed is mainly used for designing UWB fractal antennas. The use of fractal shaped slots for enhancing the performance of microstrip antennas is also reported. The design of
hybrid fractal antennas i.e. fractal antennas developed using the combinations of two fractal geometries is presented by few papers. The suitability of fractal antennas for various applications is explored by different researches and is discussed in this chapter. The organization of thesis discussed in the end of chapter shows that the thesis is divided into six chapters. The contents of the chapter are also described to present their relation with the approved objectives.