Review On: Fractal Antenna Design Geometries and Its Applications

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Abstract: *In this review paper, we provide a comprehensive review of developments in the field of fractal antenna engineering. First we give brief introduction about fractal antennas and then proceed with its design geometries along with its applications in different fields. It will be shown how to quantify the space filling abilities of fractal geometries, and how this correlates with miniaturization of fractal antennas.*

Keywords – *Fractals, self -similar, space filling, multiband*

1. Introduction

Modern telecommunication systems require antennas with wider bandwidths and smaller dimensions as compared to the conventional antennas. This was beginning of antenna research in various directions; use of fractal shaped antenna elements was one of them. Some of these geometries have been particularly useful in reducing the size of the antenna, while others exhibit multi-band characteristics. Several antenna configurations based on fractal geometries have been reported in recent years [1] – [4]. These are low profile antennas with moderate gain and can be made operative at multiple frequency bands and hence are multi-functional.

2. Fractals

According to Webster's dictionary, a fractal is defined as being "derived from the latin fractus which means broken,

irrespective of various extremely irregular curves or shapes that repeat themselves at any scale on which they are examined.

The term "Fractal" means linguistically "broken" or "fractured" from the Latin "fractus." The term was coined by Benoit Mandelbrot, a French mathematician about 20 years ago in his book "The fractal geometry of Nature" [5]. Names like G. Cantor (1872), G. Peano (1890), D. Hilbert (1891), Helge von Koch (1904), W. Sierpinski (1916) Gaston Julia (1918) and other personalities played an important role in Mandelbrot's concepts of a new geometry. Nathan Cohen, professor at Boston University built the first known fractal antenna in 1988. Cohen's efforts were first published the first scientific publication about fractal antennas in 1995, since then a number of patents have been issued.

Fractal is a geometrical shape that has the property of self-similarity, which means, each part of the shape is a smaller version of the parent shape or original shape. Fractals can be classified as natural and mathematical fractals.

Natural antennas:

As the name suggests, the fractals which are found in nature all around us are natural antennas. These are also called as random fractals. These geometries have been used to characterize the structures which are difficult to define with the Euclidean geometries. Most of these geometries are infinitely further divisible, each division being copy of the parent. Some of the examples of natural antennas are length of coastline, branches of trees and plants, rivers, galaxies etc.

Mathematical antennas:

The mathematical antennas are those which undergo iterations based on equations. They are also called as deterministic fractals. The deterministic fractals are visual. The two-dimensional fractals are made of a broken line called the generator. Each of the segments which form the broken line is replaced by broken line generator at corresponding scale for a step of algorithm. And repeating the steps infinitely results in geometrical fractals. The examples of mathematical antennas are Koch, sierpinski gasket, Mandelbrot sets etc. The number of iterations is based on iterated function systems [6].

3. Fractal Dimensions

The term "Dimension" in mathematics has different meanings. The "Topologic Dimension" is the most common of them in which a *point* has the dimension 0, a *line* has the dimension 1, a *surface* has the dimension 2 and a *cube* has dimension 3. In other words, one could describe the dimension of an object with a number of parameters or coordinates.

In fractal geometries, fractal dimension is the unique feature. There are different notations of the dimension of fractal geometries, such as topological dimension, Hausdorf dimension Box counting dimension, and self-similarity Dimension. Among these, the self-similarity dimension is one of the most important parameters for the characterization of the fractal geometries. The self-similarity dimension of the fractal geometry is defined as

$$D_s = \frac{\log(N)}{\log\left(\frac{1}{s}\right)}$$

where N is the number of self-similar copies and s is the scale factor.

4. Iterated Function Systems: Language of Fractal

Fractals have some infinitely repeating pattern. Instead of the word "repeat" we use a mathematical synonym "iterate" and the process is called *iteration.* Iterative function system (IFS) is an extremely versatile tool for convenient generation of fractal geometries. The iterative function system is a collection of self-affine transformations [7] given by,

$$W(x) = A\,x + t = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x1 \\ x2 \end{bmatrix} + \begin{bmatrix} e \\ f \end{bmatrix}$$

The matrix A is given by:

$$A = \begin{bmatrix} \left(\frac{1}{s}\right)\cos(\theta) & -\left(\frac{1}{s}\right)\sin(\theta) \\ \left(\frac{1}{s}\right)\sin(\theta) & \left(\frac{1}{s}\right)\cos(\theta) \end{bmatrix}$$

The parameters *a, b, c* and *d* are defined by scaling and rotation of initial geometry and *e* and *f* denote the translation.

Fractal design has two components:

i) Initiator (0th stage): the basic shape of the geometry.

ii) Generator: the shape which gets repeated in a pattern on the initiator in subsequent stages of different dimensions.

There are several techniques to develop and to produce fascinating images. Two techniques popularized by Mandelbrot's book are the

1. Koch construction

One starts with a straight line, which is the initiator. This is partitioned into any number of equal, say three parts, and the segment at the middle is replaced with two others of the same length. This results in the first iterated version of the geometry and is called the generator. The higher iterations of the geometry can be obtained by further repeating this process. Each segment in the first iterated curve is ⅓ the length of the initiator [8].
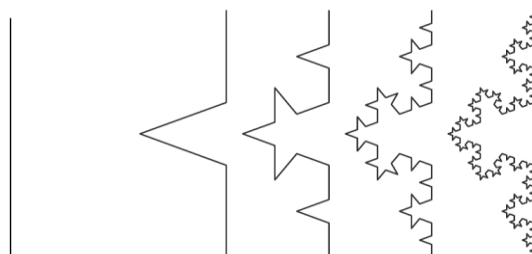

Figure 1: Geometrical construction of standard Koch curve.

2. Function iteration in the complex domain.

The generator is used to add or subtract from the area of the initiator n from each subsequent iteration stage in a fixed pattern thus culminating in the fractal structure[9].
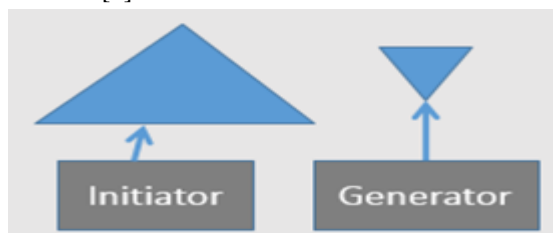

Figure 2: Initiator and Generator of A Sierpinski Gasket Fractal

Random processes can be used to generate random fractals.

5. Why Fractals are used?

Small antennas are of prime importance because of available space limitations on the devices and the oncoming deployment of diversity and multi input and multi output (MIMO) systems. Fractal geometry provides the solution by designing compact and multiband antennas in a most efficient and sophisticated way with better antenna performance [10]. Fractals can be used in two ways to enhance the antenna designs. The first method is in the design of miniaturised antenna elements. The second method is to use self-similarity in the geometry.

5.1 Fractals as space filling geometries

Hilbert curve is widely used in the miniaturization of antenna element because of its space-filling property. A line can meander in such a way as to effectively almost fill the entire sheet. The space filling property lead to the curves that are electrically long but fit into a compact space and lead to the miniaturization of the antenna elements. Due to this space filling property, the fractal antennas occupy space in more effective manner as compared to the traditional Euclidean antennas and hence results in miniature antennas [11].

5.2 Fractals as multiband antennas

Fractal show multiband or log periodic behaviour that has been attributed to self-similar scale factor of the antenna geometry. When an object is composed of smaller copies of the original geometry, it is said to be self-similar. A self-similar object can be described as a cluster, which is again made up of smaller clusters that are identical to the entire geometry. Thus, within the whole geometry, an infinite number of similar copies can be found. Hence, fractal geometries are said to have no characteristic size.

6. Fractal Geometries

Many patterns in the nature are so irregular and fragmented that they exhibit not only a higher degree, but also a higher level of complexity. Hence, Mandelbrot proposed a new geometry and its use in various diverse fields. The geometry describes many of the irregular and fragmented patterns of nature around us. Mandelbrot coined the term 'fractal' from the Latin word '*frangere*' which means to break, to create irregular fragments. He used the term fractal to describe some complex and convoluted objects such as mountains, coastlines and many other natural phenomenon.

6.1. Sierpinski Carpet

Sierpinski carpet fractal is realized by successive iterations on a simple square patch, which is called as the zeroth order iteration. A square of dimension equal to one third of the main patch is subtracted from the centre of the patch to obtain the first order iteration. This process is repeated continuously further to obtain next order iterations. The pattern is defined in such a way that each consequent etched square is one third in dimension as compared to the previous one sharing the same centre point [12].
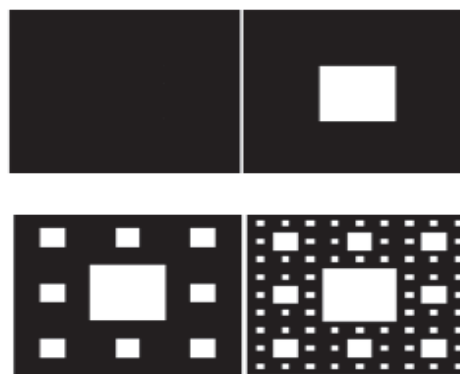

Figure 3: Sierpinski Carpet Antennas upto 3rd iterations.

Sagne et al. (2013) designed a microstrip fed Sierpinski carpet fractal antenna (SCFA) up to 3rd iteration. The size of the patch is reduced by 33.9% compared to the conventional microstrip antenna. The designed antennas can be used for various applications such as military and meteorological satellite communication(8 to 12.5 GHz), Wi-Fi (5.1 - 5.825 GHz), PTP communication in US military (6 GHz), radar and navigation services, broadband fixed wireless access (BFWA) services, UMTS (1920 - 2170 MHz), Medium and High Capacity P-P (7725-8275 MHz), Bluetooth, WiMAx applications etc [13].

6.2 Koch Curve

In 1998 the von Koch monopole became the first reported fractal small antenna that improved the features of some classical antennas in terms of resonance frequency, radiation resistance and bandwidth. A Koch curve is generated by replacing the middle third of each straight section with a bent section of wire that spans the original third. Each iteration adds length to the total curve which results in a total length that is 4/3 the original geometry [14].
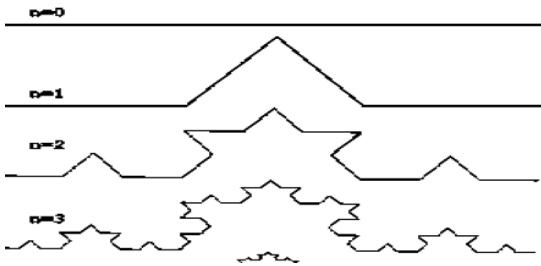
Figure 4: Construction process of Koch curve

Fazal et al. (2012) presented the partial Koch triangular patch antenna. The comparison to the traditional triangular patch is carried out which reveals that the proposed design has been improved S11 and gain. The design antenna can be used in applications such as indoor LANs, GSM booster units etc [15].

6.3 Minkowski Curve

The Minkowski curve is also known as Minkowski Sausage and was dated back to 1907 where a German mathematician, Hermann Minkowski, investigated quadratic forms and continued fractions. Minkowski loop (Fig. 5) can be used to reduce the size of the antenna by increasing the efficiency with which it fills up its occupied volume with electrical length. A Minkowski fractal is analysed, where the perimeter is near one wavelength. The comparison of several iterations with a square loop antenna is done to illustrate the benefits of using a fractal antenna.
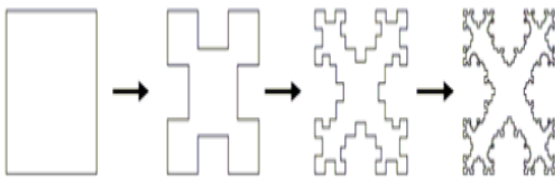

Figure 5: Iterations of Minkowski loop

Nagpal et al. (2013) proposed a multiband E-Shaped fractal patch antenna with DGS (Defected Ground Structure). After applying fractal geometry on microstrip patch antenna, E shaped fractal patch has been obtained (Figure 6), and area of patch decreases and multiband characteristics are obtained with better return loss, bandwidth, and directivity. The proposed antenna is applicable for Satellite, Wi-Fi, Bluetooth, Cellular Phones and Radar etc [16].
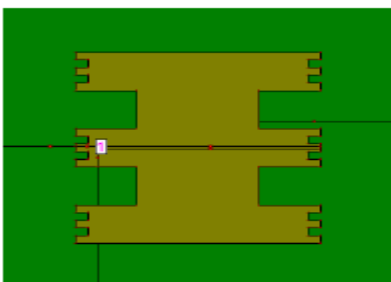

Figure 6: E-Shaped Fractal patch antenna

6.4 Hilbert curve

The first few iterations of Hilbert curves are shown in Figure 7. It may be noticed that each successive stage consists of four copies of the previous, along with the additional line segments. The geometry so obtained is a space-Filling curve that is with the large number of iterations the entire area it occupies will be filled. Apart from this the geometry also has the following properties: self-Avoidance (as the line segments do not intersect each other), Simplicity (since the curve can be drawn with a single stroke of a pen) and self- Similarity. Because of these properties, these curves are often called FASS curves [17].
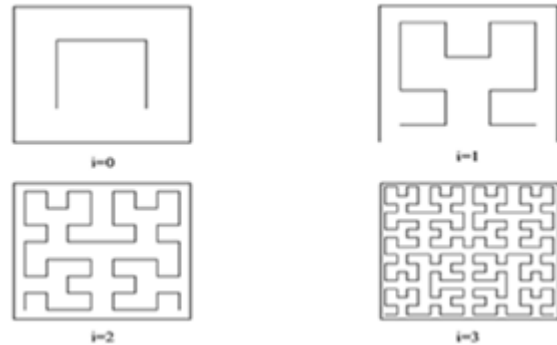

Figure 7: Generation of Iterations of Hilbert Curve

Huang et. al.(2010) proposed a Miniaturized inverted-F antennas (IFAs). By employing Hilbert geometry, an overall size reduction of 77% was achieved compared to the conventional rectangular patch antenna. The miniaturised IFA antenna can be easily built in a wireless sensor network (WSN) [18].

6.5 Circular Microstrip Antenna

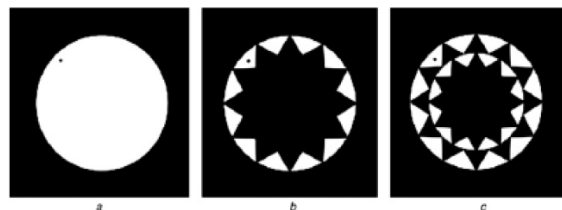The advantage of fractal antennas is that fractal shape of simple microstrip patch antennas can be obtained.

Figure 8: Circular Microstip Patch Antenna

In Figure 8, a circular metallic patch is designed and then point star shaped fractal geometry is subtracted from the circular patch with some sharpness factor and appropriate dimensions.

Thakare and rajkumar(2009) proposed a novel design of star-shaped fractal patch antenna for miniaturisation and backscattering radar cross-section (RCS) reduction. The proposed fractal antenna gives 50% size reduction. RCS reduction is important for many defense and civilian applications [19].

6.6 Pythagoren Tree Fractal

The construction of a Pythagoras tree begins with a square. Two other squares are constructed upon this square, each scaled down by a linear factor, such that the corners of the square coincides pair wise. The same procedure is then applied recursively to the smaller two squares. Figure 9 shows the iteration in the construction process.
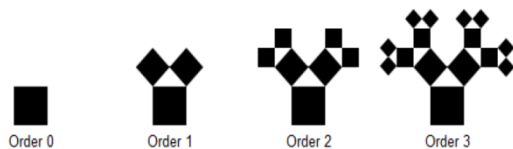
Figure 9: Iterations of Pythagoren Tree

Pourahmadazar et al. (2011) a novel modified Pythagorean tree fractal (MPTF)-based antenna using multifractal technique for UWB application. MPTF exhibited very good miniaturization ability due to its self-similar properties, without reducing the bandwidth and the efficiency of the antenna [20].

Apart from the wireless, military, UWB and communication applications discussed above, the other applications of fractal antenna are in the following fields:

Computer science

The space filling nature of fractal geometries has invited several innovative applications. Fractal mesh generation has been shown to reduce memory requirements and CPU time for finite element analysis of vibration problems. One area of application that has impacted modern technology most is image compression using fractal image coding [21]. Fractal image rendering and image compression schemes have led to significant reduction in memory requirements and processing time. Another advantage of fractal compression is that when image is enlarged, there is no pixelisation.

Medicine

Biosensor attractions can be studied by using fractals.

7. Advantages and disadvantages of fractal antenna

A fractal antenna is an antenna with are complex geometric designs that uses a self-similar design to increase the length, or the perimeter of material that can receive or transmit electromagnetic radiation within a given total surface area or volume [22]. Some key benefits of fractal antennas area:

- Fractals, through their self-similar property, are natural systems where this complexity provides the sought after antenna properties. Fractal Antennas radically alter the traditional relationships between gain, bandwidth and antenna size, allowing antennas that are more versatile, compact and powerful.

- Fractal versions of all existing micro strip antenna types can be obtained.

- Fractal Antenna's technology leads to unique improvements in antenna arrays, increasing their bandwidth, allowing multiband capabilities, decreasing size load and enabling optimum smart antenna technology.

- Increased bandwidth, gain and multiband behaviour in addition to smaller size.

- These qualities of fractals enable the production of high performance antennas that are typically 50 to 75 percent smaller than traditional ones.

- Further fractal antennas are more reliable and lower cost than traditional antennas as antenna performance is attained through the geometry of the conductor, rather than with the accumulation of separate components or separate elements that inevitably increase complexity and cost.

The disadvantages of fractal antenna are:

- Gain loss

- Numerical limitations

- Complexity

- Benefits begin to diminish with increased iterations.

8. Conclusion

In this paper we shortly review the geometries, basic properties and applications of the fractal antennas. Fractal antenna engineering represents a relatively new field of research that combines the attributes of fractal geometry with antenna theory. Research in this field has recently yielded a rich class of new designs for antenna elements as well as arrays. Fractals are space filling geometries can be used as antennas to effectively fit long electrical lengths into small areas. Through characterizing the fractal geometries and performance of the antennas, it can be summarised that increasing the fractal dimension of the antenna leads to higher degree of miniaturization. Among the topics, the fractal antenna geometries, applications and advantages of fractals have been discussed.

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