A Review of High Performance Ultra-Wideband Antenna Array Layout Design

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***Abstract*—An overview of many of the new and powerful methods for generating ultra-wideband array layouts is given, focusing mainly on the contributions of the Computational Electromagnetics and Antennas Research Lab (CEARL) at Penn State. Evolutionary strategies and optimization algorithms are used exclusively with most of these design techniques, allowing for easy creation of arrays of various sizes and properties. These ultra-wideband array design methods span multiple dimensions, ranging from simple linear arrays to planar and volumetric types. A selection of design methods will be covered here along with example arrays, their performance, and suggested applications.**

Index Terms*—*Ultra-wideband array layout, optimization, evolutionary strategy.

I. Introduction

Since the introduction of the genetic algorithm (GA), researchers have found innovative and powerful means of applying optimization algorithms and evolutionary strategies to the design of ultra-wideband array layouts. These design techniques aim to create array layouts with radiation patterns (array factors) that possess low peak sidelobe levels and no grating lobes over large operating bandwidths. Traditional periodic arrays develop grating lobes, multiple maxima in the array factor, when the electrical distance between elements exceeds one wavelength (for an unsteered array). This limits the operating bandwidth of the array system to about 2:1 for typical antennas, which usually require an element spacing of at least $\lambda/2$ due to size and mutual coupling concerns [1].

Many of the recent array design techniques that have originated are coupled to the genetic algorithm. That is, the parameters which control the array geometry through the array representation technique are determined by the GA through its iterative optimization process. Some newer optimization methods such as the covariance matrix adaptation evolutionary strategy (CMA-ES) have been shown to demonstrate improved performance compared to more established algorithms such as the GA and particle swarm optimization (PSO) in electromagnetics design [2].

In this paper, an overview is provided of ultra-wideband antenna array layout design techniques, with a focus on those developed at the Penn State CEARL. The designs considered here cover linear, planar, and volumetric arrays with frequency bandwidths up to 10:1 and beyond. Most of the techniques employ one of the aforementioned optimization strategies in their design, however, not all do. As will be shown, the various design techniques offer tradeoffs between performance, simplicity, and ease of fabrication, as well as suitability to different array sizes.

II. Optimized Array Design

A. *Designs with the Genetic Algorithm*

Perhaps the most native application of the binary genetic algorithm (GA) to the design of array layouts is the on/off element control proposed in [3], where the GA was implemented to reduce the peak sidelobe level of a base periodic array. In [4], the GA was similarly applied to thin a periodic planar lattice of elements to obtain elliptical main beams, in addition to low sidelobe levels. A similar technique was used in [5] to create pattern nulls in the directions of array interference. Bandwidths for these design techniques are limited, however, due to the fact that the elements remain on a periodic lattice. One early method for true ultra-wideband array design is the polyfractal technique introduced in [6]-[10]. The GA was combined with a linear fractal array representation technique to determine an optimal arrangement of elements, yielding designs with array factors possessing peak sidelobe levels well below -15 dB over frequency bandwidths of 10:1 and beyond. This method particularly excels in creating very large arrays (1000+ elements) due to the geometry parameter reduction through the use of branch generators and connection factors. The UWB performance of several example polyfractal arrays is shown in Fig. 1. Very low peak sidelobe levels are observed over very wide bandwidths, especially for the largest array size of 1959 elements.

Another technique introduced in [9] termed raised-power series (RPS) arrays utilizes a simple mathematical expression coupled with a GA to capably design medium sized linear arrays (50-500 elements) with some geometric similarities that lends itself to ease of fabrication. For example, a 55-element array optimized at a minimum element spacing of 10 λ yielded a maximum peak sidelobe level of -9.6 dB. Typically, the arrays are assumed to operate at a minimum element spacing of 0.5 λ at their lowest frequency, a figure determined by antenna geometries which are usually on the order of a halfwavelength. In the case of the 55-element array optimized at d_{min} = 10 λ, a frequency bandwidth of 20:1 would be achieved.

The GA has also been used extensively in the design of planar aperiodic arrays in [9], [12]. These array layouts are based on a class of geometric patterns called aperiodic tilings. Elements are placed at the vertices of these tiles or at optimized locations inside of the tiles. The infinite lattice is then truncated to the desired size to form the full array geometry. Like the polyfractal method, this design technique is also capable of producing very robust ultra-wideband array layouts. Example array performances are given in Fig. 2. This method, as well as an adapted planar polyfractal technique, was used to design swarm antennas in [13] with special attention paid to the compensation of positional errors that are likely to occur in airborne applications.

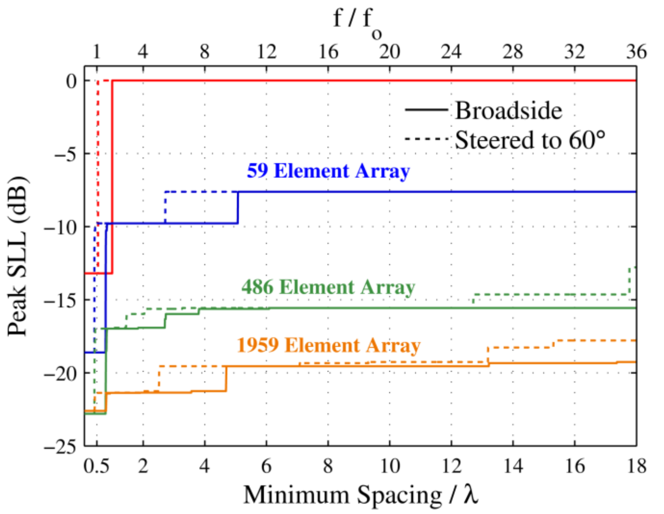


Fig. 1. Peak sidelobe level performance of various sized, optimized polyfractal arrays at broadside and when steered to ±60°.

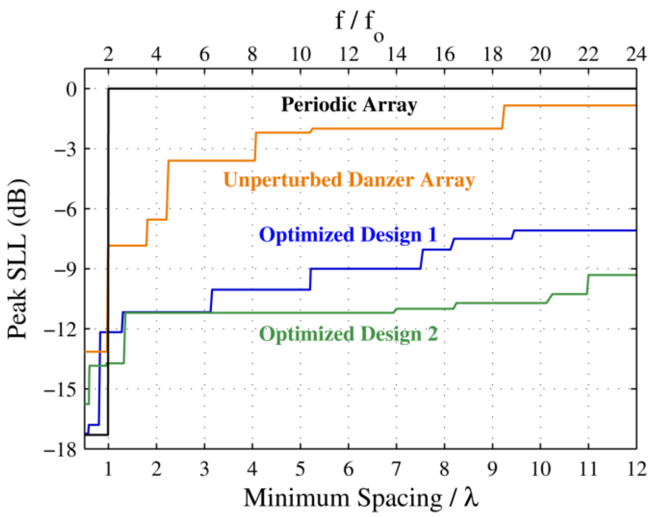


Fig. 2. Peak sidelobe level performance of various sized optimized arrays based on aperiodic tilings. The periodic array is the square-lattice variety. The unperturbed Danzer array (with elements at vertices) is truncated to 811 elements. Design 1 is an 811-element design optimized at d_{min} = 5 λ with one element per prototile. Design 2 is a 431-element design optimized at d_{min} = 6 λ with two elements per prototile.

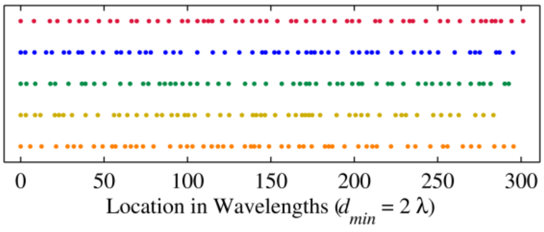
The use of aperiodic tiling was also extended to three dimensions in [14] to construct volumetric arrays based on a set of tetrahedral aperiodic tiles. A GA-optimized volumetric array was designed by controlling the positions of elements inside each of the four base tetrahedra, yielding a 720-element array with a peak sidelobe level below -10 dB over a 40:1 frequency bandwidth.

B. *Optimized Designs Using Alternative Algorithms*

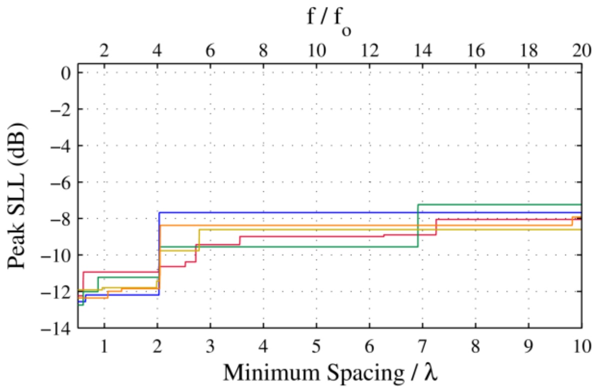
All of the previous techniques utilize some type of array representation methodology to define the array geometry. These are methods such as mathematical constructs that greatly reduce the number of optimizable parameters required to define the physical array geometries, often a necessity to design very large arrays (*i.e.* thousands of elements). For example, the polyfractal technique can be used to generate an array with thousands of elements using a few dozen parameters. This is very beneficial for creating large arrays, however, it can be somewhat constricting for smaller array designs, where a great deal of geometric flexibility is required to find the best solution (array layout).

Several new array design strategies have recently come about that take advantage of advances in evolutionary algorithms and increases in the capabilities of computer systems. In [15], a modified differential evolution algorithm was used to design linear aperiodic arrays with moderate amounts of bandwidth. This technique employed the algorithm to directly optimize spacings between elements, a method well suited for arrays with a relatively small number of elements.

In [2], CMA-ES was also applied to directly optimize the spacings between elements. For arrays up to 100 elements, the designs created with CMA-ES consistently outperformed the arrays created with PSO. In addition, several deigns were evolved that matched the size of a 46-element polyfractal array and the 55-element design from [11], far exceeding the performance attained with the previous techniques. Designs were created to compete with the 59-element polyfractal array shown in Fig. 1 as well. In Fig. 3, five identical optimizations (to obtain some statistical significance of the algorithm's performance) were carried out using a population size of 50 and terminating at 5000 iterations; the resulting arrays all have performance that far exceeds the polyfractal counterpart.



(a)



(b)

Fig. 3. Array layouts (a) and bandwidths (b) of five 59-element arrays optimized at d_{min} = 2 λ designed to compete with the 59-element polyfractal array shown in Fig. 1. All of the arrays have a peak sidelobe level lower than -10.9 dB at d_{min} = 2 λ.

Planar arrays are required when the main beam must be directional or steered in two dimensions (φ, θ). In [16], the relatively new invasive weed optimization (IWO) algorithm was used to design small thinned, aperiodic planar arrays. In planar array design, circular apertures are popular due to their intrinsic circular main beams. In [17], for example, a circular aperture was sparsely populated with rings of elements to create arrays with low sidelobe levels. This class of arrays, which intrinsically lack translational symmetry, naturally lend themselves to wideband operation.

A planar array design technique similar to that of the previous linear array design was explored in [18], where CMA-ES was applied to optimize the locations of elements in one slice of a planar rotationally symmetric array. These designs not only yield impressive performance, but also lend themselves to fabrication simplicity through the same mechanism used to reduce the problem size (*i.e.* the rotational symmetry). For example, the 220-element array shown in Fig. 4 that is 11-fold symmetric offers a peak sidelobe level of -16.2 dB over a 9.4:1 bandwidth and less than -12 dB up to a 20:1 bandwidth as shown in Fig. 5. This design uses 20 elements per rotationally symmetric tile; each (r,φ) position is determined by CMA-ES, resulting in a 40-dimensional optimization problem.

This size of the optimization problem has been shown to be well within the capabilities of CMA-ES. A 40 element per tile design with 15-fold symmetry has also been created to yield a 600-element array. The design targeted a minimum element spacing of 2.5 λ (5:1 frequency bandwidth), with a minimum element spacing of 2.68 λ achieved. An impressive peak sidelobe level of -18.9 dB was achieved, with the full bandwidth shown in Fig. 5.

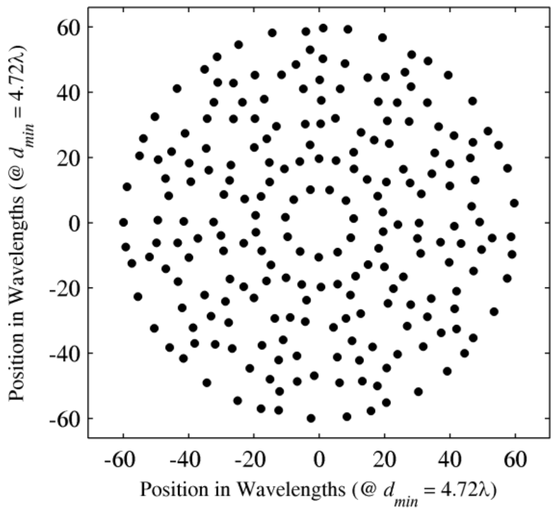


Fig. 4. Physical layout of the optimized 220-element rotationally symmetric array.

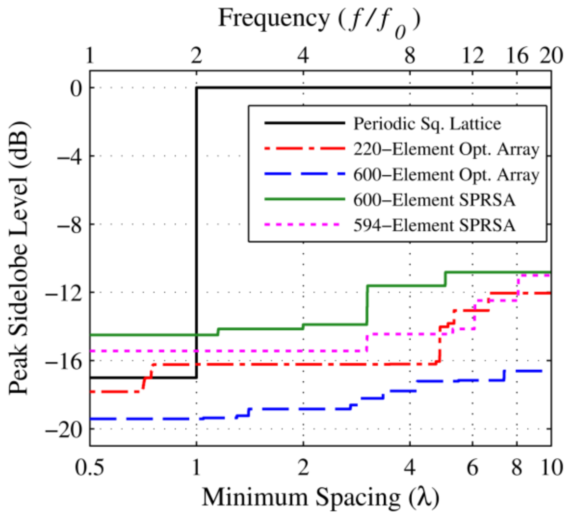


Fig. 5. Bandwidth of two optimized and two unoptimized, semi-periodic rotationally symmetric arrays. The 220-element and 594-element arrays are 11-fold symmetric. The 600-element optimized and semi-periodic designs are 15-fold symmetric. The 220-element design converged to d_{min} = 4.72 λ (5 λ target) while the 600-element design converged to d_{min} = 2.68 λ (2.5 λ target). The semi-periodic designs were configured at d_{min} = 2.5 λ.

III. Unoptimized Array Designs

In addition to the optimized array designs considered in the previous section, an unoptimized variation of the rotationally symmetric array layouts was also explored. This version uses the same type of rotationally symmetric tile, however, elements in a square or triangular periodic lattice are used to populate the sectors. In this manner, the array maintains a great deal of regularity, yet it is still void of full translational symmetry as in a standard periodic array.

A 600-element, 15-fold symmetric design in [18] offers a peak sidelobe level of -13.8 dB over a 5:1 frequency bandwidth and a 10:1 frequency bandwidth with a peak sidelobe level less than -10 dB. Performance is not as impressive as the optimized designs, however, the tradeoff for manufacturability may lend itself to more realistic array configurations. A similarly sized 11-fold, 594-element array was also created to observe the performance variations obtained by using different symmetries. The peak sidelobe level is slightly higher than the 15-fold counterpart, however, the simpler design may be more desirable from a manufacturing standpoint. As shown in Fig. 5, in addition to replicating the rotationally symmetric tiles to form a full array, the regularity of the elements inside the tiles allows for relatively simple corporate feed networks to be implemented.

IV. CONCLUSIONS

The array design techniques reviewed here cover linear, planar, and volumetric arrangements with array sizes ranging from a few to thousands of elements. Each method has different advantages and disadvantages which must be considered when choosing to create an array layout for a certain application. In any case, all of these innovative aperiodic array design techniques can offer significant performance advantages compared to standard periodic arrays and classical aperiodic designs such as purely random arrays.

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