Evolving Wire Antennas Using Genetic Algorithms: A Review

Dr. Derek S. Linden
Linden Innovation Research LLC
P.O. Box 1601, Herndon, VA 20171

Dr. Edward E. Altshuler
Air Force Research Laboratory
Hanscom AFB, MA 01731-3010

Abstract

Communication, radar and remote sensing systems employ thousands of different types of wire antennas, and there is an increasing need for high-performance, customized antennas. Current methods of designing and optimizing them by hand using simulation or analysis are time- and labor-intensive, limit complexity, increase the cost and time expended, and require that antenna engineers have significant knowledge of the universe of antenna designs. Local optimization methods are not much better, since an initial guess that is close to the final design must be provided. Using a genetic algorithm (GA), it is possible to prescribe the desired performance of an antenna and allow the computer to find the parameters for the design. The GA does not require an initial guess, and the amount of design information the engineer must supply can be very minimal. This paper will present a review of a few wire antennas from previous publications [1-5] designed by GA for unconventional purposes. This approach has the potential to revolutionize antenna design.

Introduction

Since F. Braun created the first wire antenna in 1898, a variety of wire antennas have been designed: the dipole and its counter-part monopole over a ground screen, Yagi, log periodic, helix and spiral antennas, and others. These antennas were, and in large part continue to be, designed using an inductive process. In this process, Maxwell's equations are used to formulate an equation for the current distribution on each of the antenna's structures, and the electromagnetic properties of the antenna are then calculated. If the structure is too complex for analysis by hand, it is simulated using a computer program that will approximate the structure and calculate its properties.

This design approach is generally limited to relatively simple structures. In general, an engineer finds an existing design that may have the desired electromagnetic characteristics. The engineer then works with exact or approximate equations, if any exist, to determine the design's proper dimensions and parameters, and uses a simulator to predict its performance. If the performance is not good enough, the engineer redesigns and re-simulates the antenna, using intuition to determine which parameters to change to improve performance. This design cycle has produced, over time, the many different antenna designs with varied characteristics, but it is time-consuming, and unlikely to produce truly optimal results. It requires that the engineer be familiar with the many different designs that exist, and have enough experience and expertise so that an acceptable solution can be reached in a reasonable amount of time.

When the high speed digital computer became available in recent years, it was then possible to analyze more complex wire structures in shorter times, and also to optimize wire antennas using computer aided design technologies. In these cases, the general shape of the wire antenna is still predetermined and the individual wires that constitute that particular configuration are optimized. While the computer allows for greater design complexity, there are still no completely automated design tools available. This lack of tools means the engineer must still use intuition to design an antenna in order to provide an initial guess at the final solution that must be fairly close to the optimal answer. It is faster than using pen and paper or a calculator, but there are too many variables in even simple designs for a person optimize effectively. Even years of experience may not result in useful intuition about certain aspects of electromagnetic problems.

In addition, this design cycle limits the types of designs that are tried to those that have an intuitive logic about them. Symmetry is often present, and structures are kept relatively simple to allow for easier understanding and analysis. Nearly all of the designs produced by engineers have the characteristic of "making sense" when one looks at them or their circuit schematics. Most all of them *look* like they should work. Such is not the case with the antennas designed by the GA process discussed here. Though they do work in simulation and in actual measurement, it does not appear logical or reasonable that they should work. They are quite different from those a rational human designer would have ever thought of, let alone tried.

An Introduction to Antennas

This section provides a brief tutorial on wire antenna design concepts, which will help the reader to understand the designs described in later sections. An antenna is a wire antenna if it is constructed from a wire or number of wires that are much longer than their width. Wire antennas can be fed a signal, or excited/driven, many different ways. A wire antenna can be fed most simply with a coaxial line at its base, like a car antenna. It is also possible to feed a wire antenna using a balanced, two-wire line, as in a TV antenna where there are two wires connected to the "rabbit ears," or to use even more complex schemes.

A *ground plane*—at its simplest a large, flat piece of metal underneath the antenna—is often used in conjunction with a wire antenna. It acts as a mirror for the antenna above it, and therefore changes the antenna gain pattern. A ground plane can decrease the height and/or simplify the construction of the wire antenna. The hood or roof of a car acts as a ground plane, and antennas that will be affixed to such places need to be designed for use with one.

Directivity and *gain* are two related qualities in antenna design. Directivity is the ratio of power density being transmitted by an antenna in a particular direction to the average power density being transmitted in all directions. The gain is the directivity multiplied by the ratio of power radiated to power input. Gain takes into account the losses due to resistance in the antenna, which converts some of the input power into heat. When the losses are considered to be zero, as in this paper, the directivity and gain are equal.

Gain is usually expressed in decibels (dB), which relates to a ratio of power or power densities by the following expression: $dB = 10\log_{10}(P_1/P_2)$. In the case of gain, P_2 is the power density of an isotropic radiator that transmits power equally in all directions. The abbreviation dBi refers to gain compared with an isotropic radiator. However, the "i" is sometimes left off, and is understood from context.

A *gain pattern* or *antenna pattern* plots gain magnitude versus angle, showing the proportion of power an antenna transmits in a particular direction. For 2-D antennas, or antennas symmetric in the third dimension, this angle is simply the elevation angle θ. In 3-D, there are two angles that specify a direction: θ and the azimuth ϕ. Figure 1 shows these angles on a set of axes. An antenna is considered to be *directive* if its gain pattern is heavily weighted in one direction.

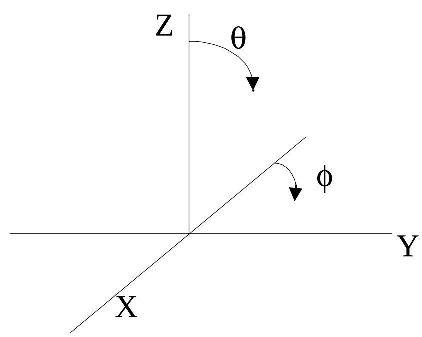


Figure 1. θ and ϕ on a 3-D axis system. Arrows begin where NEC2 defines 0 degrees for θ and ϕ.

An antenna's *beamwidth* refers to the useful angle span of the so-called main lobe or beam. This lobe usually has the highest gain in the pattern, and is what is of interest to optimize. In a uniform gain pattern, there is only one lobe, but in a directive pattern where the beamwidth is desired to cover only a certain angle span, there can exist other lobes. These other lobes are called *sidelobes*, and usually the designer seeks to minimize them.

Bandwidth is the useful range of frequencies for an antenna, and is usually desired to be as large as possible. It is given in percent, which is the ratio of the useful frequency span over the nominal operating frequency. For an antenna operating at 2GHz, a bandwidth of 3%

would mean it would operate over a 60MHz range, from 1.97GHz to 2.03GHz. For the applications covered in this paper, a bandwidth of 2-5% is usually the minimum desired, and means an antenna is very sensitive to exact dimensions and can be used in only specialized applications, 10% bandwidth is usually considered relatively broad, and 20% is considered to be quite broad.

Voltage Standing Wave Ratio, or *VSWR*, is a way to quantify the match between an antenna and a device connected to it. A standing wave is created when there is a mismatch in this connection, which prevents power from flowing to and from the antenna. If the standing wave is large, implying a high VSWR, there is a significant mismatch. If it is low, the match is good. A VSWR of 3.0 or less is considered adequate for many low-power applications, while a VSWR less than 1.5 or 2.0 is desired if power considerations are important. A VSWR of 1.0 is a perfect match, and it can never be less than 1. VSWR is easy to measure, and since it is a common parameter specified by antenna designers, it is often an important quantity to optimize.

Polarization refers to the orientation of electromagnetic waves. Electromagnetic waves are composed of two components: an E-field (electric field) component, which is a sinusoidal wave that exists in one plane, and an H-field (magnetic field) component that exists at right-angles to the E-field following the right-hand rule (**E** x **H** = a vector in the direction of propagation). Thus, the wave is asymmetric, and has a definite orientation. Since the H field is constrained by the E-field in a propagating wave, we will discuss just the E-field. In a wave of constant overall magnitude, the E-field magnitude can actually be a time-varying quantity. If one looks at a wave propagating past a fixed point in space, the E-field can oscillate back and forth in a single orientation, giving *linear polarization*, or it can actually be rotating in a circle as its x and y components oscillate back and forth out of phase, giving *circular polarization*. It can also take an orientation in between, giving *elliptical polarization*. Antennas are polarization-sensitive: an antenna that is optimal for picking up linear polarized signals will miss half of the energy of a wave that is circularly polarized and all of a wave that is cross-polarized (linearly polarized at a right angle to the antenna). An antenna that is left-hand circularly polarized (the E-field moves in a circle to the left) will miss a right-hand circularly polarized wave completely. In addition, for ground-to-satellite communications, circular polarization is very helpful because it minimizes polarization distortion that occurs as a signal travels through the atmosphere.

The size of a wire antenna can vary greatly. If a wire antenna is desired to be directive, it will generally need to be several wavelengths in size. However, a gain pattern that is to be uniform will require a much smaller antenna.

There are several electromagnetic simulators that exist for wire antennas. One particularly suited to the task of creating a general antenna synthesis system is the Numerical Electromagnetics Code, Version 2 (NEC2) [6]. This code was used exclusively on this research. NEC2 has a simple file-interface for input and output that makes it ideal for using with an optimizer. The code has been around for a long time, and is in the public domain, so obtaining and modifying the source code is cost-free and easy, as is copying the simulator between machines. But perhaps most important, it has a long track record of being accurate. The NEC2 code was produced in the early 1980s, and has been used it to simulate antenna structures for many years. It has shown itself to be in very good agreement with actual measurements, and thus we have confidence that answers we receive from simulation have validity.

Now that antennas and their design process have been covered, following is a discussion of a few wire antennas that have been designed through GAs.

The Yagi Antenna

As shown in the figure below, the Yagi antenna is a series of parallel wires, first proposed by Prof. Yagi and his student S. Uda in the late 1920s. One element is driven, one element is behind the driven element and is called the reflector, and all other elements are called directors. The highest gain can be achieved along the axis and on the side with the directors. The reflector acts like a small ground plane, allowing power that would otherwise be sent backward to be reflected forward.

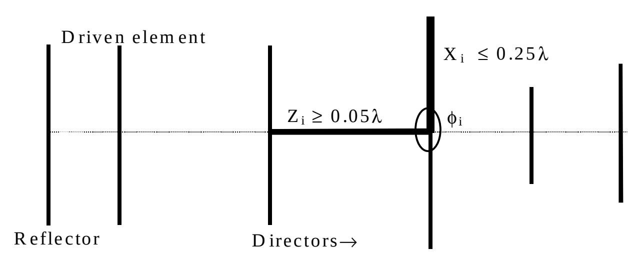


Figure 2. Yagi Antenna

The conventional Yagi design includes geometry variables of length for each element, spacing between elements, and the diameter of the wire. Thus, with N elements, there are N length variables, N-1 spacing variables, and one wire diameter variable, giving 2N variables total. The driven element is driven from its center.

One other variable beyond that of the conventional Yagi that produced good results is shown in the above figure. It is designated as ϕ_i, and is a degree of freedom relating to the rotation of the element out of the plane of the antenna. Its effect will be discussed later in this section.

One challenging application from [1] involved designing a special feed for the Arecibo 305-meter spherical reflector [7]. The antenna was to be used to search for primeval hydrogen having a redshift of approximately 5. Neutral hydrogen line emission is at a frequency of 1420 MHz; thus the frequency region of interest was about 235 MHz. Preliminary studies indicated that the band from 219 to 251 MHz had relatively little interference, particularly from 223 to 243 MHz, though the interference was still quite significant. Since it was intended that the feed illuminate only about 160 meters of the reflector and since the frequency was low, it was not necessary to correct for spherical aberration. The most important design goal was for the feed to have sidelobes and backlobes at least 25 dB down in the region from $70° < \phi < 290°$, due to the interference which came from surrounding radio and TV towers. Of lesser importance was that the E-plane (the plane parallel to the plane of the antenna) and H-plane (perpendicular to the E-plane) beamwidths be about 50°. The VSWR was desired to be under 3.0 and the gain was to be as high as possible, but was limited by the wide beamwidth. The feed would be mounted over a 1.17 meter square ground plane—that is, a ground plane only 0.92λ in size.

Since there did not seem to be any other antenna that would meet the desired specifications, it was decided to investigate the possibility of using a GA to optimize a Yagi type structure for this unconventional application. Yagi antennas are usually used for high-gain, narrowband applications. The desired bandwidth was very large for this kind of antenna, and the sidelobe and backlobe requirements were very difficult.

The GA used a real-valued chromosome and Adewuya's method of crossover. Adewuya's method consists of a sequence of crossover methods applied to real genes. First, quadratic crossover is applied, where the child's gene is taken from a predicted minimum of a quadratic curve fit using three parents. If quadratic crossover fails, heuristic crossover is applied, which pulls the child's gene from a range predicted to be better than two parent's genes. See the figure below for a graphical representation of what happens in these two methods.

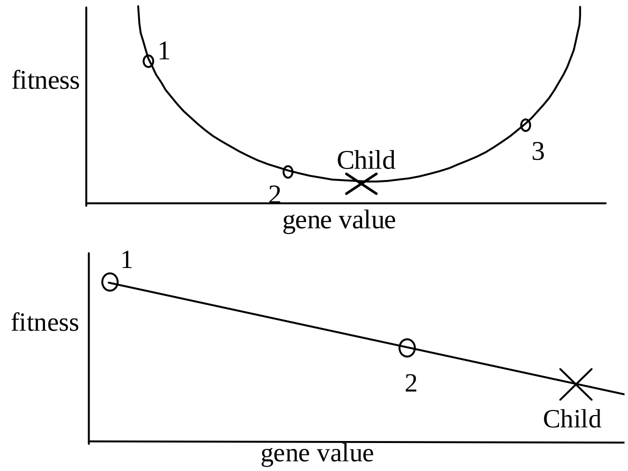


Figure 3. Quadratic and heuristic crossover. Fitness is to be minimized in these examples.

If both quadratic and heuristic crossover fail, the child's gene is one of the parent's genes taken at random. This process is applied gene by gene to create a new child. See [3, 4, 8] for a more complete explanation and comparisons with other methods. This method has been found to be particularly powerful in electromagnetics and mechanical engineering, but similar results were obtained using more traditional binary chromosomes and child-creation methods.

Mutation was Gaussian—mutated genes were pulled from a distribution with a mean equal to the unmutated gene, and a standard deviation of 0.1 of the full gene range.

The GA produced a Yagi type antenna that met most of the design goals. It was quite different from a conventional Yagi in that the director elements were very closely spaced, and it was only about a third the length of a typical Yagi having the same number of elements. This process produced an antenna that approached the above specifications, though they are quite unconventional for a Yagi antenna.

Following are the details of the Arecibo Yagi optimization. First, the number of wires was specified to be 14. The variables were: the length of each element (14 were required), each constrained to be symmetric and between 0 and 1.5λ, the spacing between each set of two elements (13 were required), constrained to be between 0.05λ and 0.75λ (the total boomlength was allowed to vary), and the diameter of the wire, constrained to be 2, 3, 4, 5 or 6 mm. Note that of the total 28 variables, 27 of them were continuous, real-numbered parameters, making this a natural problem for a real-valued chromosome. The discrete variable—wire diameter—used a real-valued gene, but it was discretized using truncation so the GA would only use one of the allowed values. Doing so is usually not recommended for the type of crossover techniques used, but the problem was insensitive to this parameter and it did not affect results adversely. 175 individuals were in the population, with a 30% overlap, and 0.6% mutation rate. These values were shown to be optimal by experimentation in other Yagi antenna optimizations.

The objective function used to optimize the design was:

$$\text{Fitness} = -G_L + C_1 * SLL^2 + \Sigma(C_2 * V_i)$$

where

G_L = lowest gain of all frequencies at 0°

SLL = highest sidelobe level within $70° < \phi < 290°$ for all frequencies

V_i = VSWR at the ith frequency. The sum is over all frequencies

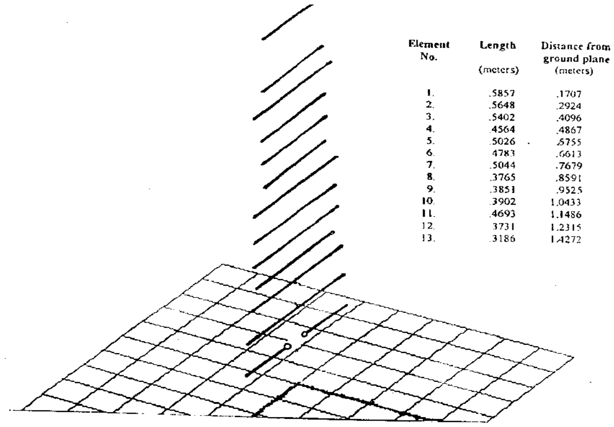
$$C_1 = \begin{cases} 0 & SLL > 25 \text{ dB} \\ 1 & SLL < 25 \text{ dB} \end{cases}$$

$$C_2 = \begin{cases} 0.1 & V < 3.0 \\ 1 & V > 3.0 \end{cases}$$

The optimization involved minimizing this function. Since beamwidth was of secondary importance, it was not included specifically in the cost function. Instead, beamwidth was implicitly defined by where the objective function began to search for sidelobes (at +/- 70°), and by the maximization of the gain. The antenna was simulated at 243 and 223 MHz, near the edges of the desired frequency band. It was assumed that if the antenna performed satisfactorily at these frequencies it would probably be acceptable over the rest of the band.

Although the feed was over a finite ground plane, it was decided to initially use a conventional reflector element in the design since modeling a finite ground plane using NEC adds a prohibitive amount of computer time. After an optimal configuration was obtained, a thorough computational analysis was conducted for the whole frequency band from 219 to 251 MHz at increments of 2 MHz to ensure that the antenna was truly broad in bandwidth. It was performed initially for the Yagi with only a reflector element and then repeated with a 1.17 meter ground plane.

As expected, the GA produced a configuration that was quite different from one that would have been obtained using conventional methods. The genetic Yagi had 13 elements (plus the ground plane) with a boom length of only 1.11λ. The directors varied in length from about 0.25λ to 0.4λ with an average spacing of less than 0.1λ, as shown in Figure 4. A conventional 14 element Yagi has a boom length about 3 times as long, with directors that are about 0.4λ in length and 0.35λ in spacing, and the lengths become slightly shorter and the spacings slightly larger the greater the distance from the driven element.



Element No.	Length (meters)	Distance from ground plane (meters)
1.	.5857	.1707
2.	.5648	.2924
3.	.5402	.4096
4.	.4564	.4867
5.	.5026	.5755
6.	.4783	.6613
7.	.5044	.7679
8.	.3765	.8591
9.	.3851	.9525
10.	.3902	1.0433
11.	.4693	1.1486
12.	.3731	1.2315
13.	.3186	1.4272

Figure 4. Genetic Yagi feed for the Arecibo Radio Telescope. From [1].

The performance of this Yagi was computed at 2 MHz increments over the band from 219 to 251 MHz, a bandwidth of 13.6%. The figure below shows the E-plane patterns and H-plane patterns for the genetic Yagi over a finite ground plane at the same frequencies. It is seen that the sidelobe levels for both planes are more than 25 dB lower than the gain at 0° from 223 to 243 MHz, the most important part of the band, and are more than 20 dB lower over the rest of the frequency band. The E- and H-plane half-power beamwidths range from 51 to 55° and 64 to 69° respectively, slightly larger than desired but certainly acceptable. The VSWRs are less than 3.0 from 227 to 245 MHz, though they are higher at the ends of the frequency band. The antenna gain ranged from 10.4 to 11.0 dB over the frequency band. This gain is approximately 1 dB lower than that for a Yagi that is optimized for maximum gain.

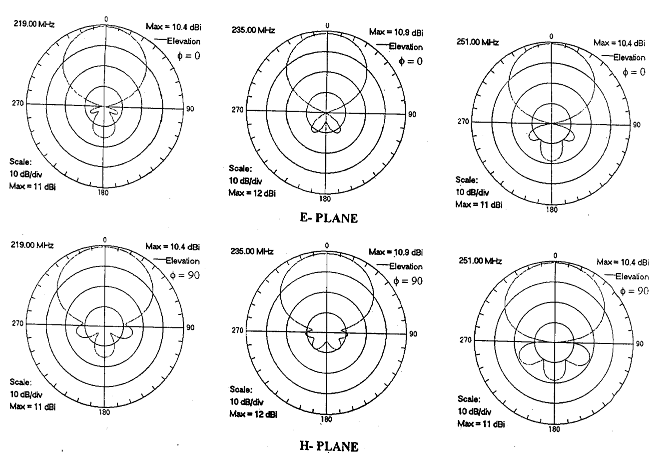


Figure 5. Computed gain patterns of Yagi over a ground plane at 219, 235 and 251 MHz. From [1].

The antenna was fabricated to a 1/6th scale and the E-plane patterns and VSWR were measured. The computed and measured patterns had reasonable agreement. The measured VSWRs were less than 3.0 over most of the band and had a maximum value of 3.7 near the ends. The measured gains were slightly less than 10 dB; however, if the reflection losses are taken into account, the corrected values for a matched antenna approach the computed gains. For more information about this application, see [1] and [2].

The GA is also not limited to Yagi designs where the elements are all co-planar. With all elements in a single plane, the Yagi antenna is constrained to be linearly polarized. However, if one wishes to communicate with satellites through the ionosphere, circular polarization is desired. A new design was optimized in [3] where the elements were allowed to rotate out of the plane of the antenna to make other polarizations possible.

An optimization with a real chromosome gave a result that was circularly polarized. The figures below show its design and its gain pattern.

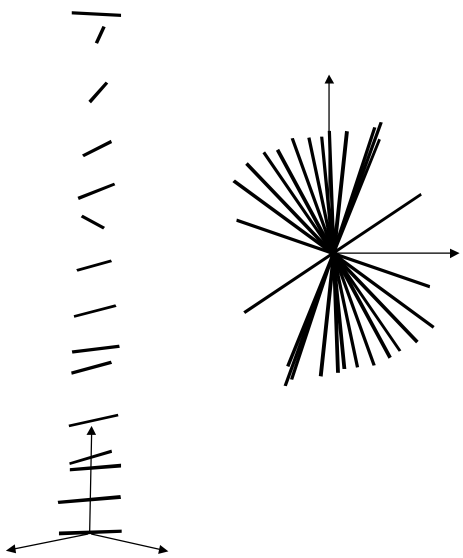


Figure 6. Rotated Yagi—side and top views. Boom length was 5.16λ

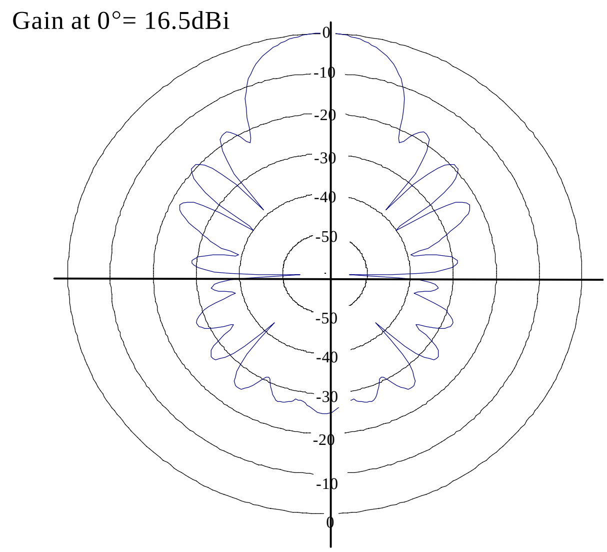


Figure 7. Normalized circular polarization gain pattern for rotated Yagi, in the plane of the antenna (ϕ=0°). Each circle is 10dB lower than the one that encircles it. Circular polarization losses have been taken into account.

Usually, this kind of pattern is achieved using a helix antenna, essentially a single wire that looks like a spring with carefully measured spacing and diameter. It is difficult to make because the wire must be wound according to exacting standards. But the GA allows the engineer to use a Yagi, which is easier to make for the same purpose. Though the Yagi must also be made to exact specifications, it is much easier to make short wires the correct size and place them at the correct spacing than to wind a single long wire to the same level of precision.

Thus, the Yagi can be applied in unconventional ways using GA optimization. However, it is not always necessary to specify a design, as the next section will show.

The Crooked-Wire Genetic Antenna

The application of interest in this section is an antenna that will be designed for ground-to-satellite communications. Such antennas that are intended to be used on cars or handsets must be cheap, robust, and have as uniform a gain pattern across the hemisphere as possible for a right-hand circularly-polarized signal. This antenna is not trivial to design, and several different designs have emerged to solve this problem to varying degrees. However, for this antenna, first described in [5], we did not specify a design. We determined the constraints of the problem and let the GA find a suitable antenna.

There were several qualities that the antenna should have. We wished the antenna to have a single feed point at its base for simplicity. We determined that the antenna should be designed for use over a ground plane. Since near-hemispherical coverage was desired, we knew the antenna should be relatively small. We chose to confine the antenna to a cube half a wavelength on a side, with its base located in the center of the bottom face.

Next, we specified the number of wires and the connection scheme for the antenna. We chose to investigate antennas consisting of 5, 6, 7 and 8 wire segments connected in series. Preliminary results showed the 7-wire antenna performed slightly better than the others. The location of the nodes defining the start and endpoints of the segments was stored in the chromosome. Since each node required three coordinates, a chromosome containing 21 different values represented the design for a 7-wire-segment antenna. A depiction of the search space is shown in the figure below.

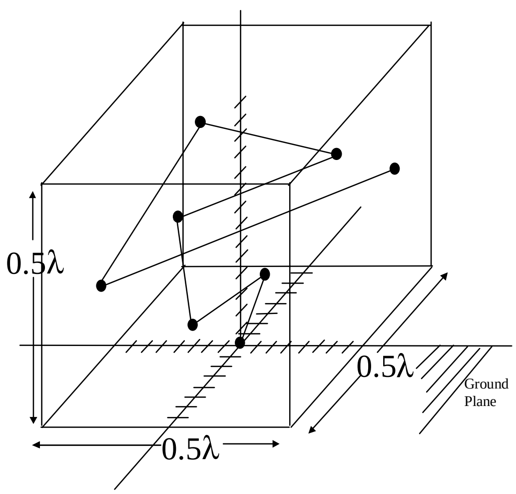


Figure 8. GA antenna design search space

After determining the constraints, it was necessary to define the cost function. Our goal was to obtain right hand circular polarization 10° above the horizon at a frequency of 1600 MHz. We determined that a good measure of this desired performance could be found in the sum of the squares of the deviation of all calculated gains from the mean. In equation form:

$$\text{Fitness} = \Sigma_{\text{over all } \theta,\phi}(\text{Gain}(\theta,\phi) - \text{Avg. Gain})^2 .$$

The GA's goal was to minimize this fitness. For this antenna, we chose a population of 500 binary chromosomes (105 bits each), and 50% were saved from generation to generation.

The GA produced a 7-wire configuration with a highly unusual shape, as shown in the inset in the figure below. The computed radiation patterns of the antenna over an infinite ground plane are shown below for azimuth angles of 0º, 45º, 90º and 135º at a frequency of 1600 MHz. This pattern varies by less than 4 dB for angles over 10° above the horizon—excellent performance, especially since the antenna is so inexpensive and simple to build.

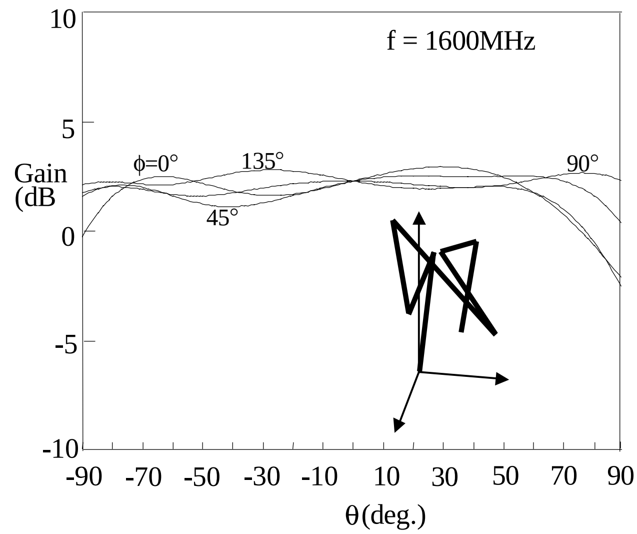


Figure 9. GA antenna design and radiation pattern

Although this antenna was only designed to operate at a single frequency, we also investigated its performance for the range of 1300 to 1900 MHz, and found it had a bandwidth of over 30%, which is excellent for a circularly polarized antenna having near hemispherical coverage.

We built the resulting design and measured its radiation properties. There was about a 6 dB variation in the field above an elevation angle of 10º as compared to the computed variation of about 4 dB. This small discrepancy exists because the measurements were made over a 1.2 m x 1.2 m ground plane, while the computations were performed for an infinite ground plane. Patterns measured over the frequency range from 1300 to 1900 MHz also compared well with the computed patterns.

Many other optimizations were run for these requirements, and the results were never the same. Two more antennas with similar performance are shown below. They are yet they are quite dissimilar in shape from each other and from the antenna above. Thus, it is apparent that this search space is highly multi-modal, with many minima that give similar performance. For more information on this antenna, see [1, 2, 3, 5].

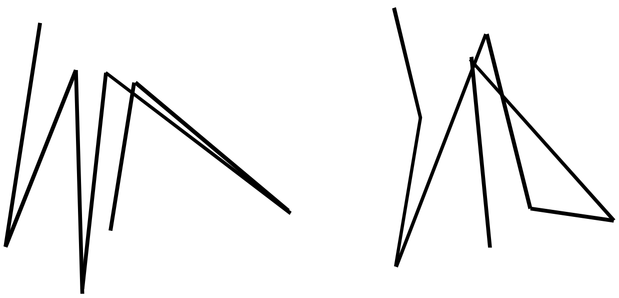


Figure 10. Two more crooked-wire antennas with nearly identical performance.

Conclusion

Each of the antennas described above demonstrated a different quality of GAs as applied to wire antenna design. The Yagi antennas showed how the GA can find solutions to real-world problems, and optimize existing designs for unusual applications. The crooked-wire genetic antenna showed the raw power of the GA to find not only an optimized design for an application, but a design almost completely undefined by the engineer.

GAs are able to optimize wire antennas for many diverse and difficult applications. The inherent power of the GA to avoid local minima, its robustness, its ability to free the engineer from making an initial guess, and its low computational overhead make it an ideal method of automated design for electromagnetic applications like wire antennas.

References

[1] E.E. Altshuler and D.S. Linden. "Wire Antenna Designs using a Genetic Algorithm." IEEE Antenna & Propagation Society Magazine, Vol. 39, pp. 33-43, April 1997.

[2] E.E. Altshuler and D.S. Linden. "Design of Wire Antennas using Genetic Algorithms." *Electromagnetic System Design using Evolutionary Optimization: Genetic Algorithms*, Y. Rahmat-Samii and E. Michielssen, eds., Wiley, 1999.

[3] D.S. Linden. "Automated Design and Optimization of Wire Antennas using Genetic Algorithms." Ph.D. Thesis, MIT, September 1997.

[4] D.S. Linden. "Using a Real Chromosome in a Genetic Algorithm for Wire Antenna Optimization." Presented at and published in the Proceedings of the IEEE APS International Symposium, Montreal, Canada, 13-18 July 1997.

[5] D.S. Linden and E.E. Altshuler. "Automating Wire Antenna Design using Genetic Algorithms." Microwave Journal, Vol. 39, No. 3, March 1996.

[6] G.J. Burke and A.J. Poffio. "Numerical Electromagnetics Code (NEC)-Method of moments." Rep. UCID18834, Lawrence Livermore Laboratory, January 1981.

[7] I.M. Avruch, et al., "A Spectroscopic Search for Protoclusters at High Redshift." Bulletin of the American Astron. Society, Vol. 27, No. 4, 1995.

[8] A. Adewuya, "New Methods in Genetic Search with Real-valued Chromosomes," Master's Thesis, Mech. Engr. Dept., MIT, 1996