Optimization of the Sierpinski Carpet Fractal Antenna

Brian G. Cordes

Executive Summary

The booming progress of wireless systems and the dramatic development of a variety of wireless applications have remarkably increased the demand for multiband/wideband antennas. While traditionally different antennas are used for different frequency bands, recent studies have suggested that small planar antennas of certain configurations may operate in several frequency bands at a time. Further efforts in combining geometry with electromagnetic theory have led to many innovative antenna designs and, in particular, to the development of the rapidly growing field of *fractal antenna engineering*.

It has been noticed that the self-similarity properties of fractal shapes can be translated into its electromagnetic behavior and result in a multiband antenna. However, so far the studies of fractal antennas have been practically limited to rather *non-systematic explorations of different design ideas* and *nearly accidental findings of fortunate characteristics.* The direct relationship between antenna characteristics and the geometry of underlying fractals remains somewhat vague. Indeed, fractals are known to be suitable models for nature, but:

- *Is the fractal geometry of an antenna optimal in some sense?*
- Which *properties* (if any) of fractal antenna geometries *may be responsible* for multiband/ wideband performance?

These key issues have been the *major motivations for the present MQP*. Addressing them, the project:

- …studies a particular structure – the *Sierpinski Carpet* (SC) *fractal antenna*;
- …develops a highly accurate numerical model of this antenna (for the finite-difference time-domain (FDTD) method) and explores related optimization options;
- …suggests an original antenna design based on a broken fractal;
- …shows that this antenna is capable of being optimized in narrow and wide frequency bands.

Therefore, the following tasks have been taken as *specific project objectives*:

- *To develop an algorithm* generating the SC fractal antenna of arbitrary iteration *i* and producing a controllable FDTD mesh and *implement* this algorithm for *QuickWave-3D* – the conformal FDTD modeling software capable of accurate modeling of planar antennas.
- Through the systematic analysis of the SC fractal antenna, *identify its parameters* which may be responsible for the wideband performance.
- Formulate a problem of numerical optimization and *determine a geometry* of the optimal (wideband) antenna – with the use of the available procedure of neural network optimization.

Method. The presentation outlines the original results in studying of the influence of fractal geometry on the basic SC antenna parameters. We develop an algorithm generating the fractal geometries: the SC fractal uses the unit square as the initial geometry and is created using *8 specific affine transformations*

$$S_0 = \{(x_1, x_2) \in \Re^2 \,|\, (x_1 \geq 0), (x_1 \leq 1), (x_2 \geq 0), (x_2 \leq 1)\}$$

$$W_1 = \left[\frac{1}{3}, 0, 0, \frac{1}{3}, 0, 0\right] \quad W_2 = \left[\frac{1}{3}, 0, 0, \frac{1}{3}, 0, \frac{1}{3}\right] \quad W_3 = \left[\frac{1}{3}, 0, 0, \frac{1}{3}, 0, \frac{2}{3}\right] \quad W_4 = \left[\frac{1}{3}, 0, 0, \frac{1}{3}, \frac{1}{3}, \frac{2}{3}\right]$$

$$W_5 = \left[\frac{1}{3}, 0, 0, \frac{1}{3}, \frac{2}{3}, \frac{2}{3}\right] \quad W_6 = \left[\frac{1}{3}, 0, 0, \frac{1}{3}, \frac{2}{3}, \frac{1}{3}\right] \quad W_7 = \left[\frac{1}{3}, 0, 0, \frac{1}{3}, \frac{2}{3}, 0\right] \quad W_8 = \left[\frac{1}{3}, 0, 0, \frac{1}{3}, \frac{1}{3}, 0\right]$$

This scheme has been implemented using a macroprogramming function of *QuickWave-3D* as a script representing a fully parameterized 3D object depending on the number of iterations *i* and controlling an applied non-uniform FDTD mesh. The resulted model has been validated against the experimental (Hara Prasad, Purushottam, et al, 1999) and computational (Du, Gong, et al, 2000) studies of the SC antenna of *i* = 1 to 3 and 196×196 mm size; our results have been found in a close agreement with the data in literature.

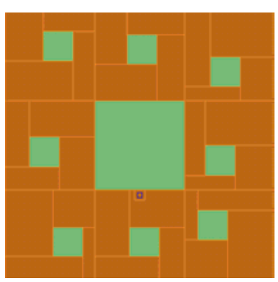
With this model, we have performed systematic numerical analysis of two types of the SC antenna (i.e., the fractal parts on a dielectric substrate are metal patches or holes in a metal strip). It has been found that the return loss characteristic of the patch antenna is unlikely to be controlled by the fractal iterations, while the hole antenna does allow for this type of control. Therefore, in our subsequent analysis, we deal with the hole SC fractal. In order to check if the fractal pattern is responsible for the multiband/wideband performance, we introduce *a modified/broken fractal* and look for *the optimal geometry among both standard and modified fractals.*

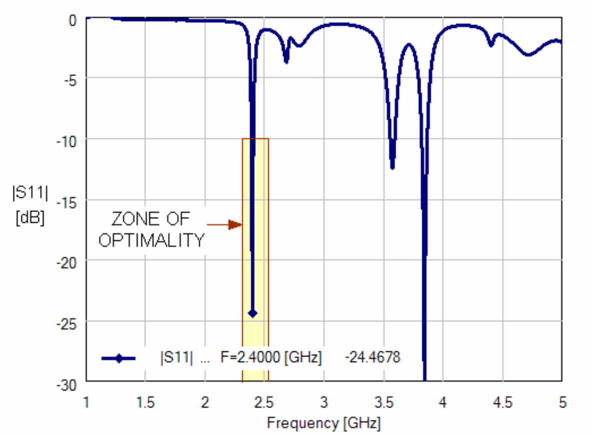
Original Results. Seeking the antenna configurations providing a specific desirable characteristic, we formulate the following optimization problem as follows:

> Find the geometry characterized by the return loss less than an assigned level S_* in a specified frequency range (f_1, f_2).

To solve it for the considered antenna, we use the neural-network optimization procedure (Murphy & Yakovlev, 2003, 2004). Two types of the SC fractal modification have been introduced. First, we allow for breaking the fractal pattern by letting small parts move from the main element to the edge of the square and rotate around the main element moving along the line connecting the centers of small parts. Second, we break the fractal pattern by allowing the smallest elements to *randomly move within its immediate rectangular sub-domains*. It has been found that breaking the SC pattern by both these ways we are in a position to notable change the return loss characteristic, especially at higher frequencies.

Optimization has been performed for $S_* < -10$ dB $= 20\log_{10}(0.316\ldots)$ and $(f_1, f_2) = (2.350, 2.530)$ GHz with the 54 and 120 numerical samples used for training the neural network for the first and second type of the fractal modification respectively. It has been shown that breaking the SC fractal by moving/rotating small elements *does not allow* for controlling the position of the main (dominant) resonance and for widening the dominant frequency band. However, random placing of the smallest elements does allow for slight *moving and widening of the dominant resonance* and for making performance at higher frequencies highly wideband. The configuration of the optimal antenna and its characteristic are shown below.





Planar pattern of the optimized Broken Sierpinski Carpet antenna (A = 78 mm, dielectric substrate of permittivity 2.33 and thickness 3.175 mm) and the frequency characteristic of its return loss

Conclusions. The developed 3D model of the SC antenna has been proven to be adequate. We have found that variations in geometry of the SC fractal antenna allow for a quite limited control over the frequency characteristics of the return loss; *the SC fractal pattern is not optimal in terms of bandwidth/wideband performance*. However, it was possible to "tune" (optimize) the antenna at particular frequencies and increase the widths of the frequency bands by using the pattern of a broken fractal.

The results constitute *a complete original engineering design of the broken SC fractal antennas*. The sample of the optimized antenna has been produced and is being tested at Hanscom AFB.

Acknowledgment: The author is grateful to AFRL/SNHA, Hanscom AFB, MA for supporting the project and Dr. Steven R. Best for inspiring and fruitful discussions of the results.

April 19, 2005