Hilbert Curve Fractal Antennas with Reconfigurable Characteristics

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Abstract: **Fractal Hilbert curve is one of the most recent geometries to be studied for antennas. This geometry results in an antenna with low resonant frequency compared to other configurations. The antenna consists of line segments arranged in a predictable fractal order, thus enabling easy generation and reproducible results compared to an arbitrary shrinkage of antenna size. This can be modeled using wire segments. An addition of few more interconnecting segments to the geometry is found to result in significant changes in its radiation pattern. With RF switches within these few selected additional segments and the necessary control units, radiation pattern of the antenna can be made adaptively reconfigurable. Similarly, switches connected in series along the length of the antenna result in frequency tuning characteristics.**

I. INTRODUCTION

With the widespread proliferation of telecommunication technology in recent years the need for small size multi-band antennas has increased manifold. However, an arbitrary reduction in the antenna size would result in a large input reactance and a deterioration in the radiation efficiency. Meander line and zig-zag antennas have been studied for their capability in antenna size-reduction [1], [2]. However, novel antenna configurations using fractal elements such as Hilbert curves are capable reducing the antenna size further. We have recently reported the use of these geometries in antenna design for the first time [3]. These fractal Hilbert curves have several important characteristics hitherto unexplored in antenna engineering. Once optimized for radiation characteristics these antennas can find many applications in UHF/VHF communication antennas.

Two important properties of fractal geometries are self-similarity and scale invariance [4]. Fractals consist of identical or similar elements repeated in different magnifications, orientations and positions, often in an inter-connected fashion to obtain the final structure. The fractal antennas using Siepinski gasket have been configured to obtain multiple frequency bands [5]. These antennas resonate at frequencies in near-logarithmic interval. The important features of this fractal antenna are low profile, possibility of multiple frequency bands, and moderate gain. Few other fractal geometries such as Sierpinski carpet, and Koch curves have also been reported in recent literature. Compared to these, antennas based on Hilbert curves have the additional feature of shrinking the antenna size significantly.

Antennas with capability to change their radiation characteristics adaptively are generally classified as reconfigurable antennas. These have been conventionally pursued for satellite communication applications, where it would often be required to change the broadcast coverage patterns to suit the traffic changes. These antennas also find applications in modern telecommunications scenario, where the same antenna could be shared between various functions (requiring frequency switching), or the antenna radiation characteristics could be altered as done in smart antennas, currently using signal processing techniques. In addition, reconfigurable antenna systems can also find applications in collision avoidance radars. These being of low power requirements are also readily amenable to MEMS based fabrication technology.

In the literature the term reconfigurable antenna is used mainly for antennas capable of modifying their beam shape and direction. But there are instances the same term is used with antennas which can adapt/change the operational frequency. For simpler wire type resonant antennas this can be achieved by adjusting the length of the antenna. RF switches can be used to connect between antenna segments to make it ‘reconfigurable’.

In this paper we explore, through numerical simulations, the effect of adding few additional short circuiting segments to the Hilbert curve fractal antenna [3]. In practice, these segments can be replaced with wires in series with RF switches. Although not modeled to incorporate the switch characteristics, this should not impede the effectiveness of the scheme at the frequencies considered.

II. ANTENNA GEOMETRY

Since the base antenna geometry itself is novel, we propose to introduce this first. Various iteration stages of fractal Hilbert curves are shown in Fig. 1. It may be observed that geometry at an iteration stage can be obtained by combining four scaled down copies of the previous iteration, connected with three additional line

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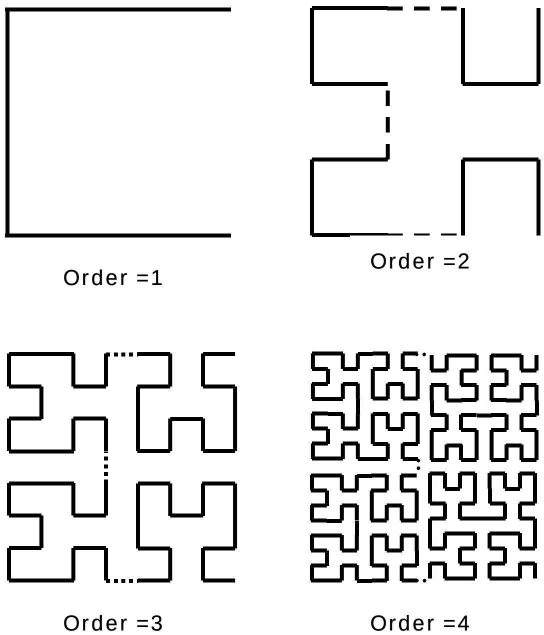

Fig. 1. Generation of four iterations of Hilbert Curves. The additional segments used to connect together copies of the previous iteration curves are shown in dashed lines.

segments. For example, the geometry of order 2, can be thought of as 4 copies (nearly halved) of the geometry with order 1 (arranged in different orientations). For the sake of clarity, these additional connection segments shown with dashed lines.

It would be interesting to identify the fractal properties of this geometry. The *plane filling* nature is very evident by comparing the first few iterations of the geometry shown in Fig. 1. The length contribution of this additional length (shown with dashed lines) is small compared to the overall length of the geometry, especially when the order of iteration is large. Hence these small additional lengths may be disregarded, which makes the geometry *self-similar*. The topological dimension of the curve is one, as it consists only of line segments. The similarity dimension of this curve approaches an integer value (two). But if we consider the length and number of line segments 1st and 2nd iterations, the dimension is 1.465. The corresponding numbers in the next two iterations are 1.694 and 1.834. These numbers point to the fact the geometry has *fractional dimension*, albeit approaching 2, as the order of fractal iteration is increased.

As the dimension approaches 2, the curve almost fills a plane. In other words, for large iteration orders, the total length of the line segments (each with topological dimension 1) tend to be extremely large. This could lead to a significant advantage in antennas since the overall

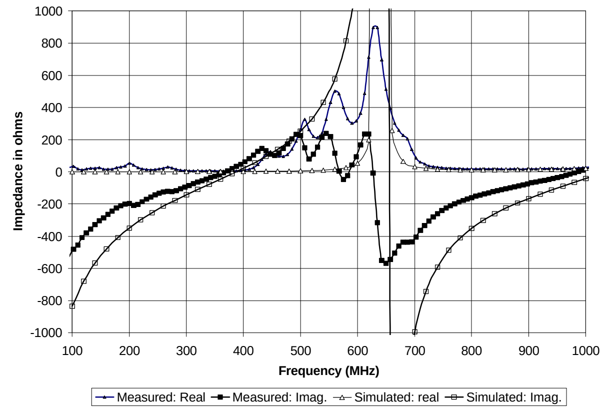

Fig. 2. The measured and simulated input impedance of a Hilbert curve fractal antenna of 3rd iteration. The outer dimensions of the antenna are 7 cm x 7 cm. Copper strips of 4 mm width is used to construct the antenna. An equivalent wire diameter is used in simulations.

effective length of the antenna is large. Thus the resonant frequency can be reduced considerably for a given area, by increasing the fractal iteration order. It may be recalled that the dimension of this curve is larger than that of Koch curves (dimension=1.262) [6], resulting in a larger reduction factor for the antenna size.

The studies presented recently indicate that, by increasing the fractal iteration order, the resonant frequency of the antenna can be significantly reduced [3]. Thus this approach strives to overcome one of the fundamental limitations of antenna engineering with regard to small antennas [7]. It may however be noted that since fractals do not come under the purview of Euclidean geometry, stipulations based on this may be relaxed for fractals [8].

III. Validation of the Model of Hilbert Curve Fractal Antenna

The antenna geometry consists only of line segments. Hence this can be modeled adequately with wire segments. We have used numerical electromagnetics code (NEC) to model these antennas. However, when the geometry is with a large fractal iteration order, individually entering these line segments may be tedious. To circumvent this, we adapted the recursive fractal generation algorithm [9] for Hilbert curves, to produce geometry definition input cards for NEC. This algorithm requires the overall spread of the geometry, the fractal iteration order, and the radius and length of the wire segments as data inputs.

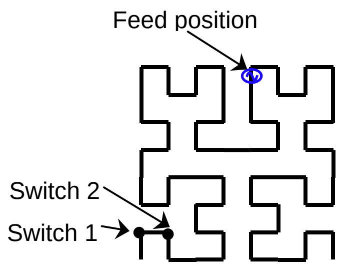

Fig. 3. The geometry of the antenna used in the study of frequency tuning characteristics. The outer dimensions of this antenna is 10.5 cm x 10.5 cm. The radiation patterns at the third resonance of this antenna is shown in Fig. 5.

The input impedance characteristics obtained by these simulation studies have been compared with experimental results. Copper strips, with width equivalent to the dimensions of the wire used in modeling, are pasted on a thin transparency sheet, to reduce any effects of the dielectric support. The feed is located at the point of symmetry for the geometry. The results indicated a close match between the experimental and simulated results (Fig. 2). However to improve the match in the real part input impedance, the location of the feed is moved along the length of the antenna. Depending on the resonance order, a position can be identified to match the input characteristics of the antenna with that of the feeding transmission line. Since the current distribution on the antenna remain the same, its radiation pattern is not altered by this relocation of the feed.

IV. Frequency Tuning Characteristics

As with any other wire antenna, the resonant frequency of the antenna can be increased by truncating its length. In this study we propose to insert low insertion loss RF switches in series with the segments constituting the Hilbert curve fractal antenna (HCFA) and study the effects on its input characteristics. We have chosen an HCFA with outer dimensions of 10.5 cm having its third resonant frequency at 620 MHz. The feed location for best impedance match with a 50 Ω transmission line is shown in Fig. 3. The VSWR for this antenna is shown in Fig. 4 as Case 1. Case 2 corresponds to the situation when switch 1 is turned off. Similarly, Case 3 is for switch 2 to be turned off. This approach is also significant in imparting frequency agility to the antenna characteristics. The change in the input characteristics in these cases does not surmount to any difference in the radiation characteristics.

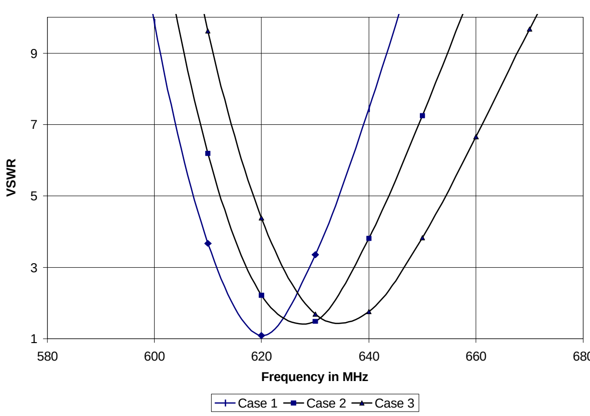

Fig. 4. Frequency tuning characteristics of the antenna by truncating the length using switches in series with the base antenna

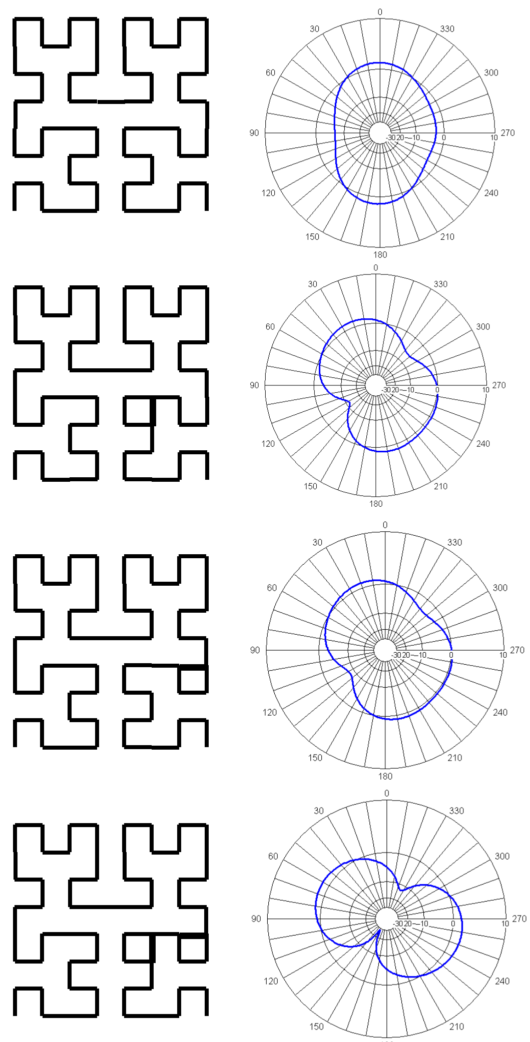

Fig. 5. Radiation patterns for a Hilbert curve fractal antenna with two additional segments. Patterns shown here are in the *xy* plane (same with the geometry). The additional segments in the geometry are shown with thicker lines for clarity. These can be realized in practice by turning ON or OFF switches connected in the additional arms.

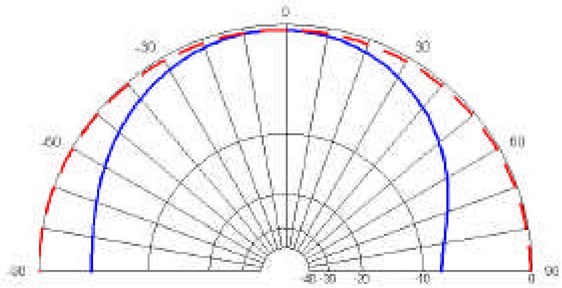

Fig. 6. The radiation pattern (θ-plane) of the base Hilbert curve fractal antenna used in this study. The plots shown are at ϕ=0° (dashed) and ϕ=90°. Only a half is shown because of apparent symmetry.

V. Modeling of Reconfigurable Antenna

Next we propose to explore the beam shaping characteristics of the antenna. The geometry is similar to the one discussed in the previous section. The additional short circuit segments are added to this selectively for the simulation studies of the reconfigurable antenna. The resulting radiation patterns in each case have been plotted in Fig. 5. The antenna lies entirely on the *xy* plane. The changes in the *xy* (*f*) plane is the most apparent, hence these are plotted in each case. The patterns in other planes are shown in Fig. 6 for the unperturbed case for the sake of comparison. The beam directions and beam widths in the *f* plane are compared in Table I. The beam width shown in the last column is for the highest peak in the radiation pattern of the antenna. These indicate that by the addition or removal of just two line segments, the antenna radiation characteristics can be changed significantly.

VI. Conclusions

Antennas using fractal Hilbert curves have been shown to reduce the antenna size considerably. These antennas can find various applications in the modern telecommunication systems, where the space available for the antenna is limited. It has been established that the input characteristics of the antenna can be made frequency agile by incorporating RF switches along its length. The change in the input characteristics in these cases does not reflect in its radiation characteristics. In addition, due to a large number of connected segments in the antenna geometry, reconfigurability of its radiation characteristics can be obtained by adding just few additional line segments to interconnect these. Significant changes in the patterns are obtained by NEC simulations. We are currently working on experimental validation of these results, first by adding, or removing the line segments manually, and then by using an appropriate switching system to automate the process. Once implemented the antenna should be able to adaptively re-orient its radiation characteristics and to tune its operational frequency to suit the requirements in a typical wireless communication environment.

Table I. Key parameters of radiation characteristics of the antenna models in various cases for beam reconfigurability from Fig. 5

Case Study	Peak Dir. 1	Gain	Peak Dir. 2	Gain	± 3dB BW
0	0	1.56	177	1.81	83
1	18	1.28	193	0.95	107
2	19	1.55	195	1.33	100
3	63	1.74	254	2.35	92

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