12-2009

Grating Lobe Reduction in Aperiodic Linear Arrays of Physically Large Antennas

William C. Barott
Embry-Riddle Aeronautical University, barottw@erau.edu

Paul G. Steffes
Georgia Institute of Technology

Grating Lobe Reduction in Aperiodic Linear Arrays of Physically Large Antennas

William C. Barott, *Member, IEEE* and Paul G. Steffes, *Fellow, IEEE*

***Abstract*— We present performance bounds obtained from the optimization of the sidelobe levels of aperiodic linear arrays. The antennas comprising these arrays are large compared to the distance between neighboring antennas, a case not addressed in previously published work. This optimization is performed in pattern-space, and is applicable over a wide range of scan angles. We show that grating lobes can be suppressed even when the elemental antennas are several wavelengths in size, provided that the ratio of the antenna size to the average spacing between the antenna center-points does not exceed 80%.**

***Index Terms*—Antenna arrays, genetic algorithms**

I. INTRODUCTION

PHASED arrays are sometimes required to have a large aperture but a relatively small number of antennas. Placing these antennas at periodic intervals exceeding one half wavelength creates grating lobes in the radiation pattern and limits the usefulness of the array. Aperiodic placement techniques can remove grating lobes and minimize the sidelobe level of the array, as shown in Fig. 1 [1].

Theories of aperiodic arrays have been described in detail [2]. For example, Haupt showed the relationship between the unit circle representation and antenna positions for aperiodic arrays [3]. However, it is difficult to apply arbitrary requirements to arrays generated using this method or other deterministic methods [4, 5]. As a result, aperiodic antenna positions are often generated with iterative search algorithms.

The optimization of aperiodic linear arrays using genetic algorithms has been studied in great detail (e.g. [1, 6]). In these studies, the elemental antennas are treated as point-sources or dipoles oriented orthogonally to the axis of the array, as in Fig. 2a. Little attention has been given to the design of arrays consisting of antennas that are physically large along the axis of the array, as in Fig. 2b. In this paper, we present results from an analysis of arrays consisting of physically large antennas. A genetic algorithm that accounts for the size of the antennas is used as the optimization tool. We show that it is possible to effectively suppress grating lobes in these arrays, providing that the antenna sizes do not exceed 80% of the mean spacing between the antenna center-points.

Manuscript received May 23, 2007.

William C. Barott: Embry-Riddle Aeronautical University, Electrical and Systems Engineering Department, Daytona Beach, FL, 32127 USA (email william.barott@erau.edu)

Paul Steffes: Georgia Institute of Technology, School of Electrical and Computer Engineering, Atlanta, GA 30332 USA

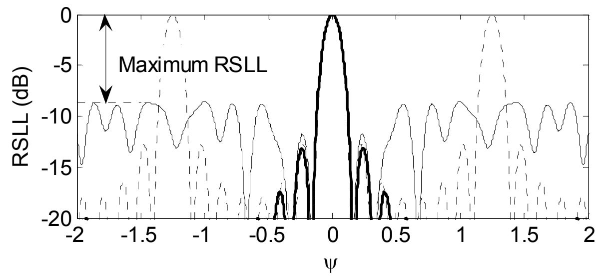

Fig. 1. Radiation patterns illustrating grating lobe reduction. Plotted for an array of 15 elemental antennas with 0.4 wavelength spacing (thick-solid), 8 elemental antennas with 0.8 wavelength spacing (dot) and 8 elemental antennas with aperiodic spacings occupying the same aperture (thin-solid).

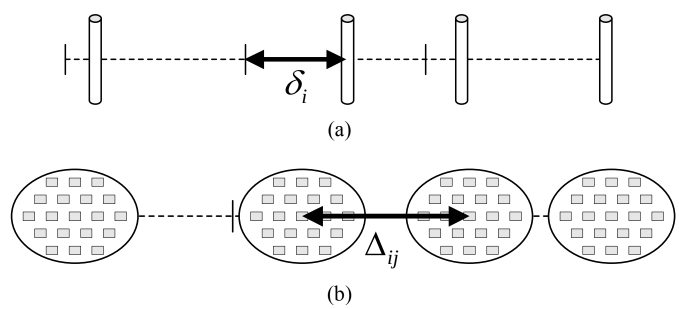

Fig. 2. (a) Aperiodic array of antennas having a negligible size along the axis of the array. (b) Aperiodic array of antennas that are physically large along the axis of the array, pictured as electronically-configured sub-array antennas. Antenna positions are described by the difference between the position of an antenna and its proximal grid (δ) or by the distance between the center-points of adjacent antennas (Δ).

II. GENETIC ALGORITHM

A genetic algorithm, or GA, is an iterative optimization algorithm designed to mimic the processes of evolutionary biology. The basic processes of a GA are well known [7] and are shown in Fig. 3. The GA employed in this study implements the concepts of mutation and crossover, and allows mutation to alter chromosome values by up to 10% during each generation. The GA stores values describing antenna positions, as in [6], instead of Boolean values describing the presence or absence of an antenna at a grid

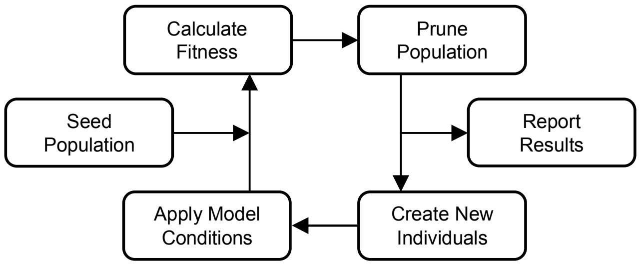

Fig. 3. Genetic algorithm processes.

point, as in [1]. The GA terminates after 20 generations without any improvement to the best solution, and each trial is repeated 10 times to ensure statistical reliability of the results. The fitness of individuals within the algorithm was defined by the inverse of the maximum relative sidelobe level, or –RSLL [1]. The algorithm maximizes the fitness of the population.

III. Calculating the Maximum Sidelobe Levels

A. Determining Sidelobe Levels

Because of the complexity in predicting the SLL exhibited by an array (the metric of performance), an efficient method of analysis is required. Simplistically, this requires determining the radiation pattern and finding the maximum value exclusive of the main lobe. For a linear array, the pattern is optimized at a maximum selected scan angle resulting in optimization at smaller angles down to broadside [6, 8]. However, because the width of pattern lobes changes as a function of angle, a simple algorithm can erroneously report the main lobe as a sidelobe, as shown in Fig. 4. The finding in [6] that linear arrays cannot be optimized for endfire pointing was probably due to this error. Uniform sampling of the pattern as a function of angle [6] also causes oversampling of the endfire lobes and reduces the speed of the algorithm.

B. Using a Pattern-Space Representation

A more efficient method, which has been used in previous studies, is to represent the radiation pattern in pattern-space. The pattern-space representation is obtained by examining the mathematical form of the beamformer. For a linear array distributed on the y-axis, the beamformer is given by

$$\mathbf{y} = \sum_{i=1}^{N} \exp\left[jkY_i \left(\sin\phi - \sin\phi' \right) \right], \tag{1}$$

where $\mathbf{y}$ is the output beam, $k = 2\pi/\lambda$, and Y_i represents the position of the i_{th} elemental antenna out of N total antennas. The angle ϕ represents the angle of arrival of a signal, and ϕ' indicates the steering direction of the array.

The pattern-space is obtained through the substitution $\Psi = \sin\phi - \sin\phi'$ [9], which has the range $\Psi = -\left(\sin\phi' \pm 1\right)$ for

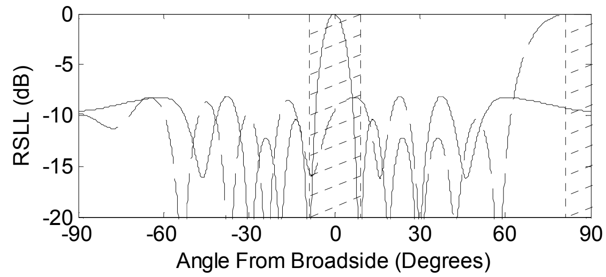

Fig. 4. Radiation pattern as a function of angle for a linear array. The main lobe of the endfire-pointed array extends past the allotted window (shaded).

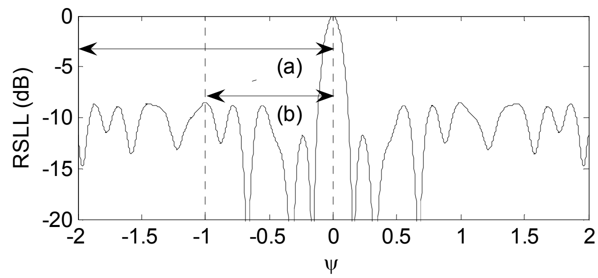

Fig.5. Pattern-space representation for a linear array. Scan range limits indicated for endfire optimization (a) and broadside optimization (b).

a total range of ± 2. The magnitude of (1) is symmetric about the main beam at $\Psi = 0$.

The optimization algorithm evaluates (1) between $\Psi = 0$ and $\Psi = 1 + \sin\phi'$, where ϕ' is the maximum scan angle, as shown in Fig. 5. The substitution of Ψ improves the speed of the algorithm and eliminates the varying lobe sizes. The pattern-space beamwidth of the main lobe is estimated from the aperture size, $BW \approx 1/\left(NS\right)$ [9], where S is the mean spacing between antennas.

IV. Array Models and Results

A. Basic Array Models

With an understanding of the optimization and analysis methods, we now proceed to the array models and optimization results. Two linear array models were examined. The first is the defined-aperture model, shown in Fig. 2a, which is similar to the model presented in [6]. The antenna positions are optimized with respect to their proximal grid points, which are distributed throughout the aperture at intervals of S. A minimum spacing filter forces the antennas to maintain a minimum distance from their neighbors and is used when the elemental antennas are large, such as in arrays of electronically steered subarrays or dish antennas [10, 11]

In the minimum spacing model, shown in Fig. 2b, each antenna's position is optimized relative to that of its nearest neighbors. This model is useful when the proximity of adjacent elemental antennas is restricted but the aperture size is unrestricted. Optimizing the minimum spacing model determines the best aperture size for a given minimum spacing.

B. Linear Array Results

Figures 8 through 9 contain plots of the sidelobe levels of the arrays for the linear array models discussed above. Fig. 8 shows the sidelobe level versus scan angle for the defined-aperture model with $S = \lambda$ and the results are consistent with the conclusions of Section III. The remaining plots are optimized for $\Psi = 0$ to 2, or an equivalent scan angle of $90°$.

Fig. 9 shows data from a defined-aperture model incorporating the minimum spacing requirement. Arrays using this model are characterized by their aperture ratio, defined as the minimum spacing between antennas divided by the average spacing between antennas. For aperture ratios less than 40%, the effect of the antenna size is negligible on the optimized sidelobe level. The sidelobe level increases slightly for aperture ratios between 40% and 60%, and increases significantly for aperture ratios above 80%. This data is consistent for arrays having different numbers of antennas and also different aperture sizes, as shown in the figure.

The 'x' marks in Fig. 9 indicate the optimized aperture ratio from the minimum spacing model for minimum spacings between 1.75λ and 3.75λ for arrays with 8 and 16 antennas. The optimized aperture ratios are grouped between 0.6 and 0.75. For a given minimum spacing, larger ratios represent smaller apertures but less optimization freedom. Smaller ratios represent more freedom at the cost of a larger aperture.

Fig. 10 shows that the incremental increase in sidelobe levels with increasing aperture size decreases as the aperture becomes large. Sidelobe levels are slightly increased when a given aperture size is found by the minimum spacing model.

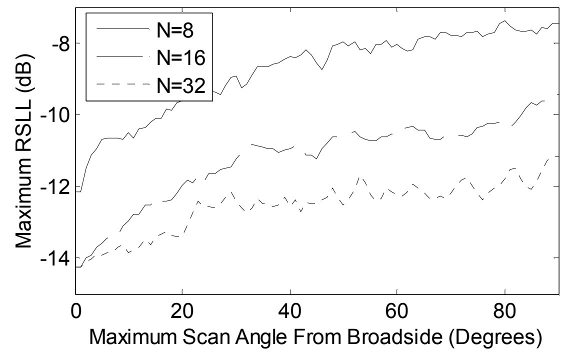

Fig. 8. Sidelobe level versus scan angle for aperiodic arrays. The defined-aperture model for small antennas is used.

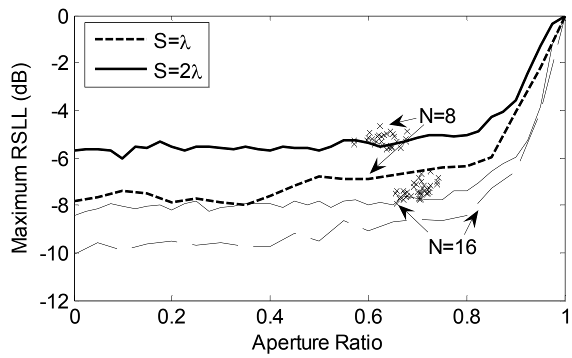

Fig. 9. Sidelobe level versus aperture ratio for the defined-aperture model with the minimum spacing requirement. Marks (x) indicate aperture ratios obtained from the minimum spacing model. The scan angle is 90°.

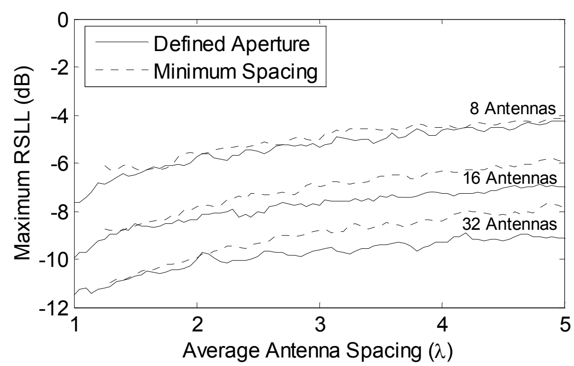

Fig. 10. Sidelobe levels versus antenna spacing for the linear array models.

V. Conclusions

Results from the optimization trials indicate some performance bounds for aperiodic linear arrays of physically large antennas. Most importantly, it was found that aperiodic placement techniques can effectively suppress grating lobes, even when the elemental antennas are more than several wavelengths in size. However, these techniques require a portion of the array to be reserved for the empty space between antennas, as is indicated by the aperture ratio. Finally, the sidelobe penalty incurred by the antenna size (found by the increased sidelobe level as compared to a similar array of isotropic antennas) was less than 2 dB for optimized aperture ratios using large antennas, as shown in Fig. 10.

References

[1] R. L. Haupt, "Thinned arrays using genetic algorithms," *IEEE Trans. Antennas Propag*., vol. 42, pp. 993-999, July 1994.

[2] A. Ishimaru, "Theory of unequally-spaced arrays," *IEEE Trans. Antennas Propag*., vol. 10, pp 691-702, Nov. 1962.

[3] R. L. Haupt, "Unit circle representation of aperiodic arrays," *IEEE Trans. Antennas Propag*., vol. 43, pp. 1152-1155, Oct. 1995.

[4] A. Camps, A. Cardama, and D. Infantes, "Synthesis of large low-redundancy linear arrays," *IEEE Trans. Antennas Propag*., vol. 49, pp. 1881-1883, Dec. 2001.

[5] D. Werner, M. Gingrich, and P. Werner, "A self-similar fractal radiation pattern synthesis technique for reconfigurable multiband arrays," *IEEE Trans. Antennas Propag*., vol. 51, 1486-1498, July 2003.

[6] M. G. Bray, D. H. Werner, D. W. Boeringer, and D. W. Machuga, "Optimization of thinned aperiodic linear phased arrays using genetic algorithms to reduce grating lobes during scanning", *IEEE Trans. Antennas Propag*., vol. 50, pp. 1732-1742, Dec. 2002.

[7] R. L. Haupt, "An introduction to genetic algorithms for electromagnetics," *IEEE Antennas Propag. Mag*., vol. 37 pp. 7-15, April 1995.

[8] B. K. Chang, X. Ma, and H. B. Sequeira, "Minimax-maxmini algorithm: a new approach to optimization of thinned antenna arrays," *1994 AP-S Int'l Symp. Digest,* vol. 1, pp 20-24.

[9] R. C. Hansen, Phased Array Antennas, New York: Wiley, 1998.

[10] D. Popovic, Z. Popovic, "Multibeam antennas with polarization and angle diversity," *IEEE Trans. Antennas and Propag*., Special Issue on Wireless Communications, pp. 651-657, May 2002.

[11] M. A. Ingram, W. C. Barott, et al., "LEO downlink capacity analysis for a network of adaptive array ground stations," presented at the 2005 Earth Science Technology Conf., Adelphi, MD, June 27-30.