# Wire-Antenna Designs Using Genetic Algorithms

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## 1. Abstract

There is a large class of electromagnetic radiators designated as wire antennas. As a rule, an inductive process is used to design these antennas. Either an integral equation is formulated or a simulator is used that gives the current distributions on the wires of the antenna, from which the electromagnetic properties of the antenna can then be determined. Once the antenna properties are known, the parameters are optimized, using guides such as intuition, experience, simplified equations, or empirical studies. However, using an electromagnetics simulator in conjunction with a genetic algorithm (GA), it is possible to design an antenna using a completely deductive approach: the desired electromagnetic properties of the antenna are specified, and the wire configuration that most closely produces these results is then synthesized by the algorithm. In this paper, we describe four antennas designed using GAs. The first is a monopole, loaded with a modified folded dipole that was designed to radiate uniform power over the hemisphere at a frequency of 1.6 GHz. We keep the same general shape of the loaded monopole, and use the algorithm to optimize its wire lengths. The second antenna consists of seven wires, the locations and lengths of which are determined by the GA alone, that radiates waves with right-hand-circular polarization at elevation angles above 10°, also at 1.6 GHz. The last two antennas are modified Yagis. One is designed for a broad frequency band and very low sidelobes at a center frequency of 235 MHz. The other is designed for high gain at a single frequency of 432 MHz. It will be obvious that these antennas, with their unusual shapes, could not have been designed using an inductive approach.

We have built and tested these antennas. The loaded monopole radiated uniform power over nearly the whole hemisphere, and the "crooked-wire" genetic antenna had nominal circular polarization at angles 10° above the horizon. Although these antennas were optimized at a single frequency, they both turned out to be broadband. The broadband/low-sidelobe Yagi had side and backlobes that were greater than 25 dB down over most of the band. The high-gain genetic Yagi, having 17 elements and a boom length of 4.88λ, had a gain that was 0.4 dB higher than that of a conventional 18-element Yagi that had a boom length of 5.16λ. The measurements agreed very well with the computational results. We believe that this new process may revolutionize the design of wire antennas.

## 2. Introduction

Since wire antennas first appeared, a variety of useful designs have emerged, such as the dipole, its counter-part monopole over a ground screen, rhombic, the Beverage, the Yagi, the log-periodic, the loop, the helix, and the spiral antenna. The design approach used by antenna engineers generally limits antennas to relatively simple structures. In general, an engineer finds an existing design that may have the desired electromagnetic characteristics. If this structure has an analytical expression that precisely predicts its performance, the engineer uses it to find the optimal parameters. If not, one works with appropriate equations to determine initial guesses for its proper dimensions and parameters, and uses an electromagnetic simulator to predict its performance. If the performance is not acceptable, the engineer redesigns the antenna, using guides such as intuition, experience, approximate equations, or empirical studies to determine which parameters to change to improve performance. This design technique has produced many different antenna designs, but it is time-consuming, and if there are many unknowns, it is unlikely to produce truly optimum results. In addition, this technique is limited to designs that have an intuitive logic about them. Symmetry is often present, and structures are kept relatively simple to allow for easier understanding and analysis. However, non-intuitive configurations can sometimes work as well as, or better than, intuitive ones. It is of interest, then, to find a way to search for such counter-intuitive solutions, using a well-validated optimization methodology. In particular, one technique, the genetic algorithm (GA), is sufficiently powerful to search large, non-intuitive solution spaces.

Motivating the search for a better design technique is a pressing need for increased antenna performance. For instance, although most hand-held transceivers currently use linearly polarized antennas, it would be advantageous to have an antenna with dual polarization, so that incoming signals that have become depolarized due to multiple reflections can still be detected. We have experimented with monopole antennas loaded with modified folded dipoles [1, 2] or loops [3], and have shown that it is possible to achieve near-hemispherical coverage with these configurations. The monopole radiates a vertically polarized wave that provides coverage at the lower elevation angles, while the folded elements or loop radiate a horizontally polarized wave that provide coverage at the higher elevation angles. Thus, the antenna provides dual-polarization coverage at all but high and low elevation angles, for which it is linearly polarized.

As another example, current and future earth-to-satellite communication and navigation systems require ground-based antennas that are circularly polarized, and have near-hemispherical coverage. Circular polarization is necessary for systems operating at frequencies below about 3 GHz, since the Faraday rotation produced by the ionosphere can cause a linearly polarized wave to rotate out of alignment with the receiving antenna. In a worst-case scenario, the incoming wave becomes cross polarized, so that no signal is received. A circularly polarized signal overcomes this problem. Near-hemispherical coverage is desirable, since the ground antenna is often required to receive a signal from a satellite


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anywhere above the horizon, except at low elevation angles, where signals have multipath components that can disrupt system performance. Currently, helical or patch antennas are used for this application. However, these antennas are generally narrow-band and require a phasing network, which increases their complexity and cost.

Another application that came to our attention was the need for a special feed for the Arecibo spherical reflector [4]. This antenna is 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 is about 235 MHz. Preliminary studies indicated that the band from 219 to 251 MHz had relatively little interference, particularly from 223 to 243 MHz. This feed had to have very low side and backlobes over this bandwidth. 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 design goals were for the feed to have sidelobes and backlobes at least 25 dB down in the region from $70° < \phi < 290°$. The E- and H-plane beamwidths were to be about 50°. The VSWR was to be under 3.0, and the gain was to be consistent with the beamwidth. The feed would be mounted over a 1.17-meter-square ground plane. We will show that it is possible to modify the typical Yagi configuration so that properties previously unobtainable using conventional design techniques can be achieved.

Finally, the Yagi antenna, because it is light weight, inexpensive, and has high gain has been used for many applications over the years. We decided to investigate the possibility of obtaining higher gain by using a genetic algorithm for the design. To illustrate this new method, we chose to optimize the gain of an 18-element Yagi with a boom length of $5.16\lambda$ at a single frequency of 432 MHz; back and sidelobes were not included. We compare this design with that of an 18-element Yagi that has been optimized using current state-of-the-art methods [5].

## 3. Approach

The GA starts with a large population (trillions, for typical problems) of potential wire configurations. These configurations are determined by the constraints of the problem and the method of encoding all configuration information (e.g., start and end points and wire sizes) into a string of 1s and 0s, called a binary chromosome, or a set of numbers, called a real chromosome. The GA randomly selects a small set, or sample population, of wire configurations. It then evaluates the performance of each member of this population, with a cost function that compares individual performance with the desired or ideal performance. The cost function returns a single number to the GA that is a measure of its fitness. In antenna design with a GA, evaluating the cost function involves simulating each member with an electromagnetics code, and comparing the results with those desired. The Numerical Electromagnetics Code, Version 2 (*NEC2*) [6], was used for these designs. As in the evolutionary process of "survival of the fittest," high-quality strings (chromosomes) mate and produce offspring, while poor-quality strings perish. Offspring are created by combining randomly selected parts of two chosen parent strings. With succeeding "generations," the quality of the strings continually improves, and an optimal solution is ultimately obtained. The GA method of antenna design is analogous to a method of breeding race horses, only the "horses" are antenna designs, and the "race track" is a simulation to determine antenna performance. "Champions" will have many offspring, while those who do not perform well will perish without offspring. In this manner, after a few thousand antenna simulations, a good solution is usually obtained. This method is resistant to becoming trapped in local maxima, which allows it to work well for antenna-design problems.

The antenna-design program we created employs a steady-state GA (i.e., a portion of the current population carries over to the next generation). A top percentage of the population, usually between 10% and 50%, is saved from each generation, after all chromosomes have been evaluated. These chromosomes are used to generate the offspring that will fill the rest of the population. A virtual "weighted roulette wheel" is filled according to each chromosome's fitness as compared to all the others'. The more fit a chromosome, the larger its share of the wheel. For each new position to be filled in the population, the wheel is "spun," and the first parent is chosen. The wheel is "spun" again, and the second parent is chosen, unless the wheel points to the same member of the population. In that case, it is spun again, since clones are not allowed. It should be noted that one parent's genetic material is not allowed to be the sole source for the child's chromosome. They can, however, be composed of the same genetic material, a case that occurs as the population converges to a single optimal chromosome. To implement mating for a binary chromosome, a single crossover site is chosen at random. The child is produced from the first part of the first parent's chromosome, up to the cross-over point, and the second part of the second parent's chromosome, and vice-versa for a second child. This process is repeated until the population is full again. For each generation, a small number of bit-flip (0 to 1 or 1 to 0) mutations occur in the new children. Much less than 1% of the bits are affected. Mutations allow the GA to search for solutions that exist outside the current gene pool.

For real chromosomes, an unusual mating scheme [7] that uses three different means of crossover in sequence was employed. Unlike typical crossover methods, where large segments of each parent's chromosome are preserved intact in the children, this scheme operates on each gene separately. The first type of crossover is called the quadratic crossover. In this method, three parents are chosen instead of two. For the gene in question, a second-order curve is fit, relating the gene value with the fitness of the parents. If a minimum exists in the valid gene range, the child's value for that gene is chosen to be at the minimum. If no minimum exists in the gene range, then the second method of crossover is used. This is called a heuristic crossover, and involves the two best parents from the three chosen in the first method, fitting a straight line between them that relates gene value to fitness. The child's gene is chosen to be a random amount past the most-fit parent's gene. If the child's gene is determined to be outside the valid gene range, the third method is used, which involves randomly selecting the value for the child's gene from one of the three parents chosen in the first method. For more information on basic GAs, see references [8] and [9].

The new population members are evaluated, and the generation process is begun anew. The program also remembers evaluations it has done, so that if a chromosome is exactly like a chromosome it has evaluated or saved, it will copy the score from it and move to the next one. This eliminates the need for duplicate computations of the same chromosome. This feature greatly decreases the time required to run the GA optimization. We generally allow this process to proceed for 70-90 such generations, though there are many criteria that can be used to determine when to halt the GA.

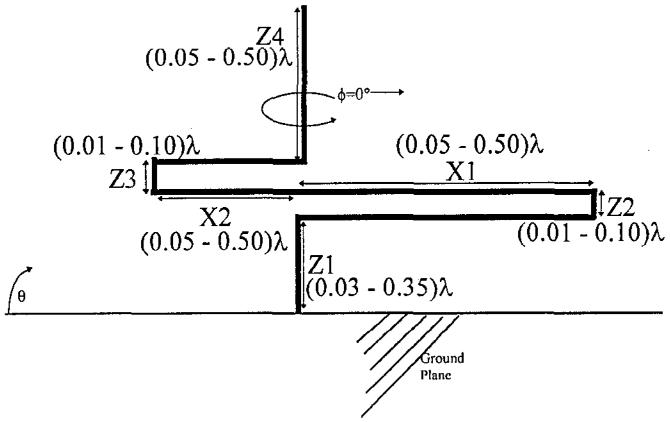



**Figure 1. A monopole antenna loaded with a modified folded dipole (numbers in parentheses indicate initial range of lengths).**

### 3.1 Loaded monopole [10]

A monopole, loaded with a modified folded dipole, has been previously investigated. It was shown that when the inserted folded element is approximately 0.1λ above the ground plane and the height of the monopole is about 0.35λ, then the $E_\theta$ pattern in the plane of the folded element approaches hemispherical coverage [1]. Here, a GA was utilized to optimize the above configuration for uniform power throughout the hemisphere by determining the optimal length of each wire. In order to implement the genetic algorithm, it was necessary to select a set of possible lengths for each wire of the loaded monopole. It was important that each range of lengths be large enough, such that the optimal length was likely to be included, yet not too large, such that the search space became unmanageable. Also, the binary-string GA requires the range of lengths for each wire to be divided into an integral number of different possible lengths from which the GA can choose. With these constraints in mind, we chose the ranges of wire lengths shown in Figure 1.

Each wire was represented by a five-bit string, and thus had 32 possible lengths. We initially chose five bits per wire because it gave a resolution (i.e., a lower bound on the smallest change) of 0.014λ to 0.003λ, depending on the wire. This was on the order of our fabrication tolerance. We stayed with five bits because our results were very good. If we had not obtained acceptable results, we would have increased or decreased the resolution. Increasing the resolution would have been valuable if we needed to fine-tune the wire lengths, but would have increased the size of the search space, and made the GA's job more difficult. Decreasing the resolution would have enabled the algorithm to search the space more quickly and/or more exhaustively, since there would be fewer solutions to choose from. However, there would have been a risk that good solutions would no longer exist in the coarser search space.

Since six wires define the loaded monopole, each configuration was represented by a 30-bit binary string: there were thus $2^{30}$ possible configurations. For our initial population, the GA randomly selected 150 samples. The radiation pattern of each of these samples was computed using *NEC2*. It was compared with the desired pattern–uniform power over the hemisphere–using a cost function containing a least-mean-square criterion, and then ranked according to performance. We chose to retain the top 50% of the solutions. The resulting 75 configurations were then mated, using the "weighted-roulette-wheel" method described above. The mutation rate varied between 0.0% to 0.9% of the bits in the new generation. The 75 new solutions were evaluated and ranked, after which the selection and mating process was repeated until it converged to a solution.

The optimal configuration was then subjected to a more complete *NEC2* analysis. Our initial cost function was limited to three θ-plane cuts, corresponding to ϕ angles of 0° (in the plane of the folded element), 45° and 90°, and a single frequency of 1600 MHz. The final computations were performed for intermediate angles, and for frequencies from 1400 to 1800 MHz. The *NEC2* output provided input impedance, current distribution, and $E_\theta$, $E_\phi$, and $E_{Total}$ fields over the hemisphere.

The antenna was then fabricated and tested. The loaded monopole was mounted over a 1.2m × 1.2m ground plane, and fed from a coaxial line. $E_\theta$ and $E_\phi$ radiation patterns were measured in an indoor range. The total $E$ field,

$$E_{Total} = \sqrt{\left(E_\theta^2 + E_\phi^2\right)},$$

was calculated. Since we were primarily interested in the directivity of the antenna, we did not attempt to measure its absolute gain or input impedance.

### 3.2 "Crooked-wire" genetic antenna [11]

For this antenna, we did not start with a basic design, as was done for the loaded monopole. Rather, we allowed the GA to find an antenna with the desired properties, subject to only very basic constraints, such as antenna size, excitation source, number of wires, and a ground plane. Regarding antenna size, since near-hemispherical coverage was desired, the antenna should obviously have been relatively small. We chose to start out by confining the antenna to a cube 0.5λ on a side. This design space is shown in Figure 2. Since this GA used binary strings to store configuration information, we had to encode the location of each wire using a

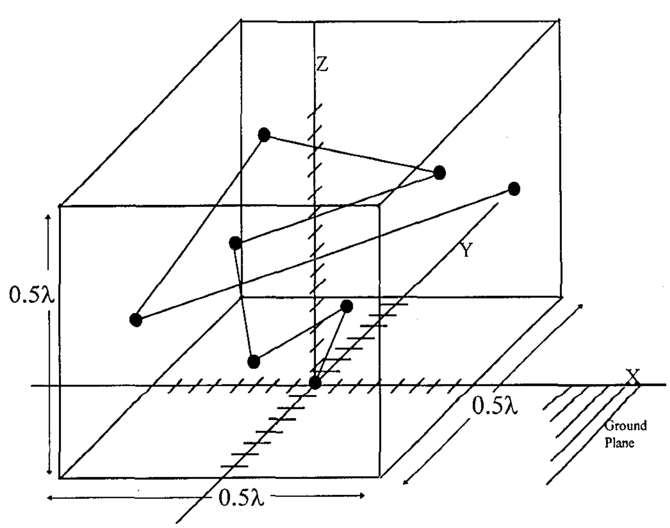



**Figure 2. The genetic antenna design space.**

binary system. We allowed five bits for each component of the $(x,y,z)$ coordinates for the beginning and end of each wire. Thus, each axis of the design space had 32 levels, and there were therefore $32^3$ possible vertices at which the wires could be connected.

Next, we had to specify the number of wires and the connection scheme that a configuration could use. We initially chose to investigate antennas consisting of five, six, seven, and eight connected-wire segments. Preliminary results showed the seven-wire antenna to perform slightly better than the five-, six-, and eight-wire antennas, so we chose to optimize the seven-wire antenna. For simplicity, we decided to make all wires connect in series. As there were five bits for each axis coordinate, three axis coordinates per point, and seven points to be designated (one point per wire, since each wire started at the previous wire's end point, and the first wire began at the origin), each seven-wire antenna required a chromosome with $5 \times 3 \times 7 = 105$ genes, or bits.

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 over the hemisphere, at a frequency of 1600 MHz, so the cost function for this system was relatively simple. The GA program computed the hemispherical-radiation pattern at increments of 5° in elevation, from $\theta = -80°$ to $+80°$, and at increments of 5° in azimuth, from $\phi = 0°$ to $\phi = 175°$. It then read the output of *NEC2*, calculated the average gain over the hemisphere and the sum of the squares of the deviations of all measured points from the mean. In equation form,

$$Score = \sum_{over\, all\, \theta,\phi} \left[ Gain(\theta,\phi) - Avg.Gain \right]^2 .$$

The GA's goal was to minimize this score. A perfectly uniform gain pattern received a score of zero. If the average gain was less than -10 dB, it was set at -10 dB, thus helping the GA to eliminate antennas that were very poor radiators.

We have called the outcome of this design process a genetic antenna, since this antenna comes directly from a GA optimization, and is not constrained by a pre-existing design. While the GA has been used previously to help determine unknowns in existing antenna designs [12, 13, 14, 15], it has not, to the best of our knowledge, been used to create a completely new design with its own unique theory of operation. After running the GA, we built the resulting design, and measured its radiation properties. The test antenna was illuminated by a right-hand-circularly polarized horn antenna. $\theta$-plane cuts were measured for azimuth angles of 0°, 45°, 90°, and 135°, and for frequencies from 1200 to 2000 MHz.

### 3.3 Broadband Yagi with low side and backlobes [16]

The Arecibo Yagi was optimized using a real chromosome. The cost function was

$$f = -G_L + C_1 S_H^2 + C_2 V ,$$

where

$G_L$ = lowest broadside gain
$S_H$ = highest sidelobe level within $70° < \phi < 290°$
$V$ = VSWR

$$C_1 = \begin{cases} 0, & S_H \geq 25\,\text{dB} \\ 1, & S_H < 25\,\text{dB} \end{cases}$$

$$C_2 = \begin{cases} 1, & V < 3.0 \\ 0, & V \geq 3.0 \end{cases}$$

The optimization involved minimizing this function. The encoding of the algorithm was done as follows:

length of element #1 (reflector)
length of element #2 (driven element)
spacing between elements #1 and #2
length of element #3 (first director)
spacing between elements # 2 and #3
length of element #4 (second director)
etc.

The antenna was simulated at 243 and 223 MHz, near the edges of the desired frequency band. We assumed that if the antenna performed satisfactorily at these frequencies, it would probably be acceptable over the rest of the band. We chose a sample population of 175 chromosomes, 30% of which was saved from generation to generation. Parent selection was based on the fitness-weighted roulette wheel.

Although the feed was over a finite ground plane, we 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, we conducted a thorough computational analysis for the whole frequency band from 219 to 251 MHz, at increments of 2 MHz. This was to ensure that the antenna was truly broadband. This was done initially for the Yagi with a reflector element, and then repeated with a 1.17-meter ground plane.

We then fabricated the antenna, and measured *E*-plane patterns. Since the antenna-pattern range did not operate satisfactorily at frequencies below about 800 MHz, and since the full-scale antenna would have been quite large, we decided to work with a one-sixth-scale model, having a center frequency of 1410 MHz. The Yagi elements were made of 0.8 mm (1/32 in) copper rod. These elements were inserted into 1.27 cm (1/2 in) PVC pipe. It was estimated that the Yagi was built to an accuracy of about ± 0.5 mm. The Yagi with a reflector element was first measured over the frequency range from 1310 to 1510 MHz at 10 MHz increments, and then the measurements were repeated using a 19.5-cm square ground plane in place of the reflector element.

### 3.4 High-gain Yagi [17]

An 18-element Yagi was optimized for gain and VSWR for a frequency of 432 MHz. Sidelobes, backlobes, and bandwidth were not included in the optimization. It was compared with a high-performance Yagi that was designed using state-of-the-art procedures. The cost function was

$$f = -G + C_2(VSWR),$$

where $G$ is the broadside gain, and $C_2$ is 1 when the VSWR is greater than 3.0, and 0.1 when the VSWR is less than or equal to 3.0. The objective was to minimize *f*. The encoding of the algorithm was the same as that for the broadband Yagi.

**Table 1. The optimal dimensions for a monopole antenna loaded with a modified folded dipole.**

| Segment | Length (m) | Length (λ) |
|---|---|---|
| Z1 | 0.0056 | 0.0299 |
| X1 | 0.0856 | 0.4565 |
| Z2 | 0.0024 | 0.0128 |
| X2 | - 0.0284 | 0.1515 |
| Z3 | 0.0079 | 0.0421 |
| Z4 | 0.0236 | 0.1259 |

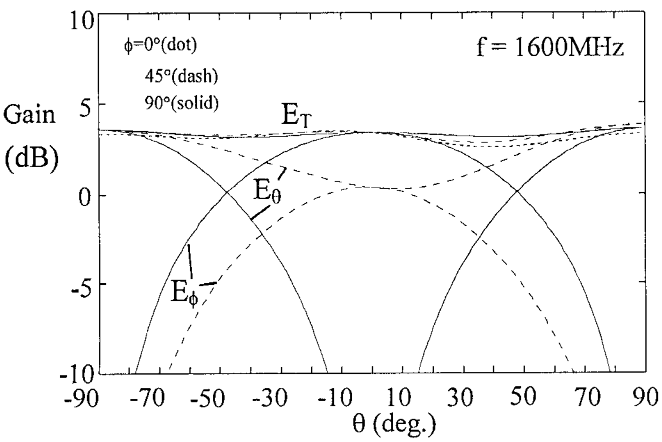



**Figure 3. The computed $E_\theta$, $E_\phi$, and $E_T$ fields in the θ plane for $\phi = 0°$, 45°, and 90°, at 1600 MHz.**

Each length or spacing was represented by six bits, so each had 64 lengths or separations. Thus, this design used a binary chromosome containing a string of 210 0s or 1s. A sample population of 175 Yagi configurations was randomly selected from the total population. A steady-state GA was used, with 30% of the population saved from generation to generation.

After an optimal configuration was produced by the algorithm, we then fabricated both antennas, and measured *E*- plane patterns and VSWRs. Once again, because of pattern range limitations, and because the full-scale antenna would have been quite large, we decided to work with a one-fourth-scale model, having a center frequency of 1728 MHz. The conventional Yagi elements were made of 1.2 mm (3/64 in) copper rod; the genetic Yagi used 1.6 mm (1/16 in) rod. These elements were inserted into 1/2 in PVC pipe. It was estimated that the Yagis were built to an accuracy of about ± 0.5 mm The measurements were made over the frequency range from 1650 to 1750 MHz.

#### 4. Results

In the optimization processes described above, only limited information regarding the desired properties of the antenna were included in the cost functions for the GAs. For example, for the loaded monopole, although we were looking for hemispherical coverage, we only optimized the radiation patterns at azimuth angles of 0, 45, and 90 degrees, and the computations were performed only at a single frequency. Limiting the cost-function criteria in this way allowed the computations to proceed much more rapidly. However, after an optimal configuration is obtained, it is then necessary to conduct a more-thorough analysis of the design. For the above designs, such an analysis was also computed using *NEC2* and, as the results were satisfactory, the antennas were then fabricated and tested. If these results had not been acceptable, we would have either rerun the GA, or included more properties in the cost function.

#### 4.1 Loaded monopole

The genetic algorithm, in a matter of two to three hours, produced a configuration that had a nearly uniform power pattern over the entire hemisphere. The optimal dimensions for the loaded monopole are shown in Table 1. The asymmetry of the resulting antenna would probably not have been produced analytically. It is hard to believe that this asymmetric structure has near-uniform coverage. Radiation patterns were computed for a set of $E_\theta$, $E_\phi$, and $E_{Total}$ (also denoted $E_T$) cuts in the θ plane, for 10° intervals in φ. The maximum difference between the maximum and minimum total fields for the whole hemisphere was less than 1.25 dB. An example of these results is shown in Figure 3. We plot the $E_\theta$, $E_\phi$, and $E_T$ fields for cuts in the θ plane corresponding to azimuth angles of 0°, 45°, and 90°. $\phi = 0°$ is a cut in the plane of the folded element, and $\phi = 90°$ is a cut in the plane orthogonal to the folded element. Note that the $\phi = 0°$ cut has only an $E_\theta$ component, whereas the $\phi = 45°$ and 90° cuts have both the $E_\theta$ and $E_\phi$ components. We found that the total field is nearly uniform in all directions, as was the case for three φ angles shown. The computed input impedance was 133 + *j*229 ohms. We did not attempt to optimize the impedance in this case, since we were interested primarily in the far-field pattern. However, future optimizations could easily include impedance in the cost function.

Finally, the frequency dependence of this antenna was examined. The $E_\theta$, $E_\phi$, and $E_T$ patterns were computed for θ-plane cuts corresponding to $\phi = 0°$, 45°, and 90°, in increments of 50 MHz, over the range from 1400 to 1800 MHz. In Figure 4, the computed results are plotted for $\phi = 45°$ for increments of 100 MHz, and are representative of results at other φ angles. It is seen that the maximum variation in power gain, over the hemisphere and over a 25% frequency range, is only about 6 dB.

The optimal wire configuration was fabricated and tested. The antenna was hand made out of coat-hanger wire (2 mm

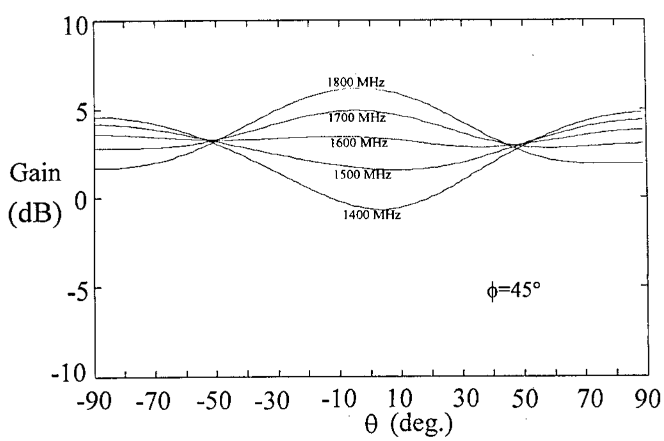



**Figure 4. The computed $E_T$ field in the θ plane for $\phi = 45°$ at frequencies from 1400 to 1800 MHz.**

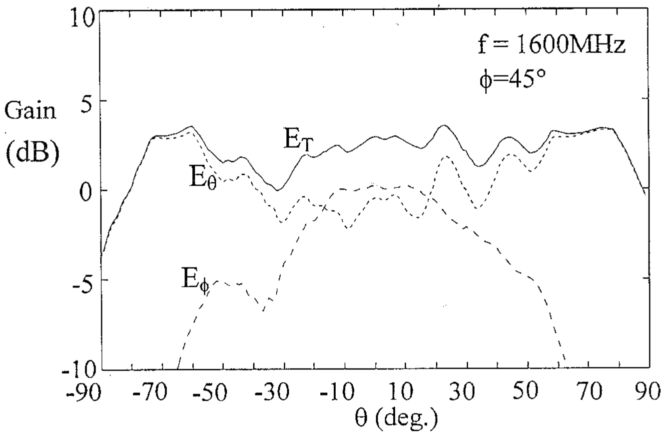



**Figure 5. The measured $E_\theta$, $E_\phi$, and $E_T$ fields in the θ plane for $\phi = 45°$ at 1600 MHz.**

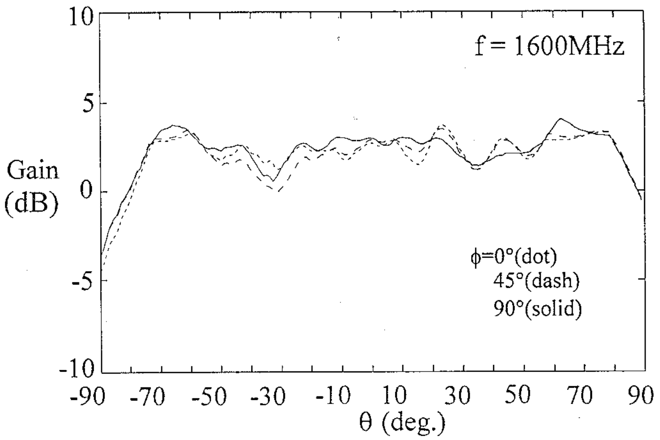



**Figure 6. The measured $E_T$ field in the θ plane for $\phi = 0°$, 45°, and 90°, at 1600 MHz.**

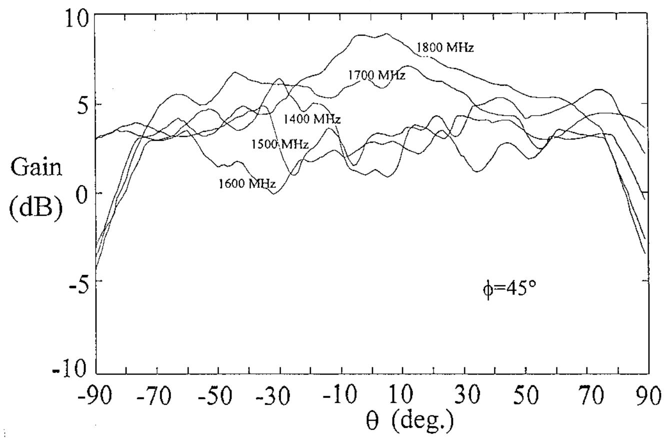



**Figure 7. The measured $E_T$ field in the θ plane for $\phi = 45°$ at frequencies from 1400 to1800 MHz.**

diameter), and the dimensions of the test antenna approximated those of the computed antenna to about ± 0.5 mm. Radiation patterns corresponding to the computed patterns shown in Figure 3 were measured. The $E_\theta$, $E_\phi$, and $E_T$ components are shown in Figure 5 for the $\phi = 45°$, θ-plane cut. The computed and measured patterns are similar, except for the ripples and loss of signal near the horizon. These effects are due to the finite ground plane, and are examined later. Computed and measured patterns for $\phi = 0°$ and 90° cuts were also in good agreement. The measured total field patterns are shown in Figure 6, for cuts in the θ plane corresponding to angles of $\phi = 0°$, 45°, and 90°. Note that the total field varies by less than 4 dB over nearly the entire hemisphere.

The $E_\theta$ and $E_\phi$ fields were then measured over the range from 1400 to 1800 MHz, and the corresponding $E_T$ field was calculated, for comparison with the computational results of Figure 4. In Figure 7, $E_T$ is plotted for $\phi = 45°$, for increments of 100 MHz over this range. The maximum variation in power over the hemi-

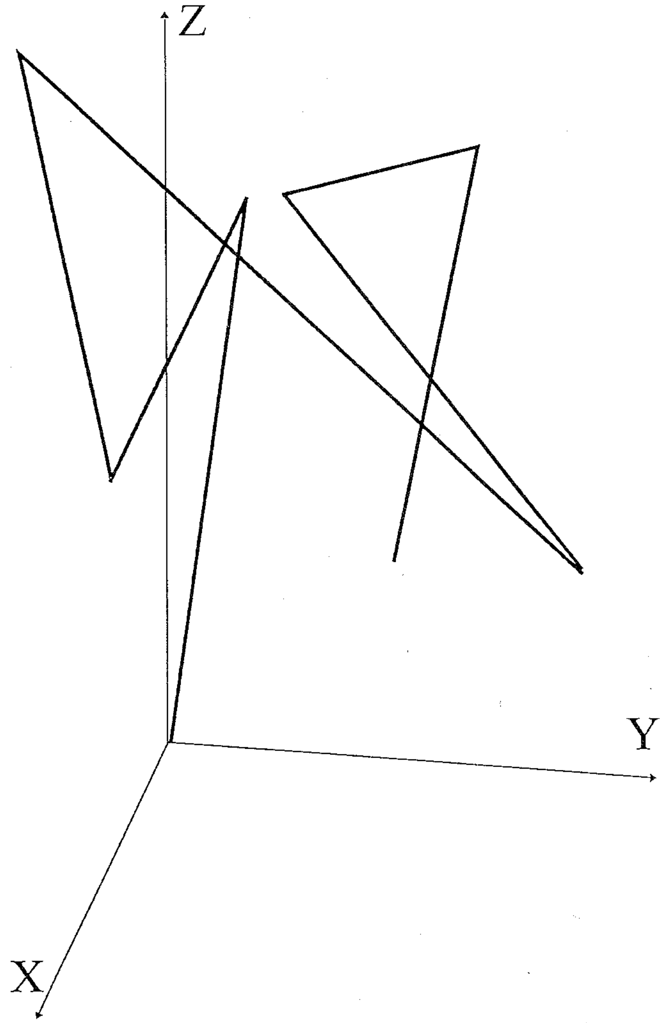



**Figure 8. The seven-wire genetic antenna with a ground plane.**

**Table 2. The seven-wire genetic antenna coordinates (meters).**

| *x* | *y* | *z* |
|---|---|---|
| 0.0000 | 0.0000 | 0.0000 |
| -0.0166 | 0.0045 | 0.0714 |
| -0.0318 | - 0.0166 | 0.0170 |
| -0.0318 | - 0.0287 | 0.0775 |
| -0.0318 | 0.0439 | 0.0140 |
| -0.0318 | 0.0045 | 0.0624 |
| -0.0106 | 0.0378 | 0.0866 |
| -0.0106 | 0.0257 | 0.0230 |

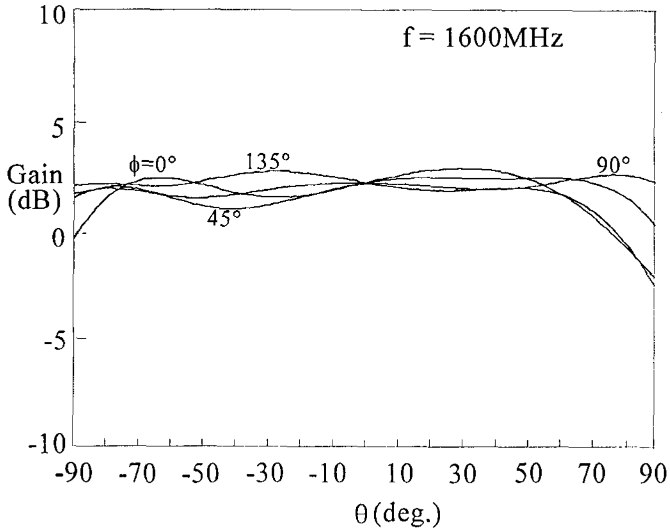



**Figure 9. The computed circularly polarized patterns in the θ plane for the seven-wire antenna over a ground plane.**

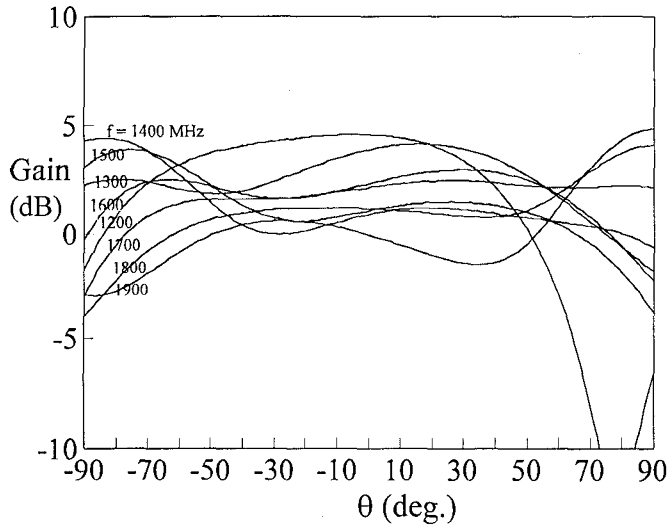



**Figure 10. The frequency dependence of the computed circularly polarized patterns in the θ plane for the seven-wire antenna over a ground plane (ϕ = 0°).**

sphere, except for very low elevation angles, was about 6 dB, as it was for the computed results.

The GA was repeated a number of times for the loaded monopole. It is interesting to note that, although it was searching for a particular performance, it never produced identical configurations. This is not surprising, since there are over one billion possible configurations, and the initial population is selected randomly, as are the crossover points for mating chromosomes.

We further investigated the loaded-monopole search space to determine the suitability of a GA as opposed to more-classical methods, e.g., gradient methods of optimization. This exhaustive study, involving over 65,000 *NEC2* runs that spanned the whole space (though at lower resolution than the GA optimization), has revealed many local minima, and a great deal of interdependence between the unknowns. The presence of these local minima, most of which are not very good, heightens the importance of the initial guess in a classical optimization. Moreover, our study has shown that symmetric antennas do not perform as well as asymmetric antennas. The more-intuitive initial guess of a symmetric antenna would probably lead to suboptimal results in a classical optimization. A robust search technique that does not require an initial guess and is not as likely to become trapped in local minima, like the GA, is probably necessary to effectively and quickly find good solutions for this kind of problem.

### 4.2 "Crooked-wire" genetic antenna

The GA produced a seven-wire configuration with an unusually weird shape, as is shown in Figure 8. The coordinates for its vertices are shown in Table 2. The computed radiation patterns of the antenna over an infinite ground plane are shown in Figure 9, for elevation cuts corresponding to azimuth angles of 0°, 45°, 90°, and 135°, at a frequency of 1600 MHz. Note that the response to a circularly polarized wave varies by less than 4 dB for angles above 10° over the horizon. The frequency dependence of the radiation pattern is shown in Figure 10, for the range of 1200 to 1900 MHz, for an elevation cut with an azimuth angle of 0°. It is seen that these patterns are relatively flat from 1300 to 1900 MHz. This corresponds to a bandwidth of over 30%, which is excellent for a circularly polarized antenna having near-hemispherical coverage. Patterns for other elevation cuts were comparable to these. It should be mentioned that true circular polarization is not achievable over large angles. From a practical standpoint, we have elliptical polarization, for which the magnitudes of the orthogonal signals approach unity and their respective phases approach quadrature. Note that as long as the receiving antenna has the same-sense polarization as the transmitter, the maximum polarization loss of 3 dB occurs when the receiver is linearly polarized. If the receiving antenna has the opposite-sense polarization, the polarization loss can become very large.

The measured normalized radiation patterns, for the "crooked-wire" genetic antenna over a ground plane, are shown in Figure 11, at a frequency of 1600 MHz, for the same elevation cuts that were previously computed. There is approximately a 6 dB variation in the field above an elevation angle of 10°, as compared to the computed variation of about 4 dB. This discrepancy can, for the most part, be attributed to the fact that the measurements were made over a 1.2 m × 1.2 m ground plane, whereas the computations were done for an infinite ground plane. The ripples in the

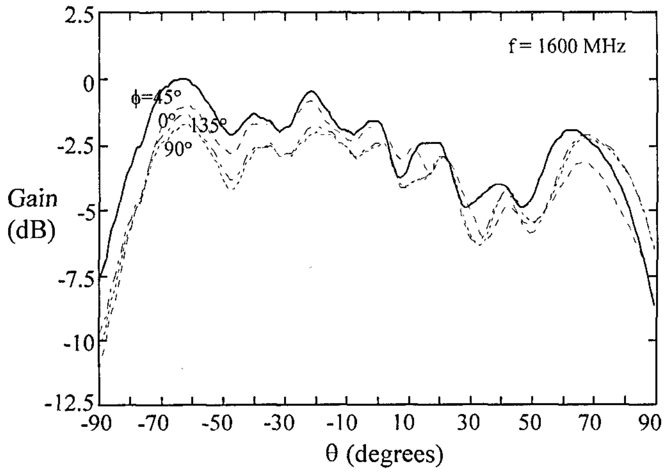



**Figure 11. The measured circularly polarized patterns in the θ plane for the seven-wire antenna over a ground plane.**

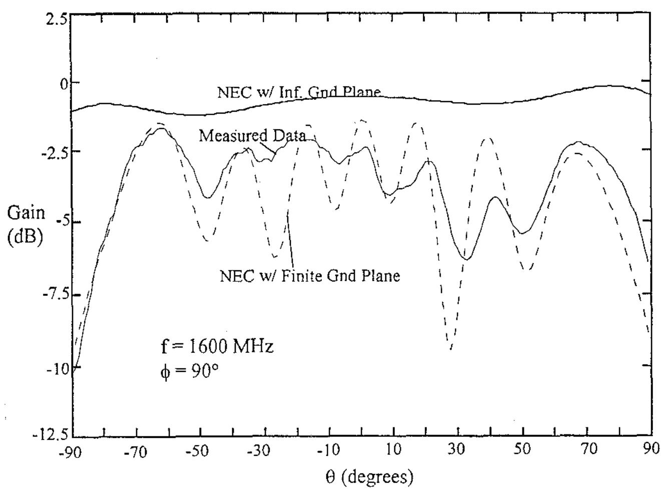



**Figure 12. The effect of a finite ground plane on the radiation pattern.**

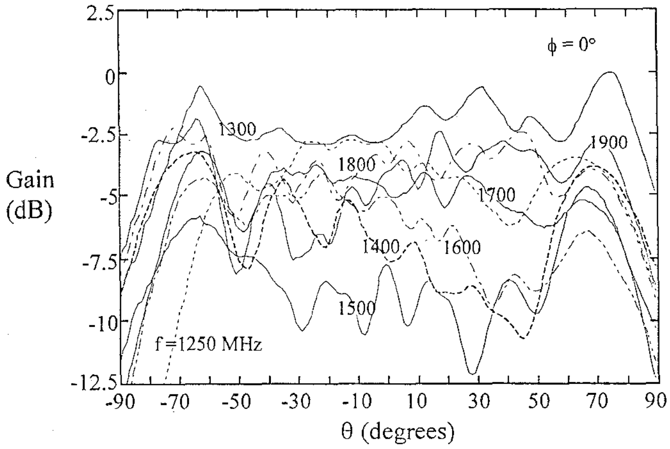



**Figure 13. The frequency dependence of the measured circularly polarized patterns in the θ plane for the seven-wire antenna over a ground plane ($\phi = 0°$).**

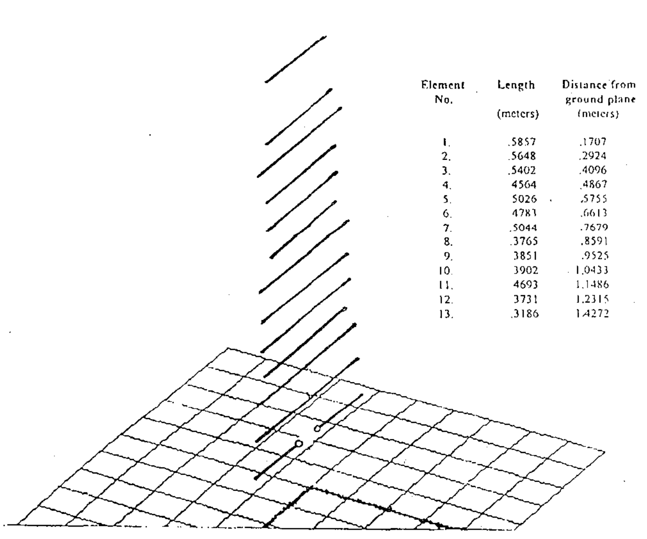
pattern arise from reflections from the edges of the ground plane. We have performed a simulation with a finite, perfectly conducting, ground screen, and have seen very good agreement with measurement results, as shown in Figure 12. Note that the peaks and valleys in both the measured data and the finite-ground-plane simulation agree well in location. Though simulation with a finite ground screen is closer to reality, we did not optimize the antenna using a finite ground screen, because each simulation takes hours to run.

The patterns were also measured over the frequency range from 1250 to 1900 MHz, for an elevation cut corresponding to an azimuth angle of 0°, and are shown in Figure 13. It should be noted that these are relative gain patterns, so only the directional properties are valid: No attempt was made to calibrate the transmitting antenna at all frequencies. As was the case for the computed patterns, these patterns show good coverage from 1300 to 1900 MHz.

It is of interest to determine how important the GA search method is to the discovery/design of such antennas. If, in fact, the search space has a high density of good solutions, it may be possible to use a simpler technique. Examples include a stochastic search, where designs are randomly generated and evaluated, or a simple stochastic hill-climber, where a design is modified in a small but random way: if it improves, the modification is kept, if not, the change is discarded, and a new one is generated. To explore this possibility, over 360,000 randomly generated designs were evaluated using *NEC2*. The distribution of the log of the scores was found to be normal, with a mean of 4.337, and a standard deviation of 0.208. This corresponded to an average score of about 22,000. About 95% of the scores (all scores within ± 2 standard deviations from the mean) lie between 8,300 and 57,000. The chances of randomly finding an acceptable solution is $1.6 \times 10^{-15}$, implying that the expected number of runs to achieve an acceptable solution is $6.3 \times 10^{14}$. An acceptable score is on the order of 500 or less in this case; for comparison, the score of the genetic-antenna design we present here was about 300. All of the randomly generated results with scores < 4000–53 such results in 360,270 runs–were also explored with a stochastic hill climber, and approximately one-fourth of these explorations resulted in scores less than 800. Thus, we estimate that approximately 26,000 *NEC2* runs are needed to find one acceptable solution using this stochastic-search-plus-stochastic-hill climber method. The GA technique, however, requires approximately 9,000 *NEC2* runs to do the same. Though it is possible that other search techniques, such as simulated annealing, would fare better than the stochastic-search methods above, the above exercise shows the relative power of the GA over a random search. It also shows that the problem at hand has a very sparse solution space, with many local minima. This is a situation ideal for the GA, but not conducive for a classical optimization technique like a gradient-based method.

### 4.3 Broadband Yagi with low side and backlobes

As expected, the genetic algorithm produced a configuration that was quite different from one that would have been obtained using conventional methods. Typical Yagi designs have directors that are about 0.4λ in length and with 0.35λ spacing. The lengths become slightly shorter and the spacings become slightly larger, the further the distance from the driven element. 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 is shown in Figure 14. A conventional 14-element Yagi would have had a boom length about three times as long.



| 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 14. The genetic Yagi feed for the Arecibo Radio Telescope.**

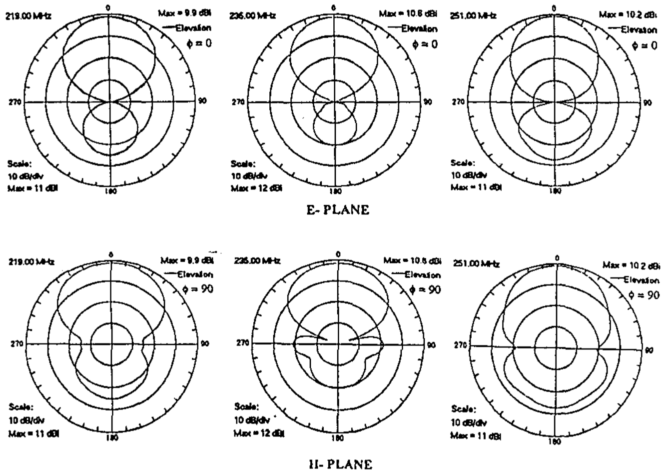



**Figure 15. The computed antenna patterns of the Yagi with a reflector element at 219, 235, and 251 MHz.**

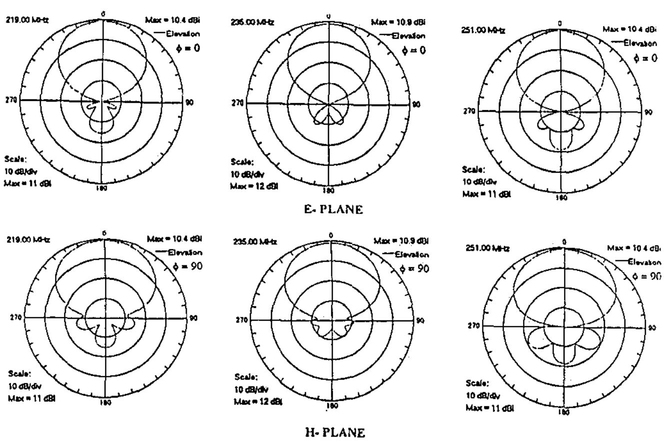



**Figure 16. The computed antenna patterns of the Yagi over a ground plane at 219, 235, and 251 MHz.**

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 initial results were for a Yagi having a reflector element and no ground plane, and are shown in Figure 15 for frequencies of 219, 235, and 251 MHz. Note that the lobes are typically higher than 20 dB down, particularly at the high frequency. We were cautiously optimistic that replacing the reflector element with a 1.17-meter ground plane would certainly reduce the backlobes, and might also lower the sidelobes. With this change, the side and backlobe levels for both planes were greater than 25 dB down from 223 to 243 MHz, the most important part of the band, and were over 20 dB down over the rest of the band. The *E*- and *H*-plane half-power beamwidths ranged from 51° to 55° and 64° to 69°, respectively, slightly larger than the desired 50°, but certainly acceptable. In Figure 16, we show the *E*- and *H*-plane patterns for the genetic Yagi over a finite ground plane at the same frequencies. 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, with the same boom length, that is optimized for maximum gain. The VSWRs were less than 3.0 from 227 to 245 MHz; they were, however, higher at the ends of the band.

*E*-plane patterns and VSWR were measured for the genetic Yagi, over a finite ground plane, for the frequency range of 1310 to 1510 MHz at 10 MHz increments. The pattern range was about 2600 feet in length. The test antenna was housed in a bay that is 20 ft × 20 ft × 20 ft, with absorbing material that was good to about 800 MHz. The VSWR measurements were made with an HP8510 Network Analyzer. In Figure 17, we show the one-sixth-scale model patterns for frequencies of 1310, 1410, and 1510 MHz. These correspond to the full-scale frequencies of 218, 235, and 252 MHz. We also show the previously computed patterns, and we see that they are comparable. The measured VSWRs are less than 3.0 over most of the band, and have a maximum value of 3.7 near the ends. The measured gains are 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. The computational and measured gains, side and backlobe levels, beamwidths, and VSWRs are summarized in Table 3.

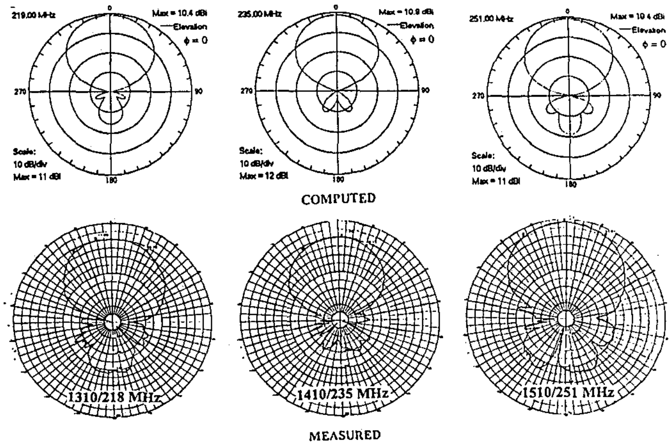



**Figure 17. The computed and measured *E*-plane patterns of the Yagi over a ground plane.**

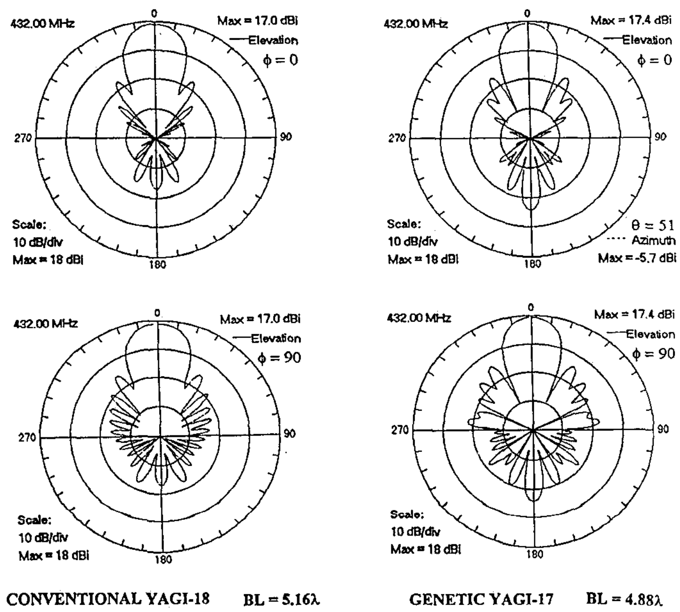



**Figure 18. The computed antenna patterns of conventional and genetic high-gain Yagis.**

**Table 3. A summary of the computed and measured parameters for the Arecibo Yagi over a ground plane.**

| | Computed | | | | | Measured (1/6 scale model) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Freq (MHz) | BW E-plane (deg) | BW H-plane (deg) | SL E-plane (dB) | SL H-plane (dB) | VSWR | Freq (MHz) 1/6 / Full | BW E-plane (deg) | SL E-plane (deg) | VSWR |
| 219 | 55 | 68 | 24.1 | 24.1 | 5.1 | 1310/218 | 56 | 18 | 3.6 |
| 221 | 54 | 67 | 24.6 | 24.6 | 4.4 | 1320/220 | 58 | 19 | 3.3 |
| 223 | 54 | 66 | 25.2 | 25.2 | 3.9 | 1330/222 | 58 | 22 | 3.1 |
| 225 | 54 | 66 | 25.9 | 25.9 | 3.3 | 1340/223 | 51 | 23 | 2.8 |
| 227 | 54 | 66 | 26.5 | 26.8 | 2.9 | 1350/225. | 51 | 25 | 2.4 |
| 229 | 53 | 65 | 26.9 | 26.9 | 2.5 | 1360/227 | 48 | 24 | 2.2 |
| 231 | 52 | 64 | 26.2 | 27.3 | 2.3 | 1370/228 | 53 | 25 | 2.1 |
| 233 | 52 | 64 | 27.4 | 27.9 | 2.0 | 1380/230 | 46 | 26 | 2.0 |
| 235 | 52 | 64 | 27.5 | 28.4 | 1.9 | 1390/232 | 48 | 25 | 2.0 |
| 237 | 51 | 63 | 27.5 | 28.3 | 1.9 | 1400/233 | 47 | 26 | 2.0 |
| 239 | 51 | 63 | 27.6 | 27.5 | 2.0 | 1410/235 | 48 | 28 | 2.0 |
| 241 | 51 | 63 | 27.7 | 26.6 | 2.1 | 1420/237 | 48 | 27 | 2.1 |
| 243 | 51 | 63 | 27.8 | 25.6 | 2.4 | 1430/238 | 52 | 24 | 2.3 |
| 245 | 51 | 64 | 27.2 | 24.2 | 2.9 | 1440/240 | 48 | 23 | 2.6 |
| 247 | 51 | 65 | 24.7 | 22.9 | 4.1 | 1450/242 | 42 | 23 | 2.7 |
| 249 | 52 | 66 | 22.6 | 21.6 | 6.0 | 1460/243 | 45 | 25 | 2.9 |
| 251 | 53 | 69 | 20.8 | 20.2 | 8.5 | 1470/245 | 48 | 25 | 3.1 |
| | | | | | | 1480/247 | 51 | 24 | 3.4 |
| | | | | | | 1490/248 | 50 | 25 | 3.7 |
| | | | | | | 1500/250 | 53 | 22 | 3.7 |
| | | | | | | 1510/252 | 53 | 23 | 3.5 |

**Table 4. The dimensions of high-gain conventional and genetic Yagis.**

| | Conventional Yagi | | Genetic Yagi | |
|---|---|---|---|---|
| Element No. | Length (cm) | Distance (cm) | Length (cm) | Distance (cm) |
| 1 | 33.66 | 0 | 33.10 | 0 |
| 2 | 32.52 | 12.70 | 30.38 | 13.45 |
| 3 | 30.00 | 18.42 | 30.92 | 23.11 |
| 4 | 29.84 | 30.48 | 29.84 | 41.29 |
| 5 | 29.52 | 45.40 | 11.40 | 55.68 |
| 6 | 29.06 | 62.86 | 29.30 | 63.45 |
| 7 | 28.90 | 82.23 | 14.10 | 88.26 |
| 8 | 28.74 | 103.03 | 28.22 | 93.18 |
| 9 | 28.58 | 124.94 | 20.62 | 96.21 |
| 10 | 28.42 | 147.64 | 27.66 | 123.86 |
| 11 | 28.26 | 171.61 | 27.66 | 158.14 |
| 12 | 28.10 | 196.53 | 28.22 | 182.95 |
| 13 | 27.94 | 222.25 | 25.50 | 221.02 |
| 14 | 27.78 | 248.60 | 27.66 | 258.14 |
| 15 | 27.46 | 275.27 | 27.66 | 283.90 |
| 16 | 27.30 | 302.74 | 28.22 | 316.29 |
| 17 | 27.14 | 330.36 | 29.30 | 339.20 |
| 18 | 26.98 | 358.14 | | |

### 4.4 High-gain Yagi

Once again, the genetic algorithm produced a configuration that was quite different from a typical Yagi. Although both designs have reflector- and driven-element lengths and spacings which were similar, the director lengths and spacings for the genetic Yagi are very different, as can be seen in Table 4. The optimal wire diameters are close: 4.8 mm for the conventional Yagi, versus 6.0 mm for the genetic Yagi. Note that the conventional Yagi has directors that start out with lengths slightly longer than $0.4\lambda$ and gradually decrease to lengths slightly less than $0.4\lambda$. The spacings start out at less than $0.2\lambda$, and gradually increase to about $0.4\lambda$. For the genetic-Yagi design, the element lengths range from about $0.07\lambda$ to slightly longer than $0.4\lambda$. The spacings vary from $0.04\lambda$ to $0.55\lambda$. Neither the lengths nor the spacings show any systematic change along the antenna. They appear, for all practical purposes, to be random.

The gain and VSWR were computed for both designs, using *NEC*. The conventional 18-element Yagi had a gain of 17.05 dB at the design frequency of 432 MHz, and a VSWR of 1.03. The genetic Yagi had a gain of 17.43 and a VSWR of 1.55. We noted, however, that the end director of the genetic Yagi was only $0.07\lambda$ in length, and had a very low current. We repeated the computations with the last director omitted, and the results were essentially the same. Thus, a genetic Yagi, with a boom length of only $4.88\lambda$, had a gain that was about 0.4 dB higher than that of a conventional Yagi, with a boom length of $5.16\lambda$.

Although the sidelobes and backlobe were not included in the optimization of the genetic Yagi, they were also examined, and found to be about 13-15 dB down. The corresponding sidelobes for the conventional Yagi were slightly better; however, the backlobe was over 22 dB down. The *E*- and *H*-plane patterns for the two antennas are shown in Figure 18. The bandwidths for both designs were also compared. As expected, that for the genetic Yagi was much narrower.

We then proceeded to measure the one-fourth-scale models of both antennas, over the frequency range from 1650 to 1750 MHz. We estimated that the gain was measured to an accuracy of about ± 0.5 dB. The conventional Yagi was relatively broadband, with a gain that was relatively flat over the whole band, and had a low VSWR. The genetic Yagi was very narrow band, with a sharp peak at a frequency of 1713 MHz, which is slightly lower than the corresponding design frequency. However, the gain was about 0.4 dB higher than that for the conventional Yagi, as was the computed gain.

## 5. Conclusions

The results seen thus far from this new process for designing wire antennas are very encouraging. Used in conjunction with *NEC2,* we were able to use a GA to optimize a loaded monopole that radiates nearly uniform power over the hemisphere. We are not aware of another antenna with a single input that provides this coverage. We have also shown that it is possible to synthesize the design of an antenna that is nominally circularly polarized over most of the hemisphere, without any pre-specified design. This "crooked-wire" genetic-antenna design is quite counter-intuitive, yet it performs well in simulation and actual measurement. We limited our investigation to the directional properties of both the genetic antenna and the folded monopole. Although these antennas were optimized to operate at a single frequency, they turned out to be very broadband. For this reason, it appears that they are non-resonant, and the dimensions of the wires are not too critical. In the future, other parameters, such as input impedance and bandwidth, could be included in the optimization process. Furthermore, we have been able to show that using a genetic algorithm, it is possible to synthesize both a broadband Yagi antenna design that has a radiation pattern that is quite different from that of a typical Yagi, and also a high-gain Yagi that outperforms a conventional Yagi by about 0.4 dB at a single frequency, even though it is 0.28$\lambda$ shorter.

In summary, we believe that this approach produces antennas that best meet these somewhat unconventional antenna specifications. This procedure, of simply defining constraints and cost functions and allowing a blind algorithm like the GA to find the proper design, appears to show remarkable promise. Using different cost functions and coding schemes, it seems that this new design procedure is capable of finding genetic antennas able to effectively solve difficult antenna problems, and will be particularly useful in situations where existing designs are not adequate.

## 6. Acknowledgment

We wish to thank Erhard Wisniewski for fabricating the Yagi antennas, and Jim Kenney and Dick Wing for assisting in the measurements. This research was supported in part by a Fellowship from the Fannie and John Hertz Foundation.

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