Fractals’ new era in military antenna design

Modern military uses of antennas have presented new challenges to the antenna designer. Only a decade ago, specific band antennas, or tall whips, met the needs of most communications, electronic warfare (EW) and surveillance applications. But with new needs and transceiver technologies, antennas have new challenges: wideband; small; and agile platforms, for software-defined radio (SDR) and modern EW, among others.

By Nathan Cohen

A new approach to antenna design was called for. In this article, we describe a successful area that meets this need, which uses fractal geometry for better antennas. Such fractal antennas have multiple bands or are genuinely wideband. They may replace a suite of antenna systems, disposing of tuning and matching circuitry, and fit in unique or constrained form factors.

Fractals[1] are complex geometric designs that repeat themselves, or their statistical properties on many scales, and are thus “self similar.” Fractals, through their self-similar property, are natural systems where this complexity provides the sought-after antenna properties.

The first use of fractals as antennas was called “fractal loading,” which uses bends, or holes, over a variety of size scales to emulate the effects of discrete inductors and capacitors[2]. The arrangement of these fractal bends or holes act as lumped or continuous loading elements. Of course, the equivalent circuit of such a loaded antenna would have multiple capacitors and coils. In contrast, the antenna made from fractals is loaded purely by shaping alone. Fortunately, shaping, as a substitute for discrete components, is a long-used approach, resulting in tuned micro-strip antennas, meander line antennas, and even “stubby coil” antennas.

What fractals bring to the shaping approach to antennas is the versatility of a huge design

Figure 2. Example of a fractal antenna.

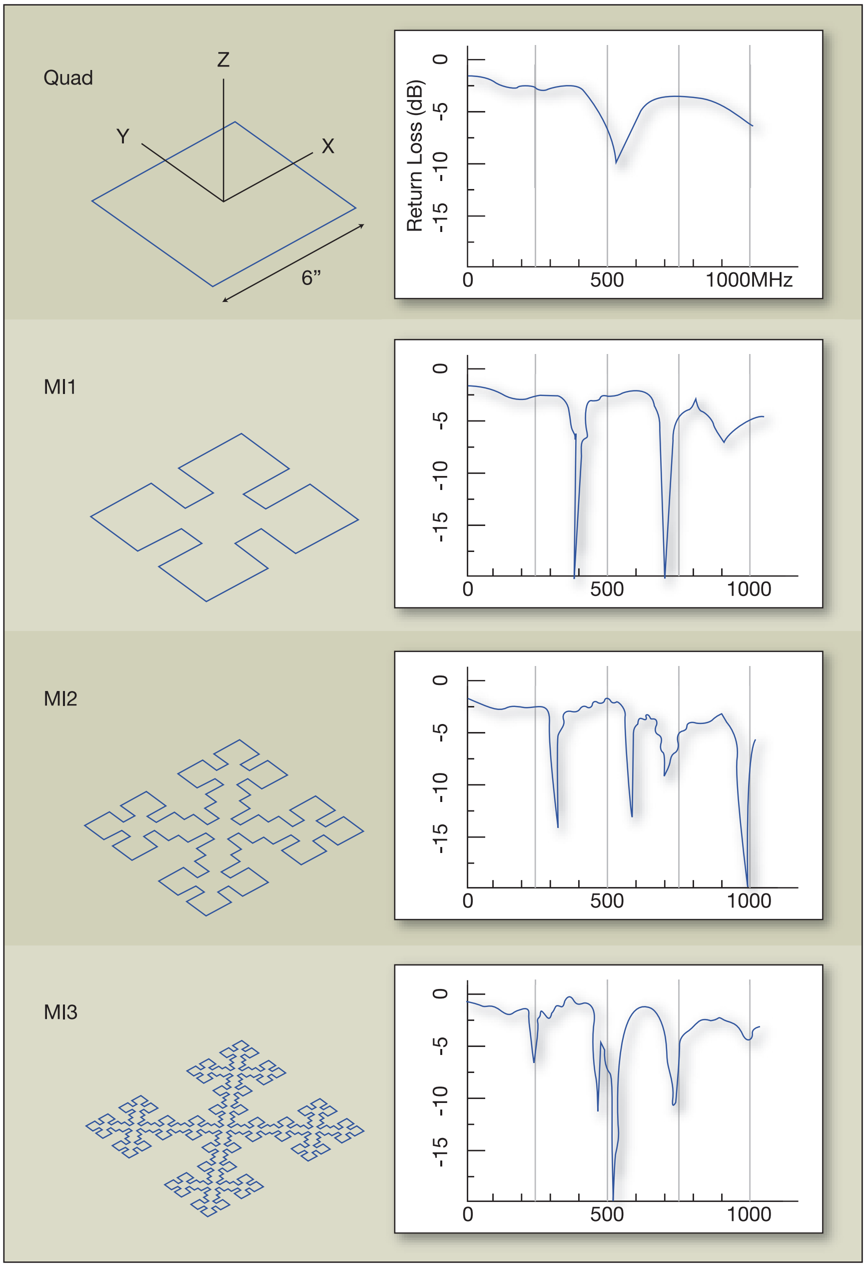

Figure 1. Resonant frequencies of a simple shaped fractal loop antenna.

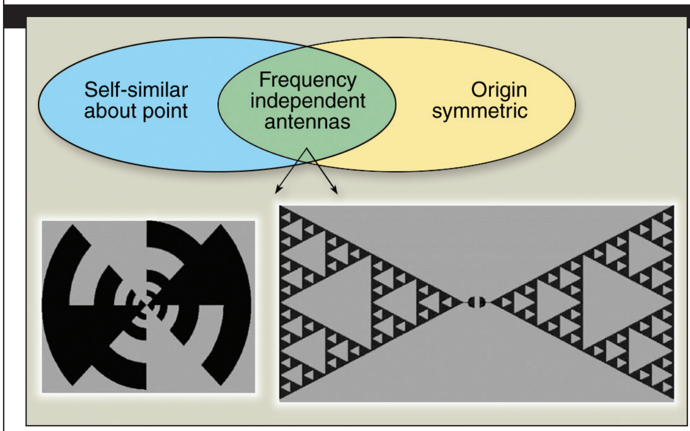

Figure 3. Hohlfield-Cohen-and-Rumsey (HCR) Conditions.

space. Earlier methods were great at solving simple problems, such as single-band, hi-Q antennas. But with more complex applications and desire for maximum shrinkage for a given performance, only fractals promise to meet the demands of modern antennas. Some key benefits of fractals are:

- Very broadband and multiband frequency response that derives from the inherent properties of the fractal geometry of the antenna.
- Compact size compared to antennas of conventional designs, while maintaining good to excellent efficiencies and gains.
- Mechanical simplicity and robustness; the characteristics of the fractal antenna are obtained due to its geometry and not by the addition of discrete components.
- Design to particular multifrequency characteristics containing specified stop bands as well as specific multiple passbands.

Put most succinctly, a shaped fractal antenna is a radiating LC circuit—with no component parts. Figure 1 illustrates the change in resonant frequencies and the number of resonant frequencies of a simple shaped loop (one of a near infinite number of fractal loop geometries). Notice that as the shaping gets more "iterated," the complexity of the shape increases, and the loading causes multiple resonances and a shifting down in frequency.

> *In effect, it is an array of two elements spaced less than a conventional spacing separation, but not so close as to be the equivalent of a single, electrically small radiator.*

The regime where fractal shaping benefits a compact antenna is on the order of two to four times smaller than conventional antenna designs. When made very electrically small, all antennas become poor radiators—a surprisingly obvious finding that escaped many antenna researchers late to the fractal approach, but was clearly reported a decade ago[2]. Essentially, fractal shaping allows an efficient use of the Wheeler radius at and beyond the small antenna limit. Also, it is obvious that, to draw a discrete component analogy, not all fractal shapes fit a desired outcome any more than a random collection of Ls and Cs will produce a desired filter. Thus, another obvious aspect of fractal antennas: Some shapes work well for an application, and others may work excessively poorly. The mere act of fractalizing an antenna only has meaning if one first addresses the adage: "What problem am I trying to solve?"

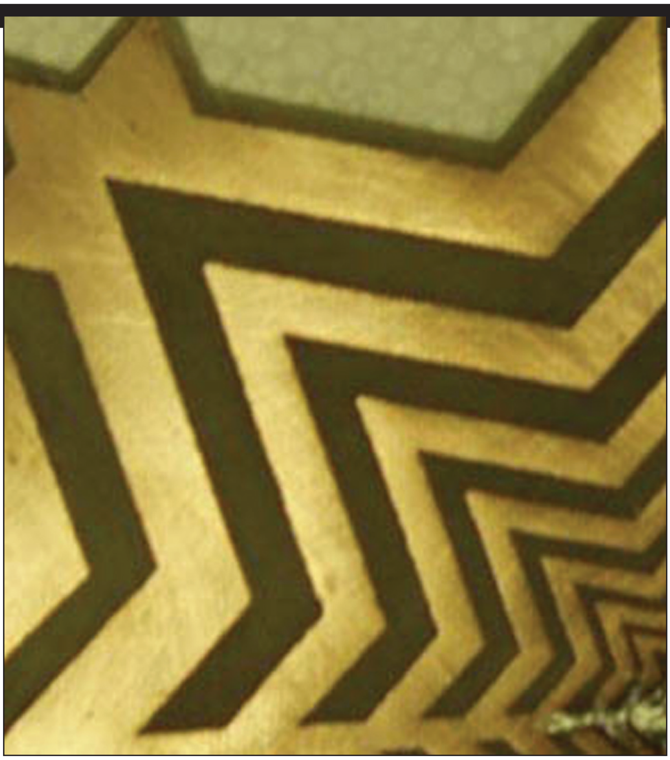

Figure 4. Portion of a wideband fractal antenna.

Because fractal antennas can have electrically long lengths in small packages, there is the opportunity for having more than one current maxima. Phasing effects from multiple current maxima within such a small region are a natural attribute of fractal design. When well within the Wheeler radius, such phasing effects have no effect—yet even just outside, over a small distance electrically, the phasing becomes important. It is also well known that a co-linear monopole, for example, manifests gain when more than one current maxima are stacked in height. Since these fractal antennas can be physically short but electrically long, it is easy to attain regimes where a small antenna has more than one current maximum, and so gain is inevitable, at least at some frequencies of interest. In effect, it is an array of two elements spaced less than a conventional spacing separation, but not so close as to be the equivalent of a single, electrically small radiator.

There is no puzzle to the good gain performance of such antennas: they can be made as self-loading, multiple current maxima structures with small size, frequency agility and bandwidth, and fall well within generations of known electromagnetic theory. Figure 2 shows a portion of one. The "magic" lies in finding the right fractal shape or shapes for the desired outcome.

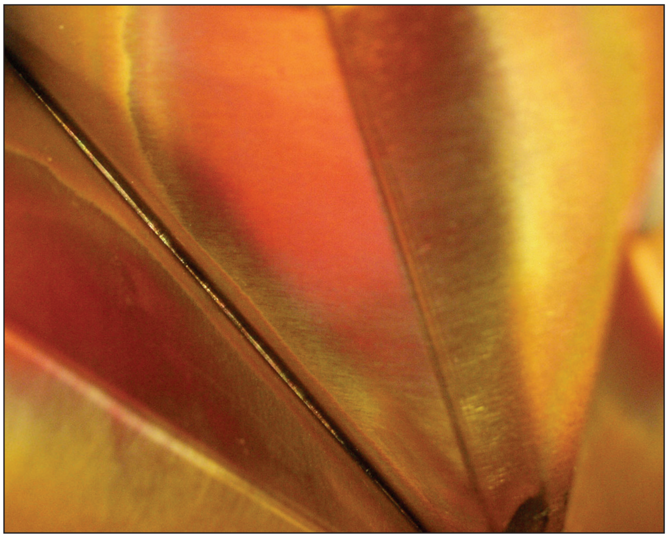

Figure 5. Portion of a fractalized wideband dipole antenna.

Figure 6. Height reduction of a wideband dipole fractal antenna.

Self-scaling for wideband

Another attribute of fractals emerged upon a re-examination of Rumsey's Principle. In Rumsey's Principle, all antennas, whose structures are solely defined by angles, are "frequency independent," or "frequency invariant." This rule dominates the design of all wideband antennas to date, and is a valid electromagnetic fact. It is commonly used in log periodic antennas. However, angle-defined structure does not address the issue: What are the necessary and sufficient geometric conditions to achieve a truly frequency invariant antenna? The issue—and thus a fundamental invariance relationship of Maxwell's Equation—was, surprisingly, only recently determined. In 1999, Hohlfeld and Cohen[2] found that all frequency invariant antennas must be self similar (fractal) about a point, and origin symmetric about that point. This includes all log periodic antennas, spiral antennas, sinuous antennas, Dyson spirals and so on, previously defined by Rumsey's Principle. However, log periodics and these other examples are a restricted subclass of the larger class of self-similar-about-a-point geometries. The finding of Rumsey's Principle is a special, albeit proven useful, case of the now more general and com-plete finding now referred to as the "Hohlfeld-Cohen-and-Rumsey" (HCR) conditions. They are illustrated as a Venn diagram in Figure 3.

Thus, the value of geometric attributes has been clearly laid out for wideband antennas: Frequency invariance, whether discrete or continuous, requires HCR conditions to produce frequency invariant antennas.

There is, of course, more to the physics than mere insight. Using HCR, it is possible to arrive at fractal shapes that are self-scaling,

Figure 7. Wideband fractal antennas have been produced in covert, transparent packages, such as the transparent antenna mounted in the window pictured here.

and unlike the convention of log periodics or spirals, for example, are smaller and far wider in their bandwidth than known systems. That means very wideband antennas are possible that do not look like conventional wideband antennas; are smaller; and fit in form factors that previous ones did not. A portion of a novel wideband antenna, which follows from HCR, is shown in Figure 4. It is planar, has a 30:1 passband, feeds to 50 Ohms, and is far less than one-half wave across at the lowest operating frequency. This has not been previously achieved with conventional designs.

Form no longer follows function

The outstanding problem with military-oriented antennas is that they are too big, too narrow-band, and too many are needed. With fractal antennas, a new era has arisen where the important attribute surfaces that form no longer follows function.

Previously, the performance and even application of an antenna was easily discerned from its form factor and appearance. While at the extremes, this is still true, combining fractal antenna attributes of self-scaling and fractal loading produces extremely wideband antennas with multiple functions and small sizes. Here are two examples.

Consider a “tube antenna.” Such an antenna may replace a whip, for example. But what is it? If it uses fractals, it may be a high gain, directive VHF to microwave array, a very wideband omni antenna, or a combination of endfire and wideband capabilities or something else entirely. Whereas before it may have been considered a short, ruggedized communications whip replacement—that has mediocre performance by virtue of its height and shape—now it is a constrained volume for a host of possibilities.

Thus, the obvious benefit to military needs: fractals offer options when the form factor has to be already constrained and other antennas won’t work. In addition, there is no longer an ability to view a radome, for example, and have even the slightest knowledge of what’s inside.

Consider an example for a fractalized wideband dipole, shown in portion in Figure 5. Placed under a radome, it may be thought of as one or two types of antennas. But this antenna fits in a smaller form factor than a conventional approach; Figure 6 shows some of the height reduction benefit from a conventional and fractalized wideband dipole. Typical volume reductions of 70% to 80% are common, with little deterioration of performance and without any matching or loading components.

Where’s the advantage?

While fractal antennas are deployed in many situations, few are readily apparent visually, nor is it common knowledge that they are being used. Nonetheless, it is important to understand where the advantages lie in existing and future uses.

EW: In electronic warfare, disrupting communications is a daunting task because of the plethora of frequency ranges available to a hostile foe. Most other antennas are not wideband but multiple band compromises that prevent allowance for future capability when the environment changes. In this application, the wideband capability of fractal antennas allows smaller antennas that have from 10:1 to 200:1 bandwidths that can handle moderate to high power. This allows fewer antennas to meet extant and future threats. As form no longer follows function, it also thwarts the ability for the foe to understand the capability of the system, in addition to adding a huge versatility to how the system may be deployed. Vehicular use is vastly aided by these advantages.

Sigint: Surveillance and information gathering is always limited by the covertness of the antenna. In general, small antennas mean limited reach and limited frequency range. Fractal antennas have been produced that have wide bandwidths, but also fit covertly in packages where no antenna is expected. Indeed, transparent antennas, when combined with fractal wideband capabilities, make proven examples of such. Figure 7 shows one such example, with a 100:1 bandwidth. Where is it? Follow the coaxial cable to see the connection point to the window-mounted antenna.

Universal tactical communications

Future communications systems will use cognitive radios that require vast bandwidths, with one antenna. For the soldier, this spells the need for a single antenna, or simple antenna system, that can be body-worn, and not physically interfering with other needs. As the future soldier looks more and more like the "Borg" from Star Trek, the communications needs will have to keep up. Since 1997, fractal antennas have been used to make body worn antennas that have the fewest compromises and work best for most terrestrial and SatCom applications. It is anticipated that such antennas will likely be the enabling choice in both legacy and future communications applications.

Future and options

Although a young extension in antenna engineering, fractals have already made great strides in expanding design space for applications. The path is there as long as the limiting physics are understood and appreciated. The design space for fractal antennas affords vast new opportunities in design and application[4], many realized and proven beyond theory. DE

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4. Fractal element antennas are protected by U.S. patents: 6476766; 6452553; 6445352; 6140975; 6127977; 6104349 with other patents pending.

ABOUT THE AUTHOR

Nathan Cohen is the founder and chief technology officer at Fractal Antenna Systems Inc. Cohen began his academic career studying under some of the world's foremost scientists, including Jack Pierce and Irwin Shapiro at Harvard and Frank Drake at Cornell. He has spent three decades as an active radio astronomer, with special emphasis on antenna and array techniques.

In 1988, Cohen built the world's first fractal element antenna and, after working to perfect his methodology, founded Fractal Antenna in 1995 to commercialize his research. He has since become recognized as one of the world's most innovative antenna designers, with fractal element antennas proving to be more compact, versatile and powerful than traditional antenna designs.

Cohen holds a bachelor's degree in physics from Brandeis University, and a master's degree and Ph.D. in astrophysics from Cornell University. He retired as a professor from Boston University in 2002. He is the inventor on a dozen patents to date; has published more than 80 articles, and two books. His innovation has been widely recognized in *Scientific American*; *Discover*; CNN; *Business Week*; *Wireless Week*; and many other publications. He can be reached at chip@fractenna.com.