

Design of a Loaded Monopole Having Hemispherical Coverage Using a Genetic Algorithm

Edward E. Altshuler, *Life Fellow, IEEE*, and Derek S. Linden, *Student Member, IEEE*

Abstract—A genetic algorithm is used to design a monopole loaded with a modified folded dipole so that it radiates uniform power over the hemisphere. Each of the wires that make up the antenna are given a range of possible lengths. The genetic algorithm randomly selects a sample population of possible antenna configurations from the total population of all configurations. The radiation pattern of each sample configuration is computed using the numerical electromagnetics code (NEC). The solutions are compared with the desired pattern and ranked in terms of performance. The best solutions are retained and mated with one another and the process is repeated until an optimal solution is obtained. The genetic algorithm quickly produced an antenna that has a nearly uniform power over the hemisphere. Although the antenna was designed to operate at a frequency of 1.6 GHz, it performed satisfactorily over the frequency range from 1.4 to 1.8 GHz. The antenna was fabricated and the computational results were verified experimentally. We have shown that the genetic algorithm is a very powerful tool for designing wire antennas; it is expected that this process can be used to design any antenna that can be analyzed using an electromagnetic code.

Index Terms—Antennas, genetic algorithms.

I. INTRODUCTION

A MONOPOLE loaded with a modified folded dipole (as seen in Fig. 1) 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_θ -pattern in the plane of the folded element approaches hemispherical coverage [1]. In this paper, a genetic algorithm (GA) [2], [3] is utilized to optimize the above configuration for uniform power throughout the hemisphere.

It is of interest to discuss the reasons to use a GA to perform this optimization instead of a more classical approach like a gradient-based method. The GA method is robust: it is not likely to be stuck in local minima and it requires no initial guess at the final solution. Classical approaches need a starting point that is reasonably close to the final solution, or they are likely to be stuck in local minima. In situations where there are few, if any, local minima, or where a good initial guess is easily obtained, classical approaches will be more efficient than the GA method. We chose to use the GA as our first attempt at automated optimization and it seemed to be a very suitable application. Further study of the loaded

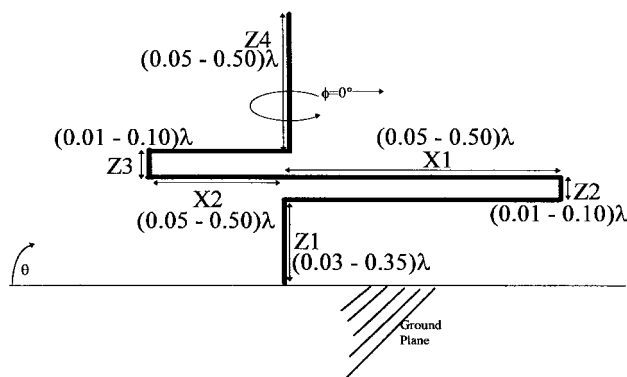


Fig. 1. Monopole antenna loaded with a modified folded dipole. Numbers in parentheses indicate initial range of lengths.

monopole design (described later) showed this approach to be reasonable.

To apply the GA, the following procedure is used. Each of the wires that make up the antenna is designated to have a range of possible lengths. The GA randomly selects a sample population of possible antenna configurations from the total population. One by one, the GA program converts each configuration from its internal representation (explained in the next section) to a file that can be read by the numerical electromagnetics code Version 2 (NEC2) [4]. The GA then calls the NEC2, which computes the sample's radiation pattern and places the results in an output file. The GA program reads the output file and the radiation pattern is compared with the desired pattern and scored. After all the configurations have been given a score they are ranked according to performance. The best results are retained and mated with one another; the poorer results are discarded. This process is repeated until an optimal solution is reached. This configuration is then fabricated and tested.

II. APPROACH

To implement the genetic algorithm it is necessary to select a set of possible lengths for each wire of the loaded monopole. It is important that each range of lengths be large enough such that the optimal length is likely to be included, yet not too large such that the number of computations becomes unmanageable. Also, the GA requires the range of lengths for each wire to be broken into an integral number of different possible lengths that the GA can choose from. With these constraints in mind, we chose the ranges of wire lengths shown in Fig. 1. The design frequency of this antenna was 1.6 GHz.

Manuscript received August 22, 1995; revised April 23, 1996.

The authors are with the U.S. Air Force Rome Laboratory, Electromagnetics and Reliability Directorate, Hanscom AFB, MA 01731 USA.

Publisher Item Identifier S 0018-926X(97)00432-8.

Each wire is represented by a 5-bit string and thus has 32 possible lengths. We chose 5 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) which was on the order of our fabrication tolerance. We stayed with five bits because our results were very good. If we had not seen adequate results, we would have increased or decreased the resolution. Increasing the resolution would have been valuable if the bandwidths were narrow and we needed to finely 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), but there would be a risk that good solutions would no longer exist in the coarser search space. Since we found good solutions with the 5-bit resolution, we did not see a reason to change it.

Since six wires define the shape of the loaded monopole, each configuration is represented by a 30-bit binary string (called a chromosome). Thus, there are 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, compared with the desired pattern (uniform gain over the hemisphere) using a cost function containing a least-mean square criterion and ranked according to performance. We chose to retain the top 50% of the solutions, destroying the rest. The resulting 75 configurations were then mated. The mating is accomplished by creating a weighted "roulette wheel," where better-performing chromosomes are given a proportionately larger share of the wheel. For each new offspring, the wheel is "spun" twice to select two parents. The selected pair of chromosomes are divided at a randomly selected crossover point. The new offspring chromosome contains the genetic code from the first parent until the crossover point, after which the genetic code comes from the second parent. The mating process is continued until the population is back to its original size of 150 chromosomes. In addition, random mutations occur in the new offspring as they occur in "real" genetics. Mutation is accomplished by randomly flipping a bit from 0 to 1 (or 1 to 0) in 0.0% to 0.9% of the bits in the new generation. This mutation allows the algorithm to search for an even better solution than is available in the current genepool. The 75 new solutions are evaluated and ranked, after which the selection and mating process is completed again. The cycle of mating, mutating, and evaluating is repeated until it converges to a solution.

After running the GA, the optimal configuration is then subjected to a more complete NEC 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 1.6 GHz. The final computations were done for intermediate angles and for frequencies from 1.4 to 1.8 GHz. The NEC output provided input impedance, current distribution and E_θ , E_ϕ , and E_{Total} fields over the hemisphere.

The antenna was then fabricated and tested. E_θ and E_ϕ radiation patterns were measured in an indoor range. The total

TABLE I
OPTIMAL DIMENSIONS FOR MONOPOLE ANTENNA
LOADED WITH A MODIFIED FOLDED DIPOLE

Name	Value (m)	Value (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

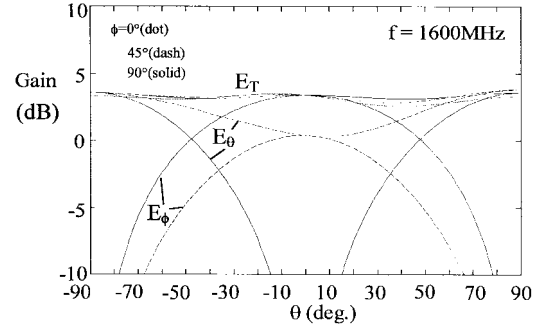


Fig. 2. Computed E_θ , E_ϕ , and E_T fields in θ -plane for $\phi = 0^\circ$, 45° , and 90° at 1.6 GHz

E-field

$$E_T = \sqrt{(E_\theta^2 + E_\phi^2)}$$

was calculated. The loaded monopole was mounted over a $1.2 \text{ m} \times 1.2 \text{ m}$ ground plane and fed from a coaxial line. Since we were primarily interested in the directivity of the antenna we did not attempt to measure its absolute gain or input impedance.

III. RESULTS

The genetic algorithm quickly (i.e., in a matter of a couple hours) produced a configuration that had a nearly uniform power pattern over the entire hemisphere. This somewhat odd shape would probably not have been arrived at analytically; the optimal dimensions for the loaded monopole are shown in Table I. It is hard to believe that this asymmetric structure produces near uniform coverage. Radiation patterns were computed for a set of E_θ , E_ϕ 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 Fig. 2 where we plot the E_θ , E_ϕ , and E_T fields for cuts in the θ -plane corresponding to azimuth angles of 0° , 45° , and 90° ; $\phi = 0^\circ$ being a cut in the plane of the folded element while $\phi = 90^\circ$ is a cut in the plane orthogonal to the folded element. Note that the $\phi = 0^\circ$ cut has only an E_θ component whereas the $\phi = 45^\circ$ and 90° cuts have both the E_θ and E_ϕ components. It is seen that the total field is nearly uniform in all directions as was the case for the intermediate angles. The computed input impedance was $133 + j229$ ohms. (As noted in the previous section, we did not attempt to optimize the impedance in this case—we were interested primarily in the far-field gain pattern. However, future optimizations could easily include impedance in the cost function.)

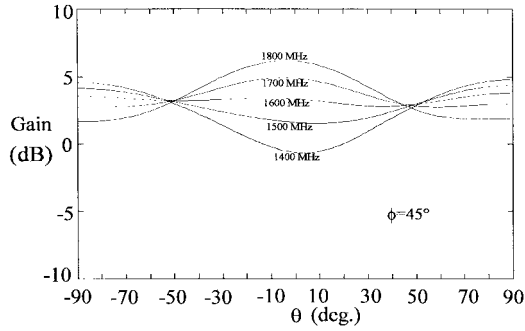


Fig. 3. Computed E_T field in θ -plane for $\phi = 45^\circ$ at frequencies from 1.4 to 1.8 GHz.

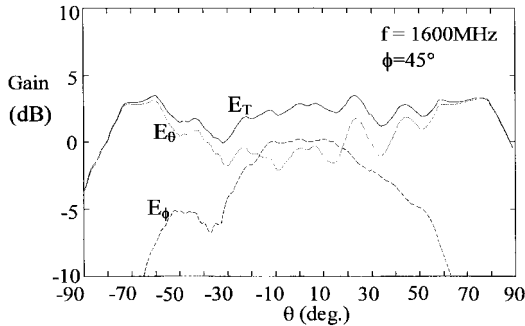


Fig. 4. Measured E_θ , E_ϕ , and E_T fields in θ -plane for $\phi = 45^\circ$ at 1.6 GHz.

Finally, the frequency dependence of this antenna was examined. The E_θ , E_ϕ , and E_T patterns were computed for θ -plane cuts corresponding to $\phi = 0^\circ$, 45° , and 90° in increments of 50 MHz over the range from 1400 to 1800 MHz. In Fig. 3, the computed results are plotted for $\phi = 45^\circ$ for increments of 100 MHz. It is seen that the maximum variation in power gain over the hemisphere over a 25% frequency range is only about 6 dB.

The optimal wire configuration was fabricated and tested. Since the antenna was handmade out of coat-hanger wire (2-mm diameter) the dimensions of the test antenna approximated those of the computed antenna to about ± 1 mm. Radiation patterns corresponding to the computed patterns shown in Fig. 2 were measured. The E_θ , E_ϕ , and E_T components are shown in Fig. 4 for the $\phi = 45^\circ$ 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. Computed and measured patterns for $\phi = 0^\circ$ and 90° cuts were also in good agreement.

The measured total field patterns are shown in Fig. 5 for cuts in the θ -plane corresponding to angles of $\phi = 0^\circ$, 45° , and 90° . Note that the total field varies by less than 4 dB over nearly the entire hemisphere. The E_θ and E_ϕ fields were also measured over the range from 1.4 to 1.8 GHz and the corresponding E_T field was calculated. In Fig. 6, E_T is plotted for $\phi = 45^\circ$ for increments of 100 MHz over this range. As for the computed results the maximum variation in power over the hemisphere (except for very low elevation angles) was about 6 dB.

The GA was repeated a number of times for the loaded monopole. It is interesting to note that it never produced identical configurations, however, they were usually very similar in shape and performance. This is due to the randomness in

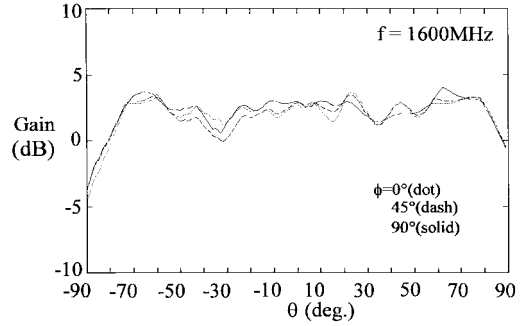


Fig. 5. Measured E_T field in θ -plane for $\phi = 0^\circ$, 45° , and 90° at 1.6 GHz.

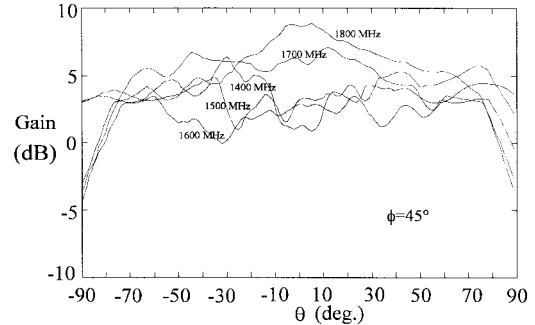


Fig. 6. Measured E_T field in θ -plane for $\phi = 45^\circ$ at frequencies from 1.4 to 1.8 GHz.

the process; the initial population is selected randomly as are the crossover points for mating the chromosomes. As there are over one billion possible configurations it is, therefore, not surprising that we see similar but not identical designs.

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 study, involving over 65 000 NEC2 runs which spanned the whole space, 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. However, as we have shown, the final shape of the antenna is not what an engineer would expect or probably try as an initial guess. 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 then 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 get stuck at local minima (like the GA) is probably necessary to effectively and quickly find good solutions for this kind of problem.

IV. SUMMARY

We have shown that the GA is a very powerful tool for designing wire antennas. Used in conjunction with the NEC we were able to design a wire structure—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. This process uses a deductive approach; that is, the desired electromagnetic properties are specified and the wire configuration that most closely produces these results is

synthesized. We expect that this process can be used to design other wire antennas and any other antenna that can be analyzed using an electromagnetic code.

ACKNOWLEDGMENT

The authors would like to thank R. A. Wing for assisting in the measurements.

REFERENCES

- [1] E. E. Altshuler, "A monopole antenna loaded with a modified folded dipole," *IEEE Trans. Antennas Propagat.*, vol. 41, pp. 871-876, July 1993.
- [2] J. H. Holland, "Genetic algorithms," *Scientific American*, pp. 66-72, July 1992.
- [3] R. L. Haupt, "An introduction to genetic algorithms for electromagnetics," *IEEE Antennas Propagat. Mag.*, vol. 37, pp. 7-15, Apr. 1995.
- [4] G. J. Burke and A. J. Poggio, "Numerical electromagnetics code (NEC)—method of moments," Rep. UCID18834, Lawrence Livermore Lab., CA, Jan. 1981.



Edward E. Altshuler (S'54-M'55-SM'62-F'84-LF'95) received the B.S. degree in physics from Northeastern University, Boston, MA, in 1953, the M.S. degree in physics from Tufts University, Medford, MA, in 1954, and the Ph.D. degree in applied physics from Harvard University, Cambridge, MA, in 1960.

Before joining Air Force Cambridge Research Labs (AFCRL), Hanscom AFB, MA, in 1960, he was employed by Arthur D. Little and the Massachusetts Institute of Technology, Cambridge, MA, and Sylvania Electric, Waltham, MA. He was Director of Engineering at Gabriel Electronics, Millis, MA, from 1961 to 1963, and Chief of the Propagation Branch at AFCRL from 1963 to 1982. He is currently conducting antenna research for the Rome Lab Electromagnetics and Reliability Directorate at Hanscom Air Force Base, MA. He was a Lecturer in the Northeastern University Graduate School of Engineering from 1964 to 1991. He was Associate Editor of *Radio Science* from 1976 to 1978.

Dr. Altshuler was Chairman of the IEEE Boston Section Antennas and Propagation Society during 1965-1966, and served as Chairman of the 1968 IEEE AP-S/URSI Symposium in Boston, MA. He was Chairman of the IEEE Boston Section Fellows and Awards Committee from 1993 to 1994 and serves on the Antennas and Propagation Society Awards Committee. He is currently Chairman of the IEEE Boston Section. He is a Member of the Commissions B and F of the International Radio Scientific Union. He has served on the Air Force Scientific Advisory Board and was Chairman of the NATO Research Study Group on Millimeter Wave Propagation and Target/Background Signatures from 1974 to 1993. He was President of the Hanscom Chapter of Sigma Xi during 1989-1990.

Derek S. Linden (S'91) received the B.S. degree in applied physics from the United States Air Force Academy, Colorado Springs, CO, in 1991, and the M.S.E.E. from the Massachusetts Institute of Technology (MIT), Cambridge, MA, in 1993. He is currently working toward the Ph.D. degree at MIT.

Since 1993, he has been with Rome Laboratory, Hanscom Air Force Base, MA working in the areas of superconductivity and antenna design. His current research interests are genetic algorithms, response surface modeling, and their application to antenna design and optimization.

Mr. Linden is a member of Sigma Xi.