CHAPTER 2
OVERVIEW OF FRACTAL ANTENNAS

This Chapter presents a discussion on fractal antennas, its characteristics and applications. It also includes details of microstrip patch antenna and various feeding techniques.

2.1 Fractal antenna at a glance

Fractals can be represented as self-similar objects at multiple scale lengths organized in a deterministic or stochastic way. These are created using the set theory and a simple feedback process called iterated function system (IFS). In IFS, the fractal generation procedure begins with a generator shape, which is input into a mapping function, and the output of this mapping function becomes the input for the next iteration. Thus, each fractal shape is composed of multiple iterations of a single elementary shape. Therefore, a typical fractal antenna may be iterated many times to satisfy the self-similarity property and space-filling properties of the fractals. This procedure of designing fractal antenna structure using IFS [58-59], can be mathematically expressed as

$$\xi = \frac{h_n}{h_n+1}$$  \hspace{1cm} (2.1)

where, $\xi$ is the scale factor ratio, $h$ is the height of iterated antenna and $n$ represents the iteration number. Using this principle, several antenna configurations based on fractal geometries have been developed. Some of these include Koch, Minkowski, Sierpinski Carpet, Sierpinski Gasket, Hilbert and Fractal trees.

2.2 Chronological development of fractal geometries

The mathematics behind fractals began to take shape in early 17th century, when mathematician and philosopher Leibniz considered recursive self-similarity properties. However, it took until 1872 before a mathematical function appeared which can be graphically analysed. This function was given by Karl Weierstrass, and has the non-intuitive property of being everywhere continuous but nowhere differentiable. However, in 1904, Helge von Koch became dissatisfied with Weierstrass's abstract and its analytic definition, and gave a better geometric
definition of a similar function, which is now called Koch snowflake. In 1915, Waclaw Sierpinski constructed his first triangle geometry based fractal and a year later, his carpet shaped fractal came. Originally, these geometric fractals were described as curves rather than 2D shapes in their modern constructions. In 1918, Bertrand Russell had recognised a notion of beauty within the mathematics of fractals that was then emerging. The idea of self-similar curves was taken further by Paul Pierre Levy. In 1938, Paul described a plane or space curves and surfaces consisting of parts similar to the whole as new fractal curves and named the same as the Levy C curve. Georg Cantor also gave examples of subsets of the real line with unusual properties [60]. These cantor sets also now recognized as fractals. Iterated functions in the complex plane were investigated over a period of late 19th to early 20th centuries by Henri Poincare, Felix Klein, Pierre Fatou and Gaston Julia. However, without the aid of modern computer graphics, they lacked the means to visualize the beauty of many of the objects that they had discovered [61].

In the 1960s, Benoit Mandelbrot started investigating self-similarity in papers, statistical self-similarity and fractional dimensions, which were built on earlier work by Lewis Fry Richardson. Finally in 1975, Mandelbrot coined the word of fractal to denote an object whose Hausdorff-Besicovitch dimensions were greater than its topological dimensions. Mandelbrot illustrated this mathematical definition with striking computer-construcation visualizations. These images captured the popular imagination with many of these being based on recursion. This leads to the popular meaning of the term of fractal [62-66].

2.3 Fractal antenna theory
A fractal antenna is an antenna that uses a fractal geometry or design to maximize the length of material that transmit/receive electromagnetic signals within a specified total surface area. Due to this reason, fractal antennas are compact and thus, useful in various modern communication devices such as cellular telephone and microwave communication devices [67-70].

As discussed above, fractals can be represented as a class of shapes which have no characteristic size. Therefore, a fractal antenna can be represented as an antenna that uses a fractal geometry or self-similar design to maximize its length, or increase the perimeter (on inside sections or the outer structure) of material that can receive or transmit electromagnetic radiation within a given total surface area or volume.
fractal is composed of multiple iterations of a single elementary shape. The iterations can continue to infinity; however, in practice, it depends upon the required shape within a finite boundary. This compactness property is highly desirable in low powered mobile wireless communication devices, as it can be used to produce antennas for their small receivers and transmitters.

2.4 Fractal as antennas
Fractals as antennas may offer better radiation pattern and may also offer more controlling parameters to designer [71]. Therefore, in this context, all the basic trigonometric shapes already utilized in designing fractal antennas and their radiation mechanisms are explored. From these studies, it is found that fractal antennas are multi-resonant and smaller in size. The multiband characteristics of fractal antenna are associated with the self-similarity of geometry. Because of these advantages, research towards quantitative relation between antenna properties and fractal parameters is still going on extensively. From these quantitative relationships, any variation of fractal parameters has direct impact on the primary resonant frequency of the antenna, its input impedance at this frequency, and the ratio of the first two resonant frequencies. In other words, the features of fractal antennas can be quantitatively linked to the fractal dimension of geometry [72]. These findings have lead to increased flexibility in designing antennas using these geometries. These results have also been experimentally validated by various engineers and researchers. From these studies, it is found that the response of fractal antenna differs remarkably from traditional antenna designs, in respect that it is capable of simultaneously operating at many frequencies with better performance. This makes the fractal antennas suitable for wideband and multiband applications. However, the standard antennas are designed and fabricated with fixed dimensions and for a specific frequency. Thus, these are limited to only particular frequency for which these are designed.

2.4.1 Features and characteristics of fractal antennas
Fractal antenna engineering is the field which utilizes fractal geometries for designing antennas. The fractal geometries are associated with many characteristics. The key ones are [60-62]:
- These have a fine structure at arbitrarily small scales.
These are too irregular to be easily described in traditional Euclidean geometry language.

- These are self-similar; whereas, the degree of similarity depends upon the shape of fractals.
- These have a Hausdorff dimension which is greater than its topological dimension (although this requirement is not met by space-filling curves such as the Hilbert curve).
- These have a simple and recursive definition.

These characteristics of fractals can be utilized in designing antennas, to have the following advantages:

a) **Miniaturization**: An antenna radiates only when its size is corresponding fraction of the wavelength of transmitting radiation. Therefore, antenna that operates at very low frequencies will be very large. The fractional dimensions of the fractals can be used to design antennas that are electrically very long but physically short.

b) **Multiband/wideband antenna**: For an antenna to be frequency independent, it must have no characteristics size or it must have many characteristics sizes, suitable to operate over many frequencies simultaneously. Due to self-similarity property of fractals, there are multiple copies of fractal objects in a typical fractal antenna, which is why fractal antennas can be utilized for multiband operations.

c) **Better efficiency**: Fractal has sharp corners and edges that causes abrupt changes in the direction of current and thus, enhances the radiations. Therefore, fractals are efficient radiators of electromagnetic energy.

d) **Input impedance matching**: Generally, small antennas are poor radiators with small input impedance and significant negative input reactance, resulting in difficulty and high expenses to match the antenna input impedance with matching network. However, small fractal antennas have comparatively greater input resistance and smaller input reactance than small traditional antennas. Fractal antennas can even resonate with a size much smaller than other traditional antennas. Therefore, the cost associated with input impedance matching can be reduced.

e) **Directivity**: The directivity of an antenna can also be improved by shaping the antenna in fractal geometry.
The above mentioned benefits of fractal antennas are dependent on two basic fractal characteristics: self-similarity and fractional dimensions of fractals. These are explained below.

2.4.2 Self-similarity

The concept of fractal is often related with geometrical objects satisfying the criteria of self-similarity. Self-similarity means that an object is composed of sub-units and/or sub-sub-units on multiple levels that (statistically) resemble the structure of the whole object. More specifically, if the fractal pattern is shrunk or enlarged with equal ratio, then its appearance remains unchanged. However, in practice, these properties do not hold indefinitely for real phenomena and there are necessarily lower and upper bounds over which such self-similar behaviour applies. Self-similarity can, therefore, be associated with fractals, which are objects with unchanged appearances over different scales [63].

2.4.3 Fractional dimension

The fractional dimension \( D \) is a statistical quantity that gives an indication of how completely a fractal appears to fill space, as one zooms down the finer and finer scales [64-65]. Considering the properties of self-similarity discussed above, the fractional dimension \( D \) of a set \( A \) can be mathematically defined as:

\[
D = \frac{\log(N)}{\log(1/r)}
\]

(2.2)

Where, \( N \) is the total number of distinct copies similar to \( A \), and \( A \) is scaled down by a ratio of \( r \). The same approach can be adopted for determining the dimension of several fractal geometries. This is done using the iterated function system, discussed below.

2.4.4 Iterated function system

In fractal theory, the fractal sets are represented by means of iterated function systems [66]. An IFS with probability (IFSP) is a system \( \{W_{\beta}(x), P_{\beta}\}_{\beta=1}^{N} \) of \( N \) contractive transformations \( W_{\beta}: R^{d} \rightarrow R^{d} \) \( (R^{d} \) is the Euclidean d-dimensional space) with the associated probability weights \( P_{\beta} > 0, \sum_{\beta=1}^{N} P_{\beta} = 1 \). In fractal antenna theory, IFS have been used to construct the fractal curves (as a model of fractal shaped wire antenna),
and to define their geometrical fractal properties. A fractal structure can be considered as the fixed point of operator \( W: h(R^d) \rightarrow (R^d), \) defined by

\[
W(B) = \bigcup_{k=1}^{N} W_h(B), B \in H(R^d)
\]  

(2.3)

Where, \( H(R^d) \) is the space of all the compact sets of \( R^d \) and \( H(R^d) \) is a complete metric space once equipped with the Hausdorff metric \( d_H \).

Considering the contractive nature of the maps defining the IFS, the operator \( W \) turns out to be contractive in \( (H(R^d), d_H) \), so that its unique fixed point \( C \) can be expressed as:

\[
C = \bigcup_{k=1}^{N} W_h(C)
\]  

(2.4)

The point \( C \) defines (Hutchinson condition) the fractal sets generated by the IFS independently of the value of probability weights \( P_h \). IFS theory provides a simple way to obtain a geometric representation (visualization) of the fractal set \( C \). It is because, \( C \) can be obtained as the limit set of the random iteration algorithm constructed starting from \( \{W_h(x), P_h\}_{k=1}^{N} \) as

\[
x_{n+1} = W_h(x_n)
\]  

(2.5)

Where the next \( x_{n+1} \) is obtained as the image of the point \( x_n \) through one of the \( N \) maps \( W_h \) randomly selected with probability \( P_h \). Amongst all the possible IFS, self-similarity IFS are particularly convenient in practical applications. For \( d=2 \), a self-similar matrix takes the form \( W_h(x) = A_h x + b_h \) (\( h=1 \ldots N \)), where \( A_h \) are self-similar matrices obtained by the composition of similitude \( A = S_h I \) (\( 0 < S_h < 1 \), \( I \) is Identity Matrix), rotations of an angle \( \theta_h \), and mirror reflections around one of the two axes; while \( b_h \) are translation vectors.

2.5 Microstrip patch antennas

A typical microstrip patch antenna consists of a very thin patch (a small fraction of a wavelength) above a conducting ground plane. The patch and the ground plane are separated by a dielectric. The patch is normally made of copper material and can constitute any shape. However, for simplicity, a diamond and square shaped patch is used in this thesis. In practice, the patches are usually photo etched on the dielectric substrate, which is usually non-magnetic. The relative permittivity of the substrate is an important parameter to consider. It is because relative permittivity will enhance the
fringing fields; that will also account for radiation. This type of antenna is characterized by its length $L$, width $W$, and thickness $h$, as shown in Fig. 2.1. Microstrip patch antennas radiate primarily because of the fringing fields between the patch edge and the ground plane. For efficient antenna performance, a thick dielectric substrate having a low dielectric constant is preferred, as this will provide better efficiency, large bandwidth, and better radiation. However, such configuration usually leads to a large antenna in size. In order to design a compact microstrip patch antenna, higher dielectric constants need to be used. However, these are comparatively less efficient and have narrow bandwidth. Therefore, a compromise needs to be made between antenna dimensions and their performance [73-87].

![Figure 2.1: A typical rectangular patch antenna [73].](image)

Microstrip patch antennas use radiating elements of wide variety of shapes such as square, rectangle, circle, triangle, ellipse, star and semi-circle. The selection of a particular shape depends on the parameters optimising, such as bandwidth, side lobes, cross polarization, and antenna size. The electrical characteristics of the microstrip patch antenna are determined by the substrate. In terms of their electrical characteristics, microstrip antennas usually have inherently narrowband structure due to their resonant nature and confinement of fields between the patch and ground plane. Thus, narrow bandwidth can be considered as one of the principal disadvantage of microstrip patch antennas. Therefore, in recent years, significant research contributions have been devoted to the bandwidth enhancement technique of the microstrip patch antenna. In addition, the other areas of development in microstrip
patch antennas include enhancing bandwidth, combating surface wave effects, development of compact antennas, active antennas and development in the analysis tools.

2.5.1 Advantages and disadvantages of microstrip patch antennas

Microstrip patch antennas, in recent years, are getting popular in wireless applications due to their low-profile structure. These are found very suitable as embedded antennas in handheld wireless devices such as cellular phones and pagers. In addition, the telemetry and communication antennas on missiles need to be thin and conformal and are often microstrip patch antennas. These have also been used successfully in satellite communications. The key advantages of fractal antennas include [73]:

1. Light weight and low volume.
2. Low profile planar configurations which can be easily made conformal to host surface.
3. Low fabrication cost, which is why these can be mass produced.
4. Support both linear and circular polarization.
5. Can be easily integrated with microwave integrated circuits (MICs).
6. Capable of dual and triple frequency operation.
7. Mechanically robust when mounted on rigid surfaces.

Microstrip patch antennas also suffer from a number of disadvantages comparing to conventional antennas. Some of the major disadvantages are:

1. Narrow bandwidth.
2. Low gain.
3. Extraneous radiation from feed and junction.
4. Poor end fire radiator except tapered slot antenna.
5. Low power handling capacity.
6. Surface wave excitation.

Microstrip patch antennas have a very high quality factor (Q). Q represents the losses associated with the antenna and a large Q leads to narrow bandwidth and low efficiency. Q can be reduced by increasing the thickness of dielectric substrate. But as the thickness increases, an increasing fraction of the total power delivered by the source goes into a surface wave. This surface wave contribution can be counted as an unwanted power loss, as it usually scatters at the dielectric bends and causes degradation of the antenna characteristics. However, surface waves can be minimized...
by use of photonic band gap structures. Other problems such as lower gain and lower power handling capacity can be overcome by using an array configuration for the elements.

2.6 Feeding techniques
Microstrip patch antennas can be fed by a variety of methods [73]. These methods can be classified into two categories: contacting and non-contacting. In the contacting method, the RF power is fed directly to the radiating patch using a connecting element such as a microstrip line. In the non-contacting scheme, electromagnetic field coupling is done to transfer power between the microstrip line and the radiating patch. The four most popular feed techniques are the microstrip line, coaxial probe (both contacting schemes), aperture coupling and proximity coupling (both non-contacting schemes). These are discussed below.

2.6.1 Microstrip line feed
In this type of feeding technique, a conducting strip is connected directly to the edge of microstrip patch as shown in Fig. 2.2. The conducting strip is smaller in width as compared to the patch and in kind of feed arrangement has the advantage that the feed can be etched on the same substrate to provide a planar structure [73].

![Microstrip line feed](image)

Figure 2.2: A typical example of microstrip line feed [73].
The purpose of the inset cut in the patch is to match the impedance of the feed line to the patch without the need for any additional matching element. This can be achieved by properly positioning the inset. This is an easy feeding scheme, as it provides ease of fabrication and simplicity in modeling as well as impedance matching. However, as the thickness of the dielectric substrate being used increases, surface waves and spurious feed radiation also increases, which hampers the bandwidth of antenna. The feed radiation also leads to undesired crosspolarized radiation.

2.6.2 Coaxial probe feed

The coaxial probe feed is a very common technique used for feeding microstrip patch antennas [73]. As shown in Fig. 2.3, the inner conductor of coaxial connector extends through the dielectric and is soldered to the radiating patch; while, the outer conductor is connected to ground plane.

![Coaxial probe feed rectangular patch](image)

**Figure 2.3**: Probe feed rectangular patch [73].

The key advantage of this type of feeding scheme is that the feed can be placed at any location inside the patch in order to match its input impedance. This feed method is easy to fabricate and has low spurious emissions [74]. However, on its downside, it provides narrow bandwidth and is difficult to model. It is because a hole needs to be drilled in substrate and the connector protrudes outside of the ground plane [75].
makes it non-planar for thick substrates \((h > 0.02\lambda_0)\). Also for thick substrates, the increased probe length makes the input impedance more inductive. This usually leads to impedance matching problems. Thus, for a thick dielectric substrate with broad bandwidth, the microstrip line feed and the coaxial feed suffer from numerous disadvantages. These problems can be better addressed with non-contacting feed techniques.

### 2.6.3 Aperture coupled feed

In this type of feed technique, the radiating patch and microstrip feed line are separated by ground plane as shown in Fig. 2.4. Coupling between the patch and feed line is made through a slot or an aperture in the ground plane [76].

![Image of Aperture coupled feed](image)

**Figure 2.4: Aperture coupled feed [73].**

The coupling aperture is usually positioned centred under the patch, leading to lower cross-polarization due to symmetry of the configuration. The degree of coupling from the feed line to patch is determined by the shape, size and location of aperture. As the ground plane separates the patch and feed line, spurious radiation is minimized. Generally, a material with high dielectric constant is used for the bottom substrate and a thick material with low dielectric constant is used for the top substrate to optimize radiation from the patch. The major disadvantage of this feed technique is the
difficulty involved in its fabrication due to multiple layers, which also increases the antenna thickness. This feeding scheme provides narrow bandwidth [81-82].

2.6.4 Proximity coupled feed
This type of feed technique is also called electromagnetic coupling scheme. It is shown in Fig. 2.5, in which two dielectric substrates are used. The feed line is between the two substrates and the radiating patch is located on top of the upper substrate. The main advantage of this feed technique is that it eliminates spurious feed radiation and provides comparatively higher bandwidth, due to the overall increase in thickness of microstrip patch antenna. This scheme also provides choices between two different dielectric media, one for the patch and one for the feed line to optimize the individual performances [77-78].

Matching can be achieved by controlling the length of feed line and the width-to-line ratio of patch. The major disadvantage of this feed scheme is that it is difficult to fabricate, as the two dielectric layers need proper alignment. Also, there is an increase in the overall thickness of antenna [85-87]. The summary of key characteristics of different feeding techniques is given in Table 2.1.
Table 2.1: Characteristics of different feeding techniques.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Microstrip Line Feeding</th>
<th>Coaxial Feeding</th>
<th>Aperture Coupled Feeding</th>
<th>Proximity Coupled Feeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spurious feed radiation</td>
<td>More</td>
<td>More</td>
<td>Less</td>
<td>Minimum</td>
</tr>
<tr>
<td>Reliability</td>
<td>Better</td>
<td>Poor due to soldering</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Ease of fabrication</td>
<td>Easy</td>
<td>Soldering and drilling needed</td>
<td>Alignment required</td>
<td>Alignment required</td>
</tr>
<tr>
<td>Impedance matching</td>
<td>Easy</td>
<td>Easy</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2-5%</td>
<td>2-5%</td>
<td>2-5%</td>
<td>13%</td>
</tr>
</tbody>
</table>

2.7 Key fractal geometries

Fractals can be either random or deterministic. Most fractal objects found in nature are random. These are produced randomly from a set of non-determined steps. Fractals that are produced artificially as a result of an iterative algorithm, generated by successive dilations and translations of an initial set, are deterministic [63-64]. Some of the key fractal geometries are shown in Fig. 2.6. There are many types of fractal antennas based on different fractal geometries, these are discussed in the next section.

Figure 2.6: Different types of fractal geometries.
2.7.1 Sierpinski Gasket

Sierpinski's Gasket triangle is a deterministic fractal. The deterministic construction algorithm for the Sierpinski Gasket is shown in Fig. 2.7. From Fig. 2.7, it is evident that this geometry has self-similar properties like other fractals. It is because, whatever part of the triangle taken (say in Fig. 2.7c) it replicates the same triangle (Fig. 2.7a) on magnification. For example in Fig 2.7, an equilateral triangle is used to start with. The midpoints of each side of this triangle are used as the vertices of a new triangle, which were then removed from the original one as shown in Fig. 2.7b. This process can be continued further to produce smaller triangles [88-89].

![Sierpinski Gasket stages](image)

a) Stage 0  
b) Stage 1  
c) Stage 2

Figure 2.7: Sierpinski Gasket fractal antenna [64].

2.7.2 Sierpinski Carpet

The Sierpinski Carpet is also a deterministic fractal which is a result of the generalization of Cantor set into two dimensions, as shown in Fig. 2.8. In order to construct this fractal, the process is started with a square in a plane, which is further subdivided into nine smaller congruent squares. Among these nine squares, the opened central one is dropped out and the same process is repeated for each of the remaining eight squares. This process is a continued process; however, a limitation can be obtained from the generation of the Cantor set [88].
2.7.3 Koch curves

Koch curve is constructed with a straight line, as shown in Fig. 2.9. In this case, the line is divided into three equal segments and middle segment is replaced by two sides of an equilateral triangle of the same length, as the segment being removed [67-68]. This makes four line segments, as shown in stage 1. This process is repeated for each of these four segments as shown in stage Fig. 2.9. This procedure can be further applied repeatedly to the remaining lines.

Figure 2.9: Koch curves [67].
2.8 Modelling techniques of microstrip patch antennas

There are many methods for modelling and analysis of the microstrip patch antennas. These can be broadly classified into two categories: approximate methods and full wave methods. The approximate method includes the transmission line model, cavity model and segmentation model. The approximate models are easy to implement for single element antennas. These methods give good physical insight with small solution time; however, are limited in accuracy [73]. The most popular full wave methods that can be used to model probe-fed microstrip patch antenna are the method of moment (MOM), the finite element method (FEM) and the finite-difference time-domain (FDTD) method [74].

2.8.1 Transmission line model

Transmission line model represents the microstrip antenna by two slots of width $W$ and height $h$, separated by a transmission line length $L$ as shown in Fig. 2.10. The microstrip is the non-homogeneous line of two dielectrics, typically the substrate and air.

![Figure 2.10: Microstrip line [73].](image)

The electric field lines of microstrip line is shown in Fig. 2.11, in which most of the electric field lines reside in substrate; with some part in air. As a result, this transmission line cannot fully support transverse electric-magnetic (TEM) mode of
transmission. It is because the phase velocities would be different in air and substrate. Also, the dominant mode of propagation would be the quasi-TEM mode. Thus, an effective dielectric constant ($\varepsilon_{\text{eff}}$) is required in order to account for the fringing and wave propagation in line. The value of $\varepsilon_{\text{eff}}$ is slightly less than $\varepsilon_r$ because the fringing fields around the periphery of patch are not only confined in the dielectric substrate but also spread in air surrounding the patch, as shown in Fig. 2.11.

![Electric field lines](image)

Figure 2.11: Electric field lines [73].

The expression for $\varepsilon_{\text{eff}}$ can be given as [26]:

$$
\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}}
$$

(2.6)

Where,

- $\varepsilon_{\text{eff}}$: Effective dielectric constant,
- $\varepsilon_r$: Dielectric constant of substrate,
- $h$: Height of dielectric substrate, and
- $W$: Width of the patch.

To better understand, consider the Fig. 2.12, which shows a rectangular microstrip patch antenna of length $L$, width $W$ resting on a substrate of height $h$. The axes are selected in a manner that the length is along the $x$ direction, width is along the $y$ direction and the height is along the $z$ direction.
In order to operate in the fundamental $TM_{10}$ mode, the length of patch must be slightly less than $2\lambda$, where $\lambda$ is the wavelength in dielectric medium and is equal to $\lambda_{0}/\varepsilon_{\text{eff}}$. The term $\lambda_{0}$ refers to the free space wavelength. The $TM_{10}$ mode implies that the field varies every one $2\lambda$ cycle along the length, and there is no variation along the width of patch. The structure of microstrip patch antenna is shown in Fig. 2.13, in which it is represented by two slots separated by a transmission line of length $L$ and open circuited at both ends. Along the width of patch the voltage is maximum, however, the current is minimum due to open ends.
The fields at the edges can be separated into normal and tangential components with respect to the ground plane. In Fig. 2.14, the normal components of electric field at the two edges along the width are in opposite directions and out of phase. It is because the patch is $2\lambda$ long and the out of phase electric fields cancel each other in the broadside direction. On the other side, the tangential components are in phase, which means the resulting fields combine to give maximum radiated field normal to the surface of structure. Thus, the edges along the width can be represented as two radiating slots, which are $2\lambda$ apart, and excited in phase and radiating in the half space above the ground plane. The fringing fields along the width can be modelled as radiating slots and electrically the patch of microstrip antenna looks greater than its physical dimensions.

2.9 Engineering applications of fractals

Over the last several years, fractals are gaining increasing popularity and are thus, being used in various domains of science and engineering. Some of these include: geology, atmospheric sciences, forest sciences and physiology. Several books and monographs are available on the use of fractals in physical sciences. In engineering, fractal mechanics is a key area that has benefited significantly from the application of fractals [90-91].

The space-filling nature of fractal geometries has attracted several innovative applications. Fractal mesh generation has been shown to reduce memory requirements and CPU time for finite element analysis of vibration problems [91]. Another key
application of fractals is image compression using fractal image coding [92-94]. In this area, fractal image rendering and image compression schemes have led to significant reduction in memory requirements and processing time.

In electromagnetic engineering, scattering and diffraction from fractal screens have been studied extensively. For example, diffracted fields from self-similar Sierpinski Gasket in the Fraunhofer zone were found to exhibit self-similarity properties [95]. These studies of wave interactions within the self-similar structures are termed fractal electrodynamics [96-98]. Recently, fractal geometries have also been successfully used in frequency selective screens [99-102]. The self-similarity properties of the fractal geometries are very crucial and attributed to many properties such as dual band nature of their frequency response and also helpful in surface impedance matching of metallic patterns of fractal geometries on a dielectric slab [103].

2.10 Summary

The key motivation of fractal antenna engineering is to incorporate and extend Euclidean geometry design and properties to design and develop small sized antennas with multiband characteristics [62]. In this context, the use of fractals in antenna array synthesis and fractal shaped antenna elements have been extensively investigated by various engineers, researchers and also similar studies have been investigated through this thesis in designing fractal antennas.

From the discussion made above and taking into account the benefits and advantages of fractal theory and geometries, the key objective, hereafter, is to investigate the ways to incorporate these to design and develop the small sized fractal antennas suitable for various low powered handheld wireless devices. The antenna characteristics such as frequency range of operation, radiation pattern and power will be discussed further in this thesis. In particular, the reported research is focused on the self-similar properties of fractal antennas having frequency independent multiband characteristics [103-104].

This use of fractals is expected to benefit in reducing the fractal dimensions, which leads to a better control of sidelobes [105]. For example, fractal trees have already been explored for the same reason by Puente et al. [106]; and they found the same to have multiband characteristics. A review of key research studies already made and/or in progress in the domain of using fractal geometries for miniaturizing the antenna and enhancing its multiband characteristics is reported in chapter 3.