Small Antennas

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Exploring the limits of Fractal Electrodynamics for the future telecommunication technologies could also bring answers to the search of efficient small antennas. In the miniaturization of wire antennas it has been found that the electromagnetic coupling between wire angles limits the reduction of the resonant frequency with increasing wire length. This coupling effect has been studied for several Euclidean and Fractal shapes of different fractal dimension, in order to draw conclusions that could lead to guidelines for the reduction of self-resonant antennas size.

INTRODUCTION

Since Hertz times, the design of electrically small antennas has always been a topic of great interest, related first to the development of radiotelegraphy and radio broadcasting. More recently, near field antenna measurements have been the driving force in building probes that produce a minimum distortion of the measure environment and in establishing procedures for correcting the interactions. In the last few years, the fast growing development of mobile-communication brought the need for devices that require their components to be ever smaller and lighter, and also capable of adjusting its frequency of operation. A well known bottleneck for achieving a software radio is the antenna, which should operate in a multiband mode.

Some results that have been recently published show that fractal antennas have excellent multiband properties [1] or low resonant frequencies [2]-[3]; an overview of the early work on these antennas can be found in the first chapters of “Frontiers in Electromagnetics” [4]. Since these antennas are becoming increasingly popular, many European SMEs, driven by the need of offering up-to-date state-of-the-art products, may decide to tackle risks by including them in their production lines. For that reason, a careful study of electrical performance versus technological complexity trade-offs is the core activity in FRACTALCOMS, an European project (http://www.tsc.upc.es/fractalcoms) involving research groups in Spain, Italy and Switzerland, searching to provide answers about the potential interest of fractal antennas. This paper is built upon the results and conclusions of the numerical simulations and measurements carried out in the project, now in its second year of progress, and will focus on the miniaturization aspects, addressing the issue if fractal forms yield optimum miniature antennas.

Radiation efficiency and impedance bandwidth decrease with the size of the antenna, making small antennas inefficient by nature, for these effects are accompanied by high currents in the conductors, high ohmic losses and large values of energy stored in the antenna near field. The inefficient performance of small antennas is summarized by the high values of its Quality factor (Q), predicted by the fundamental limit stated by Chu [5] and reexamined by McLean [6]. This limit was set assuming that an infinitemisally small antenna radiates only a TE_{01} or TM_{01} spherical mode that depends on the electric size of the antenna \( k_0 a \), being \( k_0 \) the wave number at resonance and \( a \) the
radius of the smallest sphere that encloses the antenna. However, real antennas radiate more reactive modes, contributing to larger Q values. Lowering the Q factor of an electrically small antenna, defined as $k_0a < 1$, is only possible by a proper use of the volume that surrounds it with the objective of exciting only a TE$_{01}$ or TM$_{01}$ mode [7].

MINIATURIZATION OF ANTENNAS

Wire antennas miniaturization is usually based in packing a long wire inside a small volume. The aim is to achieve the smallest antenna having a given resonant frequency or, equivalently, achieving the lowest resonant frequency of an antenna having a fixed size. The Koch fractal curve is taken as an example to understand the behavior of the resonant frequency of fractal antennas as a function of the antenna geometry and wire length.

Some fractal geometries have complex, highly convoluted shapes. This property can be used to build pre-fractal antennas with arbitrary wire length enclosed in a finite surface or volume. In principle, it is expected that the longer the wire length, the lower the resonant frequency. The Koch pre-fractal monopole shown in Fig. 1 is a well-studied example of such objects. It is a pre-fractal antenna generated by an Iterated Function System (IFS) that in the limit converges to the Koch fractal curve [8], a one-dimensional curve, on which, unfortunately, the numerical simulation cannot be applied using a wire model because the convoluted shape of the curve invalidates the thin-wire approximation. However, our antenna prototypes are built using printed strip technology and the strip can be easily modeled by a triangular mesh, which can be accurately analyzed if enough integration points are used on each triangle. For easier meshing, the strips are obtained by extrusion of the curve in the direction perpendicular to the plane containing the curve (Fig. 2). This is a different shape than a printed antenna, but if the strip is thin enough it may be a good approximation to the ideal wire.

It has been already shown that the resonant frequency of the Koch monopole decreases as the number of fractal iterations (K1, K2, K3...) increases [2]. However, other authors showed later that some non-fractal configurations that enclose a long wire into a finite volume also lead to a similar or better reduction in the resonant frequency, compared to the straight monopole having the same enclosing volume [9].

A closer look at our results in [2] reveals that the resonant frequency of a Koch monopole is higher than that of a straight monopole of the same wire length (Fig. 3). At each iteration, the wire length of the Koch antenna is increased by a factor 4/3, and therefore it might be naively expected that the resonant frequency would be reduced in a factor $\frac{3}{4}$. It is not so, as can be clearly seen in [2] and in Fig. 3. In fact, the reduction factor in the resonant frequency of the Koch antenna, as the iteration number increases, tends monotonically to one.

One possible explanation for this behavior has been found recently for the Hilbert pre-fractal antenna [10]: a high degree of coupling between parallel wire segments with opposite current vectors causes a significant reduction in the effective length of the total wire, and therefore an increase in the resonant frequency.

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![Fig. 1. Iterative construction of the Koch fractal curve. The height of the monopole is h.](image)
A great effort has been made in the Project to further investigate in the dependence of the resonant frequency with the monopole geometry, in order to acquire guidelines for the design of self-resonant small antennas, in which an increase of the wire length effectively leads to a reduction in the resonant frequency \[11\].

The observed behavior is due to the coupling between sharp angles at curve segment junctions. These angles radiate a spherical wave with phase center at the vertex (Fig. 4). Each angle not only radiates, but also receives the signal radiated by other angles. As a consequence, part of the signal does not follow the wire path, but takes “shortcuts” that start at a radiating angle. The length of the path traveled by the signal is, therefore, shorter than the total wire length.

This hypothesis agrees with the fact that the resonant frequency of a Koch monopole corresponds to a straight monopole much shorter than the Koch curve length (Fig. 3). The higher iteration number in the Koch antenna, the more angles it has and the closer to each other they are, so the more signal takes shortcuts and the less signal follows the whole curve path. It can be noticed in Fig. 3 that the resonant frequency reduction between K4 and K5 is negligible, although the curve length increases in a factor 4/3. The reason is that the signal follows the shortcuts and the length of the path followed by the signal is the same.

This hypothesis has been verified by numerical simulations in the frequency and time domains.

\[\text{Figure 3: Resonant frequency of Koch strip monopoles, from iteration 0 to 5, compared with the straight monopole of height equal to the wire length of the Koch pre-fractal. The Koch monopoles are strips obtained as extrusion of the Koch curve (Fig. 2), 6cm-height and 1mm-wide. The results have been obtained by numerical simulation using Method of Moments.}\]
FREQUENCY DOMAIN ANALYSIS

Wire antennas can be analyzed using integral equation methods (IE) in conjunction with Method of Moments (MoM) discretization. The numerical electromagnetics code (NEC) is a well-known example of a computer code that can deal with these problems efficiently. NEC, as most wire-modeling codes, assumes that the current is constant around the wire circumference, which is not the case in problems having non-collinear wire segments very close to each other. Moreover, highly iterated pre-fractal antennas have wire segments of length comparable to the wire diameter, which either break the commonly used thin-wire approximation or lead to problems with the exact kernel integration around the wire circumference.

For the above reasons, we have chosen to model highly iterated pre-fractal antennas as a strip, instead of a wire. This is in agreement with the fact that, in practice, the antenna prototypes are built using printed strip technology. The strip can be easily meshed in triangle, rooftop or quadrangular basis functions, leading to an accurate MoM discretization of the Electric Field IE (EFIE), if enough integration points are used on each triangle.

We have considered two kinds of strips: planar, the usual strips contained in a plane, like printed antennas, and extruded, strips obtained by extrusion of the pre-fractal curve in the direction perpendicular to the plane containing the curve (Fig.2). A numerical code denoted FIESTA (Fast Integral Equation Solver for scaTterers and Antennas) developed at UPC, running under MATLAB and based on the Method of Moments has been used for the simulations.

For low-iteration Koch antennas, both kinds of strips lead to the same antenna resonant frequency if the strip width is the same. On the other hand, for high-iteration pre-fractals, in planar strips the width of the strip interferes with the strip angles, while in extrusion strips it does not. Obviously, the effect is less noticeable for thinner strips. Therefore, the geometry of a highly iterated planar strip losses the main properties of fractals (auto scaling and fractal dimension), while extrusion strips preserve these properties.

It is known that, for a straight monopole antenna, the resonant frequency slightly decreases if the monopole diameter –or strip width- is increased. Our first finding is the opposite, that is, the resonant frequency of a pre-fractal antenna increases if the strip width is increased. The reason is very simple: the wider the monopole, the more coupling and, thus, a larger fraction of the signal takes the shortcuts between the pre-fractal curve angles. The result is a shorter signal path length and, therefore, higher resonant frequency.

The second effect is that pre-fractal antennas of the same class and the same number of IFS iterations have shorter electrical height at resonance if the physical size of the antenna is larger. The obvious reason is that larger antennas have longer distance between pre-fractal curve angles and, therefore, the coupled signal that follows the shortcuts between angles is weaker.

NUMERICAL VERIFICATION IN THE TIME DOMAIN

The near fields in the vicinity of a single-iteration Koch monopole have been computed in the time domain for very short-pulse excitation (Fig.5). The antenna has been modeled as a thin wire using DOTIG code from University of Granada [12].

It can be noticed that the sharp angles of the pre-fractal curve become the center of spherical wave radiation, which corroborates the coupling effect hypothesis.

Figure 5: Near fields in the time domain in the vicinity of a single-iteration Koch monopole (K1) with short-pulse excitation. The sharp angles of the pre-fractal curve become the center of spherical wave radiation, which corroborates the coupling or shortcut effect hypothesis.
COMPARISON WITH OTHER PRE-FRACTAL AND NON-PREFRACTAL MONOPOLES

We can expect reasonably that the coupling or shortcut effect is also present in other kinds of pre-fractal and non-fractal miniature monopoles. However, different kinds of miniature wire monopoles having the same wire length exhibit different length of signal leaps between wire angles, resulting in a different amount of signal coupling through the shortcut. For that reason, these antennas will have different resonant frequency while having the same monopole height $h$ and the same wire length.

Some of the different monopole configurations that have been analyzed are shown Fig. 6. Among them, there are two pre-fractals: the conventional Koch antenna and a generalized version. In the limit of infinite IFS iterations, they converge to fractal curves of fractal dimension respectively equal to 1.26 and 1.5. There are also two non pre-fractal configurations: both are zigzag antennas of different meanders size.

The resonant frequency of the four-monopole families, as a function of the wire length, are compared in Fig. 7. The antennas have been modeled as extrusion-strips of 1-mm width. Each marker in the plot corresponds to an IFS iteration in the pre-fractal geometries or the number of meanders in the zig-zags.

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The reason can be found in the fact that the generalized Koch and the wide zigzag configurations, for equal wire length, show longer signal leaps than the Koch or the narrow zigzag.

CONCLUSIONS

These small antennas are just a sample of the many different shapes that have been studied in the project, including Fractal and Euclidean three dimensional space-filling curves. Genetic algorithms have also been applied by us and other authors [13]-[14] to search for shapes that best utilize the volume within which the wire antenna is confined, trying to answer the question: do those
wire antennas provide optimum small antennas? Complex problems usually do not have simple answers, and this is one of the cases. All the information available at this time [15] points out that, at self resonance, fractal dimension does not seem to play a significant role in the behavior of the antenna. The experience resulting from this work also shows that other configurations perform even better than prefractal structures with the same size reduction ratio.

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