Analytical solution and simulation of multiband fractal Antenna for IoT applications

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Abstract: This paper would give an insight into finding analytical solution for designing fractal antennas of Koch curve type fractal geometries. An analytical equation to generalize for any Koch curve length is derived, which meet the basic nature of any Koch curve type fractal geometries. A numerical example detailed explains the validity and generality of the derived analytical solution. A micro-strip patch of snowflake structured fractal geometry considered for multi-band antenna, fulfill the needs of antenna for IoT applications. The dimensions of the fractal antenna are related to the resonance frequencies and input impedance. The figures of merit of fractal antennas are analysed by simulating micro-strip patch antenna of Koch curve type snowflake fractal geometries, using HFSS tool.

The fractal antenna simulated would fit with the specifications of Internet of Things (IoT) applications, like Omni directionality and the frequencies of operation. The simulated results have resonant frequencies 5.58GHz, 12.50GHz and 18.56GHz which are all part of IoT spectral bands. The simulated bandwidth of operation 1.9 GHz, 1.29 GHz and 1.43 GHz and the quality factor Q is 2.93, 9.68 and 12.97 respectively.

Keywords: FRACATAL ANTENNAS; KOCH CURVES; SNOWFLAKE STRUCTURES; MULTIBAND ANTENNAS, IOT ANTENNA.

INTRODUCTION

The fractal antennas gain popularity from past several years specifically where it is necessary to efficiently utilize the spatial geometry of the antennas[1][4]. In other words, the optimal utilization of the size of the structure (micro-strip patch antenna) to optimize the key parameters of the antenna. Outwardly the geometries of the fractal antenna appear to be irregular in nature [5]. But the close focus gives insight into its relations with the parameters of the antenna.

From the past few decades antenna designers are successful to relate the geometry of the fractals with the primary parameters of the antenna[4]. However some of the relations derived appears to be not so precise. Here an attempt is made to address such issues. The beauty of similarity and repetitiveness are responsible for multiband characteristics and better bandwidth of the fractal antennas [10]. The widely used and most popular fractal geometry is the Koch curve [5][1]. The curious geometries of fractal antenna not only bestow multiple resonant frequencies of operation [5] but also have a say in radiation characteristics at these resonant frequencies.

This paper focuses on a step closer to build precise analytical relationship for antenna parameters in terms of fractal geometry.

Section II is about understanding Koch curve on snow flake structures.

Section III details on existing mathematical relations in terms of geometries and also on its limitations. The changes in those relations and its impact on precision is detailed in...
Section IV. Also complete analytical solution with numerical example to depict its precision.

Section V explains the fractal geometry and its relationship with multiple bands. Along with the analytical solution described and also substantiates with simulation results using HFSS.

II. MULTIPLE ITERATIONS OF KOCH CURVES ON SNOWFLAKE STRUCTURE.

Construction of Koch curve is simple and the steps followed are shown Fig. 1. With minimal iterations, there is significant increase in perimeter of the Koch curve can be observed from Fig.1. Applying similar iterations on all the three edges of a triangle enhances the perimeter of the triangle.

Fig. 1. Steps followed to construct Koch curve fractal and its iteration details

Fig. 2. Construction and iteration details of snowflake Koch curve fractals with triangle as base.

Fig. 2 depicts generations of snowflake fractal structure, considering triangle as the base. As shown in Fig.2, after iterations on all the three edges of the triangle, the triangular shape appears like a snow flake and hence referred as snowflake structure. The significant increase in perimeter of snowflakes compared to triangle can be observed from iterations 0-3 of Fig.2.

Another interesting factor to be noted here is: area of snow flake almost remains constant, but the perimeter of snowflake increases significantly and tends towards infinity for higher iterations.

III. ANALYTICAL SOLUTION OF KOCH CURVES AND ITS GENERALIZATION.

The generalized equation for calculating the coordinates of the Koch structure is as shown in eq.1. Let us consider an initiator of length q is placed on x axis of the x,y coordinate system. Let its left end is at origin. The transformations to obtain segments as shown in Fig.3 are described in equation 2 [1].

\[
W_1 \begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ r & r \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \left(\frac{n}{t}\right) \quad --1
\]

\[
W_2 \begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ s & s \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \left(\frac{q}{s}\right) \quad --2
\]

\[
W_3 \begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ s & s \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \left(\frac{q}{s\times\sin\theta}\right) \quad --3
\]

\[
W_4 \begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ s & s \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \left(\frac{(s - 1)\times q}{s}\right) \quad --4
\]

The generator can be obtained by vector summation of W1 to W4. It can be imagined from Fig.1 and Fig.3 that physical distance between start and end point of all iterations remains same [1]. In this case the length q remains same. From equation 1 to equation 5, it is understood that the constant term q need to be added to generalize from unit length expressions given in [1]. Here ‘s’ refers to scaling factor and \(\theta\) is indentation angle, varies from 0 to 90 degree. \(\theta\) equal to 0 degree means no fractals and \(\theta\) equal to 90 degree refers to maximal complex fractal structure [1][4].
IV. EXAMPLE OF A KOCH CURVE.

A simple Koch curve is as shown in Fig.3, has four segments: f, g, h, and i of equal length. Consider the 2-dimensional Koch curve is on x, y coordinate system. The location point A is at origin. The segments f and i are on the horizontal x axis. Therefore the weights W1, W3 and W4 have zero y value for iteration 1 as shown in Table 1. Consider the horizontal length, q (as variable mentioned in Eq.3 to Eq.5) between origin A to W4 is 15 units, and each segment length as 5 units as shown in Table 1 for 1st iteration. But the total length or the perimeter of Koch curve after iteration 1 increased by 1/3 times the initial value and equal to 20 units. From Table 1 it is observed that the vector summation of weights W1 to W4 yields the same perimeter value 20 units for iteration 1. Iteration 2 in Table 1 details the numerical values for applying 1st iteration only on segment f in Fig.3. Here the value of q is 5 units. As the segment length considered for iteration 2 in Table 2 is 5 units.

From the above analysis and numerals in Table 1, it is observed that the perimeter is 20 units, increased 1/3 times the physical length, 15 units in a single iteration.

Therefore there is significant increase in perimeter value within few iterations. Hence the electrical length of the antenna can be increased with a little increase in physical size. Therefore Koch curves are promising structures for antenna design to enhance the electrical length, maintaining miniature size of the antenna structure and intern supports lower resonant frequency bands of operation.

Table 1. Iterations 1 and 2 for values W1 to W4

<table>
<thead>
<tr>
<th>Iteration</th>
<th>[x]</th>
<th>[y]</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>W4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>0</td>
<td>5</td>
<td>7.5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0</td>
<td>1.67</td>
<td>2.5</td>
<td>3.33</td>
<td>5</td>
</tr>
</tbody>
</table>

V. SIMULATION OF FRACTAL ANTENNA USING HFSS TOOL

The dimensions for snowflake fractal micro-strip patch antenna with Koch curve type is mentioned in Fig. 4. The micro-strip patch with the listed dimensions are used, to simulate the antenna using HFSS tool. The ground plane dimensions (17mmX12.5mm) of this patch antenna are complementary part of radiating patch and is at other side of the FR4 substrate as shown Fig. 4. The micro-strip line feeding technique [11] with 1mm width and 12.5mm length is as shown in the Fig.4.

Table 1 details the numerical calculations for weights W1 to W4 for both iteration 1 and 2. Applying numerals given for x and y, the values of W1 to W4 can be calculated for any given Koch curve length q.

Using HFSS tool, the snowflake structure is designed and the simulated structure is as shown in Fig. 5. The different stages while constructing is detailed as ‘a’ for iteration 0, ‘b’ for iteration 1 and ‘c’ for iteration 2, are clearly depicted in Fig. 5. The intensity of Electric field
distribution when excited with 1W signal using micro-strip line feeding technique is as shown Fig.6. It is observed that the maximum field is at the edges. If higher iterations are considered, the snowflake structure has better radiating length and in turn supports better gain.

**Fig.6.** The E field variation of the simulated snowflake fractal structure.

Also as the overall radiating area increases, hence improves the bandwidth. From Fig.6, it can be noted that if 3rd iteration is considered then spatial radiation increases. The IoT antennas have special requirements, one of that is Omni directionality. As the application insists the signals need to be accessed all 360 degree [11]. Hence the simulated snowflake fractal structure is highly suitable. Fig.7. depicts the 3D gain plot at three resonant frequencies, 5.58GHz, 12.50GHz and 18.56GHz. From Fig.7 it is observed that the above said snowflake antenna exhibits better gain in all 360 degrees, therefore this antenna can be recommended for IoT applications.

**Fig.7.** The three dimensional radiation with gain details for resonant frequencies 5.58GHz, 12.50GHz and 18.56GHz of plot 1, plot 2 and plot 3 respectively.

An antenna performance can be observed from various parameters. Table.2. gives the complete details of the key parameters of the antenna. Looking at the Table.2, it is implicit to say that the given snowflake antenna fulfills the needs of IoT application. Like Omni directionality, radiation efficiency, improvement in gain and radiation intensity, U as detailed in Table.2.

**Table.2.** The figures of merit of the simulated snowflake fractal Antenna.
The far field distribution patterns at different resonant frequencies is broad side in nature and the same can be observed from Fig.8.

![Fig.8. The far field distribution pattern at resonant frequencies 5.58GHz, 12.50GHz and 18.56GHz.](image)

The important parameter for any antenna is its return loss, the lower the return loss better the performance [4][11][24]. It is observed from Fig.9, that at resonant frequencies 5.58GHz, 12.50GHz and 18.56GHz, the return loss is -15.6392dB, -17.9265dB, -16.2633dB and the bandwidth of operation is 1.9 GHz, 1.29 GHz and 1.43 GHz respectively. The quality factor, Q is 2.93, 9.68 and 12.97 at resonant frequency bands 5.58GHz, 12.50GHz and 18.56GHz respectively. At all the resonant frequency bands, the return loss is very promising and much below -10dB[4]. Most of the IoT applications demand narrow frequency band of operation and is fulfilled by obtaining higher value of Q.

![Fig.9. The return loss S11 plot at resonance frequencies 5.58GHz, 12.50GHz and 18.56GHz.](image)

In this paper, the generalization of the existing analytical solution of fractal geometries to relate antenna parameters are addressed. The validity of generalized relations with respect to resonant frequencies in terms of fractal geometries is clearly depicted with an example. The simulations results of Koch curve type snowflake fractal geometries, reflect on the validity of generalized formulations between antenna parameters and fractal geometries. The elaborated result columns would address and substantiate the suitability of fractal geometries as antennas for IoT applications. The omnidirectional radiation patterns of the simulated antenna and the simulated results, describe the suitability for IoT applications. Fabrication of simulated structure and comparison between their results is future scope of this work. Further the validity of analytical solution for other fractal geometries need to be verified.

### VI. CONCLUSION

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