Design of Electrically Small Wire Antennas Using Genetic Algorithm Taking into Consideration of Bandwidth and Efficiency

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Introduction

Recently, Altshuler reported on the use of genetic algorithm (GA) for designing electrically small wire antennas [1]. The wire configuration that results in maximum bandwidth was generated using GA for a given antenna size. However, it is well known that antenna miniaturization impacts antenna efficiency as well as bandwidth. In this paper, we consider the use of GA for designing electrically small wire antennas taking into consideration of both bandwidth and efficiency. For the antenna configuration, we employ the multi-segment structure similar to that used in [1]. The Numerical Electromagnetics Code (NEC) [2] is used to predict the performance of each wire structure. To efficiently map out the multi-objective problem, we implement a Pareto GA approach. An optimal set of designs that consider bandwidth, efficiency and antenna size is generated. The performance curve achieved by the GA approach is also compared against the well-known fundamental limit of small antennas [3,4]. Finally, to verify our GA results, several GA designs are built, measured and compared to the simulation.

GA for Multi-Objective Optimization

Pareto GA is implemented to optimize wire structures in order to achieve broad bandwidth and high efficiency [5]. In our GA implementation, each wire configuration consisting of N connected wire segments is encoded into a binary chromosome. The design space of a half sphere is evenly discretized into 2^n grid points and each location of the wire bent is encoded into an n-bit binary string. Thus the total number of bits in the chromosome is nN. For numerical stability, a geometrical filter is applied to prevent the wires from crossing one another. NEC is used to predict the antenna performance and to compute cost. The two costs associated with the design goals are:

$$\begin{aligned} &Cost\,1 = 1 - (\,Antenna\ Bandwidth\,/\,Theoretical\ Bandwidth\ Limit\,) \\ &Cost\,2 = 1 - Efficiency \end{aligned} \qquad (1)$$

In the above definition, the theoretical bandwidth limit of $2/(1/kr+1/(kr)^3)$ derived in [4] is used. After evaluating the two cost functions of each sample structure using NEC, all the samples of the population are ranked using the non-dominated sorting method [6]. Based on the rank, a reproduction process is performed to refine the population into the

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next generation. In order to avoid the solutions from converging to a single point, we perform a sharing scheme described in [7] to generate a well-dispersed population.

Results

Fig. 1 is an illustration of the wire antenna structure under consideration. We use N=7 wire segments for each antenna and n=8 bits to discretize the design half-sphere of radius r. Copper wire with a conductivity of 5.7e9 and a radius of 0.5mm is used. The target design frequency is 400 MHz. An infinite ground plane is assumed in the simulation. Fig. 2 shows the top 70 optimized designs in the population after 100 generations of the Pareto GA process. The antenna size is restricted to kr=0.63. Each dot represents a design with a particular bandwidth and efficiency. The bold line shows the Pareto front, on which the best solutions in the population lie. From the Pareto front, we observe that efficiency and bandwidth are inversely related. To obtain a design with a better bandwidth, its efficiency must be sacrificed.

Next, we map the Pareto fronts for various antenna sizes. Fig. 3 depicts the resulting 3-D plot for bandwidth, efficiency and antenna size. To more easily interpret the results, we project the 3-D plot to the bandwidth and efficiency plane in Fig. 4. At point A in the figure, where the antenna size is restricted to kr=0.50, the achievable bandwidth is about 9.82% with an efficiency of 96.5%. At point B where the antenna size is restricted to kr=0.42, the achievable bandwidth is reduced to 5.5% with about 93.5% efficiency. This clearly shows that both the achievable bandwidth and efficiency drop as we reduce the antenna size. Fig. 5 compares the well-known fundamental limit [4], shown in dashed line, with the performance of GA-designed antennas. All the samples on the 3-D Pareto surface are group into different efficiency ranges in the figure. The solid line shows the maximum bandwidth achievable by the GA designs as a function of antenna size. We observe that it follows a very similar trend to the fundamental limit. However, to achieve such a bandwidth as the antenna size is decreased, the efficiency of the antenna must also fall, as seen by the efficiency associated with each design along the maximum bandwidth curve.

To verify our GA results we built and measured the two GA-optimized designs at points A (kr=0.50) and B (kr=0.42) in Fig. 4. We used copper wire of radius 0.5mm, and a 1.6m x 1.6m conducting plate as ground plane. Fig. 6(a) is the resulting return loss (dB) of antenna B as a function of frequency from simulation and measurement. The comparison shows, except for a slight shift in the resonant frequency, nearly the same bandwidth (about 5.3% based on $|S11| \leq -3$dB) from simulation and measurement. Fig. 6(b) is the resulting efficiency of the antenna. The Wheeler cap method was used in the measurement [8]. The measured efficiency agrees reasonably well with that from the simulation at 400 MHz. Strictly speaking, the Wheeler cap measurement is only valid at the resonance frequency of the antenna. However, it gave reasonable results over a broader range except for around 385MHz, which corresponds to an anti-resonance of the antenna. Similar good agreements were also found for antenna A. The results validate our GA design methodology.

Conclusion

Pareto GA was applied to design electrically small wire antennas by considering both the bandwidth and efficiency. It was shown that broader antenna bandwidth must be traded off against lower antenna efficiency. Our results also showed that the maximum achievable bandwidth and efficiency both decrease as the antenna size is reduced. The performance achieved by the GA approach was also compared against the well-known fundamental limit of small antennas. Several GA antennas were built, measured and compared to the simulation to verify the GA results.

Acknowledgments

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References

[1] E. E. Altshuler, "Very small genetic antennas," *2001 USNC/URSI Nation Radio Science Meeting*, pp. 226, Salt Lake City, UT, July 2000.

[2] G. J. Burke and A. J. Poggio, *Numerical Electromagnetics Code (NEC)-Method of Moments*, Lawrence Livermore Laboratory, 1981.

[3] L. J. Chu, "Physical limitations of omnidirectional antennas," *J. Appl. Phys.*, vol. 19, pp. 1163-1175, Dec. 1948.

[4] J. S. McLean, "A re-examination of the fundamental limits on the radiation Q of electrically small antennas," *IEEE Trans. Antennas Propagat.*, vol. 44, pp. 672-676, May 1996.

[5] D. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison Wesley, Reading, MA, 1989.

[6] N. Srinivas and K. Deb, "Multiobjective optimization using nondominated sorting in genetic algorithm," *J. Evolutionary Computation*, vol. 2, pp. 221-248, 1995.

[7] J. Horn, N. Nafpliotis and D. E. Goldberg, "A niched pareto genetic algorithm for multiobjective optimization," *Proc. First IEEE Conf. Evolutionary Computation*, vol.1, pp. 82-87, 1994.

[8] E. H. Newman, P. Bohley, and C. H. Walter, "Two methods for the measurement of antenna efficiency," *IEEE Trans. Antennas Propagat.*, vol. 23, pp. 457-461, July 1975.

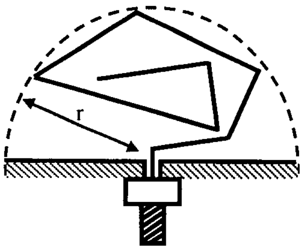

Fig. 1. Configuration of the multi-segment wire antenna used in the GA design.

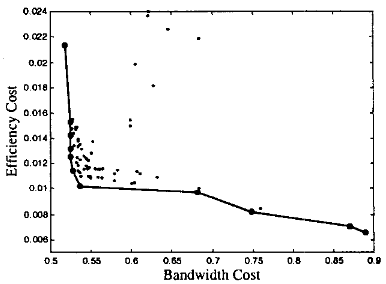

Fig. 2. GA-optimized solutions after 100 generations (kr=0.63).

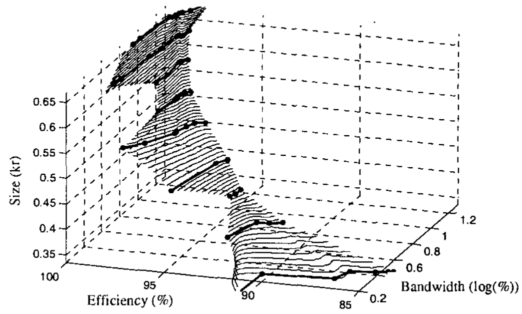

Fig. 3. The Pareto front in terms bandwidth, efficiency and antenna size.

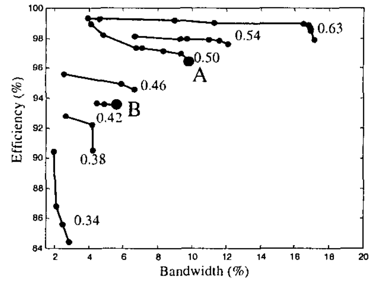

Fig. 4. Projection of the Pareto front to the bandwidth and efficiency plane.

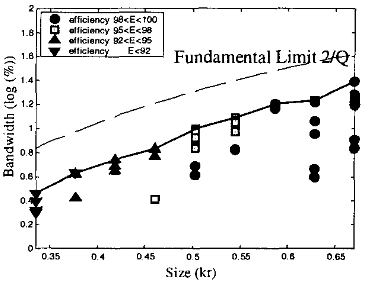

Fig. 5. Bandwidth vs. antenna size. The efficiency of each solution is labeled by a different symbol.

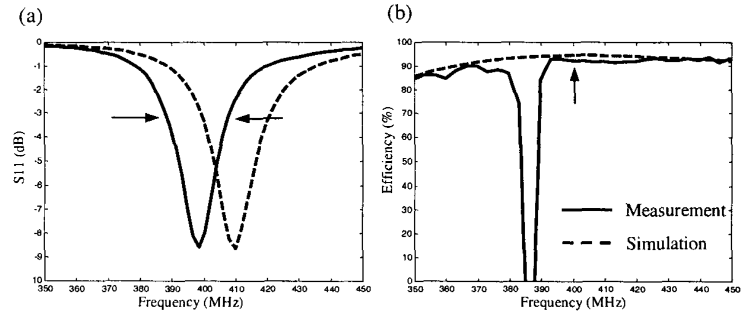

Fig. 6. (a) Return loss and (b) efficiency versus frequency for antenna B. The efficiency measurement was done using the Wheeler cap method.