A Decompose-Solve-Recompose (DSR) Technique for Large Phased Array Antenna Analysis

K. Y. Sze[1], K. F. Sabet[2] and D. Chun[3]

Abstract: **A novel spatial Decompose-Solve-Recompose (DSR) technique is demonstrated to be very attractive for analyzing uniform and non-uniform large phased array (LPA) antennas, because it can accurately account for array edge effects. A simple concurrent periodic/non-periodic analysis scheme, similar to that utilized in the Progressive Numerical Method (PNM), is presented for the modeling of planar large phased array antennas. The resulting 2D spatial DSR technique, known as the Hybrid Edge-Periodic DSR technique, requires the decomposition of a large planar array into an outer edge "ring" array and a central periodic array block.**

Index Terms: **spatial DSR, large phased array (LPA) antenna, PNM, periodic, non-periodic, Hybrid Edge-Periodic, uniform array, non-uniform array.**

I. INTRODUCTION

The full-wave analysis of large-scale phased array systems poses a very challenging computational electromagnetic problem. Conventional full-wave techniques such as the Method of Moments (MoM) can handle small- to medium-scale problems relatively easily. When the size of the array exceeds a hundred elements, full-wave techniques reach their limit of applicability. For larger arrays, periodic simulators are often utilized, whereby the array is assumed to have an infinite extent. However, periodic techniques cannot predict edge effects due to the radiating elements located at the boundary of the finite-size array structure. Therefore, it is essential to develop a technique that utilizes the full-wave analysis of the array in an efficient manner while being able to recognize the finite size of the array and account for the edge effects.

Several techniques are presently available in the literature on the analysis and design of large phased arrays. The truncated Floquet Wave/GTD formulation [1], [2] utilizes a Floquet mode truncation method to model a plane wave illumination of a large array of dipole elements in conjunction with the GTD technique to account for edge element diffractions. This approach was also extended to include a mildly tapered plane wave illumination of the dipole array [3]. Another new hybrid technique, the Discrete Fourier Transform/Moment Method (DFT-MoM) [4], also incorporates the high frequency GTD analysis to include edge diffractions. Additionally, for a large scatterer analysis, a relatively similar technique used is one that is based on MoM and combined with a new asymptotic formulation known as the asymptotic phase-front extraction (APE) [5]. This technique utilizes results from low frequency simulations to predict solutions at higher frequencies, so that computational effort and memory requirements are significantly reduced. Nevertheless, all these asymptotic techniques are generally very complex and are presently applicable only to simple geometries. In addition, a somewhat new matrix decomposition technique was introduced in [6], using the Generalized Forward-Backward Method (GFBM), in which the global impedance matrix is decomposed into forward and backward components instead of the submatrices. Although this is proven to be accurate and efficient for rough surface scattering problems, further studies are necessary to confirm its accuracy, efficiency and robustness applicable to large phased array analyses.

On the issue of mutual coupling in a non-uniform (aperiodic) array, papers [11]-[14] discussed some analysis methods using periodic sources for modeling a single source in an otherwise large uniform array, which is a singly-perturbed non-uniform array problem. Nevertheless, there is still a great demand for a more generalized method that handles a multiply-perturbed non-uniform array problem, and this is thus the focus of this paper.

In this paper, a brief overview is given of a proposed simpler concurrent periodic/non-periodic analysis scheme, the *Decompose-Solve-Recompose* **(**DSR**)** technique [7], adapted to the modeling of planar large phased array (LPA) systems. The resulting 2D spatial DSR technique, known as the Hybrid Edge-Periodic DSR technique, requires the decomposition of a large planar array into an outer edge "ring" array and a central periodic array block. In addition, its computation speed and efficiency may be further enhanced by means of a 2D Progressive Numerical Method (PNM) like algorithm described in [8]-[10]. An analysis using the Hybrid Edge-Periodic DSR technique is

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presented for uniform and non-uniform LPA examples, similar to that for the uniform 12x12-element LPA reported in [7]. These studies are part of an effort to understand the characteristics of the Hybrid Edge-Periodic DSR technique for applications to more general uniform and non-uniform LPA analyses and designs. Traditional approaches, such as, that computed by a brute force Method of Moments (MoM) technique, and a simpler approximation approach using the periodic array windowing approach, are employed for comparisons.

II. HYBRID EDGE-PERIODIC DSR TECHNIQUE

A 2D spatial DSR analysis, using the Hybrid Edge-Periodic DSR technique, is employed for the modeling of a planar array of dipoles depicted schematically in Fig. 1. This DSR technique is new, and involves the decomposition of an LPA into an outer edge "ring" array and a central block of periodic array, as shown in the figure. Each of these decomposed arrays are solved independently using the full-wave MoM (or any other full-wave analysis methods), and subsequently, recomposed back as a solution to the original problem.

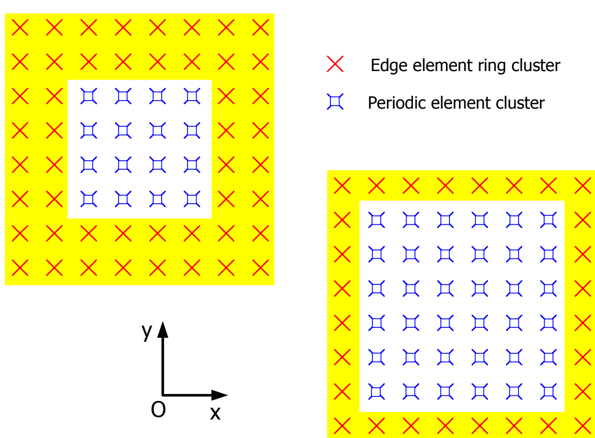


Fig. 1: Discarding an edge element ring for an 8x8 planar array using the Hybrid Edge-Periodic DSR technique. The original edge element ring cluster (top left) is 2 rings wide, and with the second ring in the cluster discarded (i.e. overlapped by the periodic element cluster), only the first ring is retained (bottom right).

Additional improvements of the Hybrid Edge-Periodic DSR technique may be achieved through the use of region "overlapping" between edge rings and the periodic array block, as implemented similarly in a PNM algorithm in [8]. An optimal choice of edge element ring width can also yield better accuracy. The mechanism of region "overlapping" requires that inner edge rings be discarded and outer rings retained during the recomposition of solution. Periodic elements are then substituted in their place so that the final solution will still represent the correct number of array elements and their spatial positions in Euclidean space, as illustrated in Fig. 1. That is,

$$\text{Total Rings} = \text{Rings Retained} + \text{Rings Discarded}. \quad (1)$$

These discarded rings actually served as "pawns" for approximating the mutual coupling effects on the rings retained.

Fig. 2 shows a matrix block representation of a decomposed full-wave MoM impedance matrix, consisting of different submatrix blocks. These blocks are $[A_a]$, $[A_b]$, $[A_c]$, $[A_{ctr}]$ and $[A_{edg}]$, which respectively represent couplings (interactions between basis and test functions) between elements in the overlap and edge ring regions, overlap and central block regions, overlap region only, central block region only, and edge ring region only.

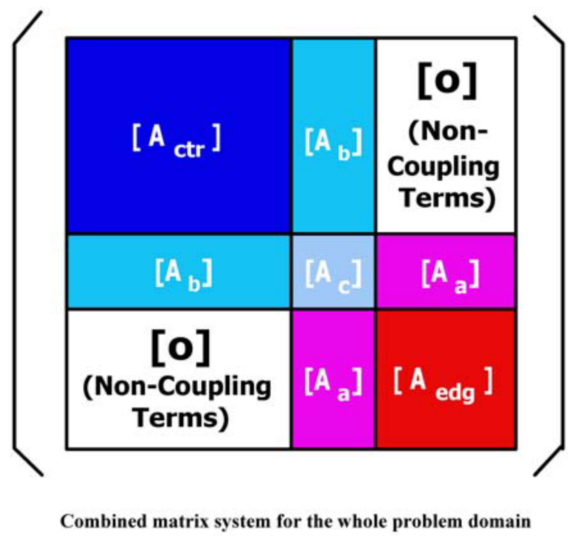


Fig. 2: Decomposed matrix blocks of the full-wave MoM impedance matrix.

However, this combined matrix system is not directly solved as a single matrix system, but rather, as two separate smaller matrix problems. In particular, one solution is computed for the central block of periodic array, and another for the edge ring array. Mathematically, this method may also be considered as a form of matrix decomposition technique, with its methodology based on physical 2D spatial decomposition. Further detailed mathematical formulations are found in [9], [10].

For the central block region, with the solution (current) vector assumed as $[\,c_{ctr}\ \ c_b\,]^{-1}$ and the voltage vector represented as $[\,b_{ctr}\ \ b_c\,]^{-1}$, the submatrix equation becomes

$$[\,A_{ctr}\,][\,c_{ctr}\,] + [\,A_b\,][\,c_b\,] = [\,b_{ctr}\,], \quad (2)$$

$$[\,A_b\,][\,c_{ctr}\,] + [\,A_c\,][\,c_b\,] = [\,b_c\,]. \quad (3)$$

Similarly, for the edge ring region, with solution (current) vector $[\ c_a \ \ c_{edg}\ ]^{-1}$ and voltage vector $[\ b_c \ \ b_{edg}\ ]^{-1}$, the submatrix equation becomes

$$[\,A_c\,][\,c_a\,] + [\,A_a\,][\,c_{edg}\,] = [\,b_c\,], \quad (4)$$

$$[\,A_a\,][\,c_a\,] + [\,A_{edg}\,][\,c_{edg}\,] = [\,b_{edg}\,]. \quad (5)$$

Subsequently, by recomposing the solution vectors of (2) through (5) into a new single solution vector, which becomes $[\ c_{ctr} \ \ c_b \ \ c_{edg}\ ]^{-1}$, with the subvector $[\ c_a\ ]$ discarded.

For the modeling of an LPA on a platform in the vicinity of objects such as screws, fasteners and pins, as schematically depicted in Fig. 3, the Hybrid Edge-Periodic DSR technique can be employed, with additional considerations for adjacent objects to be solved as part of the edge element array in the DSR algorithm. For the ease of developing the DSR technique, however, uniform and non-uniform LPAs are utilized as simple test examples in the proving of concepts in this paper, since their radiation behaviors are generally well understood.

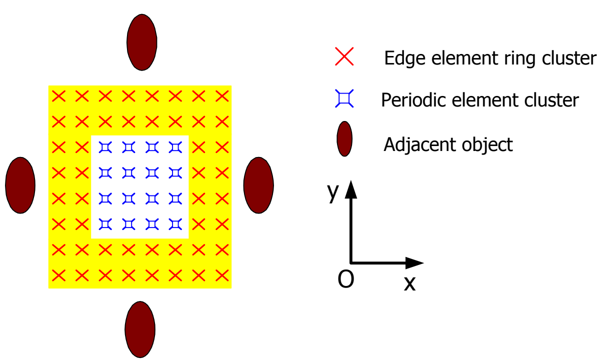


Fig. 3: Schematic of a Hybrid Edge-Periodic DSR model for the analysis of an LPA in the vicinity of other objects.

III. LARGE PHASED ARRAY MODELS

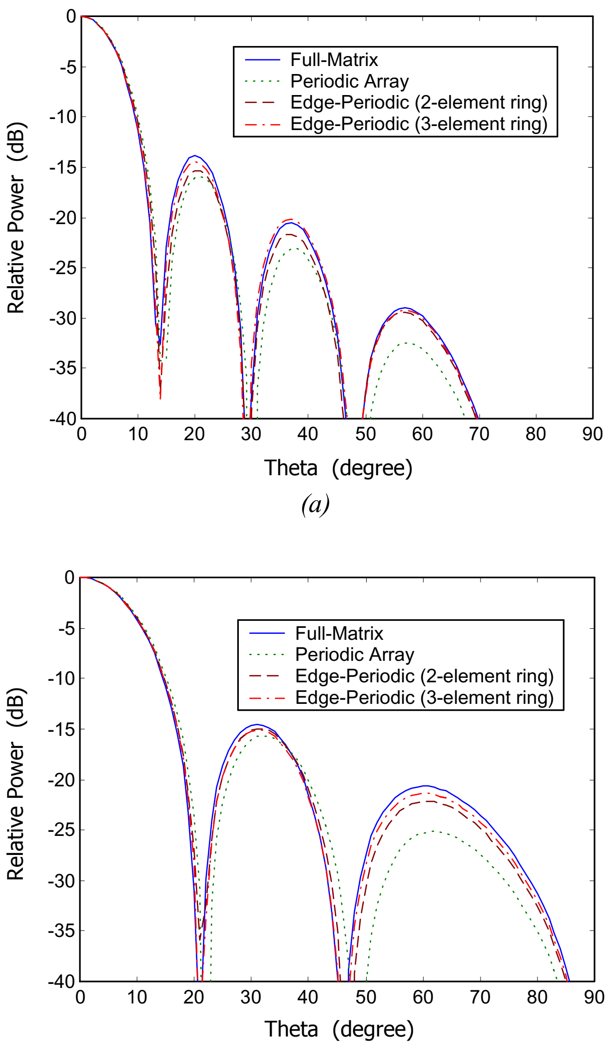
In this analysis, a uniformly-excited 8x8-element array of microstrip dipoles etched on a foam substrate (ε_r=1.03) of thickness 0.19λ_o is employed, with dipole length and width being 0.39λ_o and 0.002λ_o, respectively, and element spacings in the x- and y-directions being 0.5λ_o and 0.333λ_o, respectively. The accuracy of this spatial DSR technique over the traditional periodic array windowing approach is also investigated for a 24x24-element uniform array of microstrip dipoles etched on a ε_r=2.2 substrate of thickness 0.188λ_d, where $\lambda_d = \lambda_o/\sqrt{\varepsilon_r}$. The array dipoles are center-fed, each having a length and width of 0.578λ_d and 0.003λ_d, respectively, and their center-to-center element spacings in the x- and y-directions are 0.742λ_d and 0.494λ_d, respectively. These dipoles are oriented parallel to the x-axis, giving an E_x field polarization. The full-wave MoM solutions are computed using *EM*PiCASSO, a well-established commercial EM CAD software tool from EMAG Technologies, Inc.

For the 24x24-element array, the full-matrix solution is equivalent to the case having a total of 12 square rings with no rings discarded (i.e. with no periodic element utilized in the DSR modeling), while the periodic array windowing solution is equivalent to that without any rings (i.e. with only periodic elements utilized in the DSR simulation). For example, a zero number of rings corresponds to a windowed periodic array solution. For a total number of rings between these two extremes, results obtained are from combinations of solutions for both edge rings and inner periodic elements. The amount of region overlap is thus implicitly represented by the number of rings discarded.

Extending the modeling to a non-uniform LPA, the uniform 24x24-element LPA is subsequently modified to consist of 48 cross-polarized dipoles arranged alternately at the array edge. A similar DSR procedure is then utilized for this non-uniform case.

IV. FAR-FIELD RADIATION CHARACTERISTICS

Far-field radiation characteristics for the uniform 8x8-element LPA are computed using the full-matrix (full-wave exact solution), periodic array windowing and Hybrid Edge-Periodic DSR (using 2 and 3 edge element rings without any region overlap) techniques. Thus, directivities computed for this LPA are 21.670dBi, 21.590dBi, 21.644dBi and 21.671dBi, respectively. These techniques all exhibit good accuracy, with the 3-element ring Hybrid Edge-Periodic approach producing the best accuracy. Fig. 4 illustrates the far-field radiation patterns of this LPA. The Hybrid Edge-Periodic technique with both 2- and 3-element rings shows excellent agreement with the full-matrix solution. Although results for the periodic array windowing technique indicate relatively good accuracy for near broadside observation angles, its predictions of side-lobe levels (SLL) at far observation angles incur large errors. The Hybrid Edge-Periodic technique, on the other hand, significantly improves this discrepancy.



(b)

Fig. 4: Far-field radiation patterns of a uniform 8x8-element array of microstrip dipoles etched on a foam substrate (ε_r=1.03) of thickness 0.19λ_o: (a) E-plane, and (b) H-plane. Dipole lengths and widths are 0.39λ_o and 0.002λ_o, respectively, and element spacings in the x- and y-directions are 0.5λ_o and 0.333λ_o, respectively.

Far-field radiation characteristics for the uniform 24x24-element LPA are computed using the same full-matrix, periodic array windowing and Hybrid Edge-Periodic DSR techniques described above. Their far-field radiation patterns are shown in Fig. 5, and their corresponding directivities are 30.89dBi, 30.94dBi and 30.87dBi, respectively. For the Hybrid Edge-Periodic modeling, radiation patterns are obtained using a total of 7 edge element rings with a 4-ring overlap. With realistic array edge effect incorporated into the analysis, this model predicts pattern SLL with good accuracy. More accurate SLL may be obtained through the use of an optimal choice of the number of edge rings and overlapping. For the periodic array windowing approach, on the other hand, distinct nulls are predicted which are especially unrealistic in the H-plane.

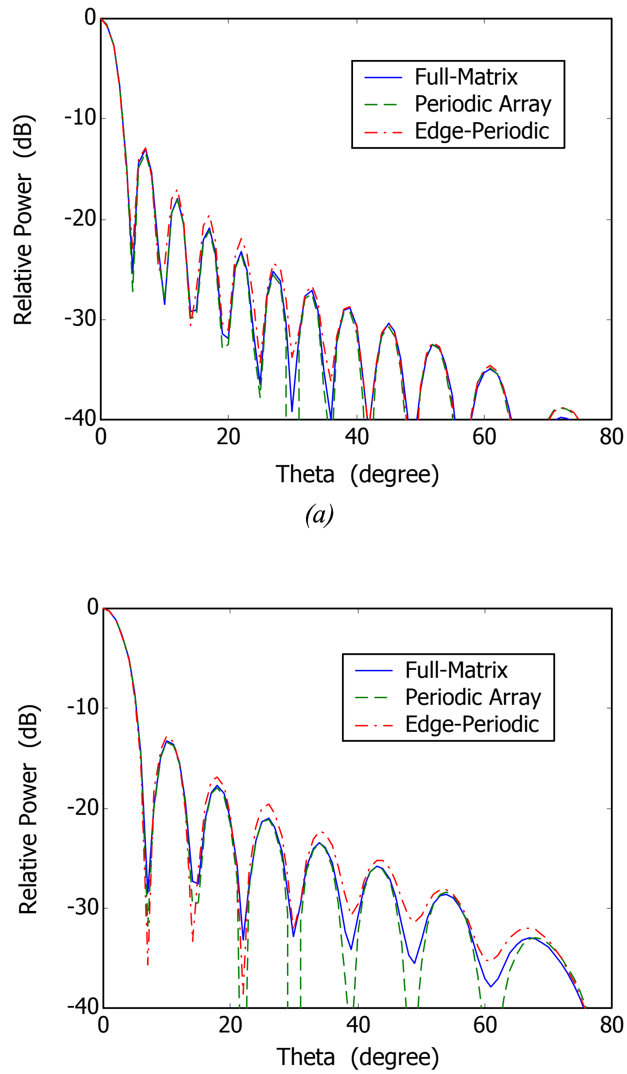


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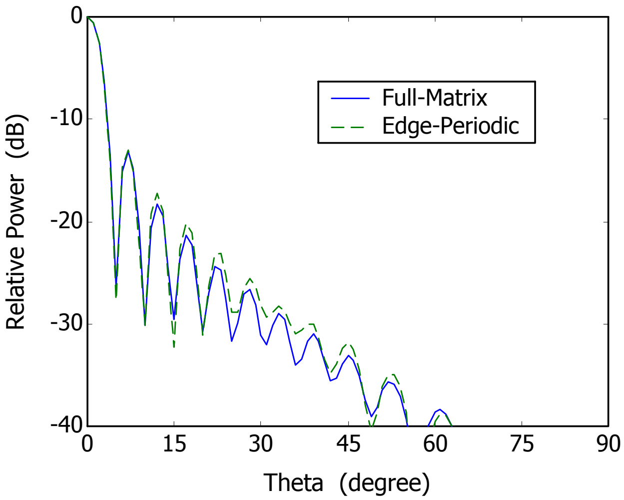
Fig. 5: Far-field radiation patterns of a uniform 24x24-element array of microstrip dipoles etched on a ε_r=2.2 substrate of thickness 0.188λ_d (where $\lambda_d = \lambda_o/\sqrt{\varepsilon_r}$), obtained using different techniques: (a) E-plane, and (b) H-plane. Oriented parallel to the x-axis, the dipoles have lengths and widths 0.578λ_d and 0.003λ_d, respectively, and element spacings in the x- and y-directions are 0.742λ_d and 0.494λ_d, respectively. The Hybrid Edge-Periodic results are computed using a total of 7 edge element rings with a 4-ring overlap.

In addition, the Hybrid Edge-Periodic DSR technique is capable of accurately predicting far-field radiation characteristics of a non-uniform 24x24-element LPA, as illustrated in Fig. 6 and Fig. 7. For this case, directivities for the full-matrix and Hybrid Edge-Periodic techniques are 30.48dBi and 30.51dBi, respectively, and their cross-polarized "main" lobes are 18.90dB (for full-matrix approach) and 18.49dB (for Hybrid Edge-Periodic technique) below their co-polarized counterparts, respectively.



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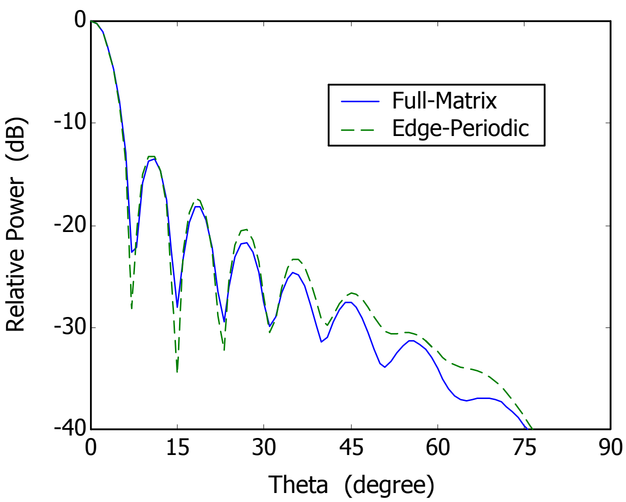
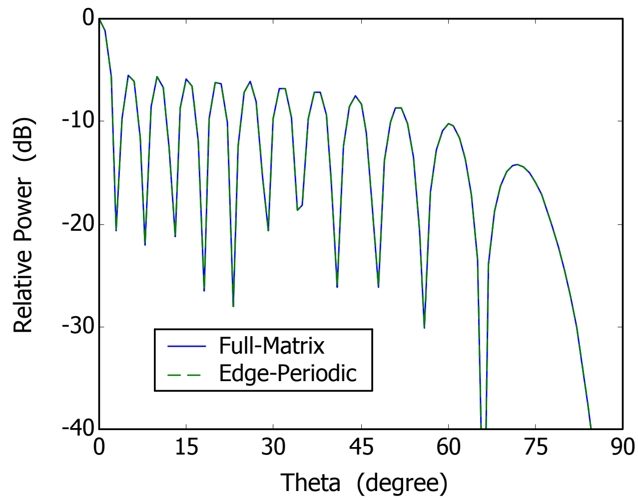


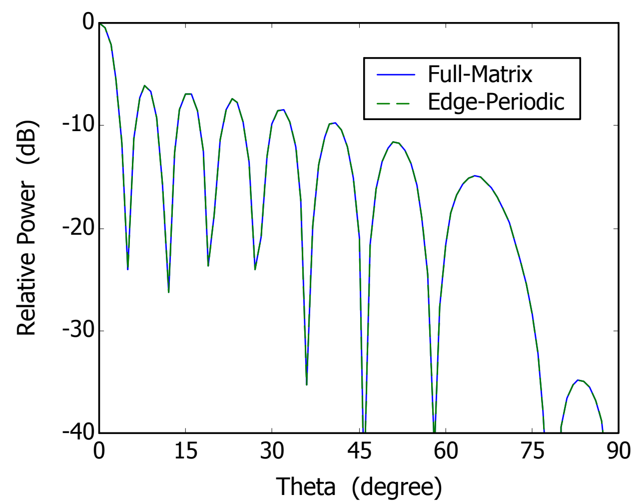
(b)

Fig. 6: Co-polarized far-field radiation patterns of a non-uniform 24x24-element array of microstrip dipoles: (a) E-plane, (b) H-plane. Hybrid Edge-Periodic plots are non-optimal results computed using a total of 7 edge element rings with a 4-ring overlap, while all other array parameters are the same as in Fig. 5.

Fig. 7 also demonstrates that very accurate cross-polarization results can be achieved through the Hybrid Edge-Periodic technique. This is attributed to the cross-polarized fields, which are contributed only by the y-directed dipoles at the array edge, as being solved using the full-wave MoM as part of the edge ring array, and that, there is no coupling of these y-directed dipoles with elements beyond a 6-element distance. Furthermore, with a proper choice of the number of edge rings and overlapping utilized, co-polarized radiation patterns can be further improved as well.



(a)



(b)

Fig. 7: Cross-polarized far-field radiation patterns of a non-uniform 24x24-element array of microstrip dipoles: (a) E-plane, (b) H-plane. All array parameters are the same as in Fig. 6.

V. COMPUTATIONAL PERFORMANCE

CPU times and memory storage requirements for simulations of the uniform 12x12- and 24x24-element LPAs are briefly investigated in this section. More rigorous quantitative studies and benchmarkings of these are necessary, which will be addressed separately.

A cost function analysis using the Hybrid Edge-Periodic DSR technique is also presented in this section for the non-uniform 24x24-element LPA described in Section IV. A similar analysis for the uniform 12x12-element LPA was reported in [7]. These are part of an effort to determine the accuracy of the solutions obtained and to understand the convergence characteristics of the DSR technique.

Table 1 compares the CPU times for modeling a uniform 12x12-element LPA using the Hybrid Edge-Periodic DSR technique, with 23 mesh segmentations on each dipole element. As compared to that of the full-matrix MoM simulation (full-wave MoM simulation), the number of unknowns required using this technique is reduced by approximately 25%, and its CPU time is decreased by more than 55%. From Table 2, its memory storage size is also decreased by more than 40%. Nonetheless, the conventional periodic array windowing technique (which does not account for finite array edge effects) is still the most computationally cost efficient technique of the 3 cases investigated, if array edge effects can be neglected.

Table 1: Comparisons of CPU times and the number of unknowns required for simulating a uniform 12x12-element LPA at 23 mesh segmentations per dipole element.

Computational technique	***Number of unknowns****	***CPU time* (minutes)***
Full-matrix MoM	3312 (100%)	187.8 (100%)
Periodic array	23 (0.69%)	0.02 (0.01%)
Hybrid Edge-Periodic (3 edge element rings, with 1-ring overlap)	2507 (75.69%)	80.3 (42.76%)

** Values in parentheses are relative percentages to that of the full-matrix MoM simulation.*

Table 2: Comparisons of memory storage sizes for simulating a uniform 12x12-element LPA at 23 mesh segmentations per dipole element.

Computational technique	***Memory* (MB)***
Full-matrix MoM	822 (100%)
Periodic array	0.04 (0.005%)
Hybrid Edge-Periodic (3 edge element rings)	471.1 (57.31%)

** Values in parentheses are relative percentages to that of the full-matrix MoM simulation.*

As for the uniform 24x24-element LPA, modeled using 8 mesh segmentations per dipole element, the number of unknowns required is reduced by more than 55%, and more than 15%, for the case of 3 and 7 edge element rings, respectively. These results are as presented in Table 3. Their memory storage sizes are also decreased by more than 80%, and more than 30%, respectively (also shown in Table 3).

These observations of results from Table 1 through Table 3 indicate, that, the larger the array size is, the greater is the computational cost saving in terms of CPU time and memory storage requirements.

Table 3: Comparisons of memory storage sizes times and the number of unknowns required for simulating a uniform 24x24-element LPA at 8 mesh segmentations per dipole element.

Computational technique	***Number of unknowns****	***Memory* (MB)***
Full-matrix MoM	4608 (100%)	1590.9 (100%)
Hybrid Edge-Periodic (3 edge element rings)	2024 (43.92%)	307.1 (19.30%)
Hybrid Edge-Periodic (7 edge element rings)	3816 (82.81%)	1091.1 (68.58%)

** Values in parentheses are relative percentages to that of the full-matrix MoM simulation.*

For the non-uniform 24x24-element LPA, its cost function analysis results are illustrated in Fig. 8. A full-matrix solution (full-wave MoM solution) is used as exact solutions for comparing the errors in directivity. For instance, for the DSR modeling results shown in Fig. 6, the error in directivity is 0.03dB, which can be further improved if necessary. Although this error in directivity is relatively small, errors in its far-field radiation patterns can be significant.

The directivity sensitivities to total number of rings used, retained and discarded (overlapped) are also illustrated in Fig. 8. That is, the directivity becomes less sensitive as more rings are retained (or, less rings are discarded/overlapped), and the total number of rings utilized is increased. However, the computational cost is also increased. Nonetheless, two types of convergence behaviors are observed in the figures. Namely, a convergence occurs for an increasing total number of rings utilized, and another, for an increasing number of rings retained (or, for a decreasing number of rings discarded/overlapped). The cost function curves also appear to indicate a convergence to a non-zero dB error, which is mostly attributed to numerical round-off errors in the directivity computations. Thus, based on these observations, optimal DSR parameters for a best accuracy at minimal cost can easily be obtained from data in the figures.

The cost function analysis results for the uniform 24x24-element LPA, described in Section IV, can also be similarly determined. Nevertheless, the discarding of edge element rings is generally more expensive since more rings are necessary and the computational cost increases with the increasing number of total rings (due to the use of full-wave technique for the edge array computation).

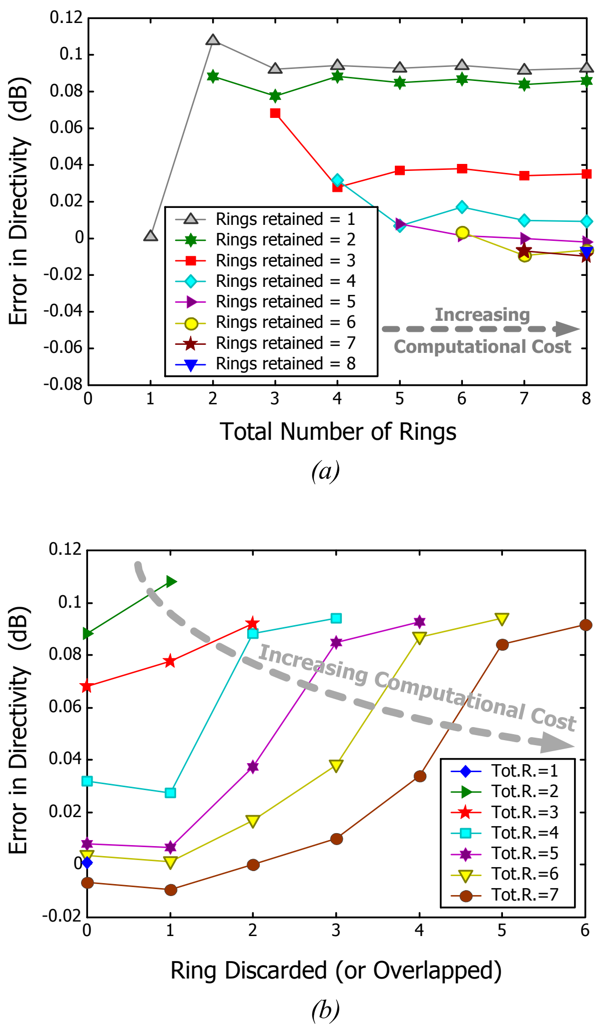


Fig. 8: Hybrid Edge-Periodic cost function curves for a non-uniform 24x24-element array: (a) effect of increasing number of rings retained, and (b) effect of overlapping regions, represented as rings discarded (where Tot.R. ≡ Total Rings), for a particular total number of rings. All other array parameters are the same as in Fig. 5.

VI. CONCLUSION

A region overlap mechanism, similar to that utilized in PNM, is implemented into a newly proposed Hybrid Edge-Periodic DSR technique for the 2D spatial DSR analysis of planar LPA systems. Simulations of the uniform 8x8- and 12x12-element LPAs, and both uniform and non-uniform 24x24-element LPAs, provide very good results and also demonstrate high computational efficiency. Although the periodic array windowing approach produces unrealistic distinct nulls in its far-field radiation patterns, but yields acceptable accuracy for a uniform LPA, the Hybrid Edge-Periodic DSR technique has proven to be more superior for a large-scale non-uniform LPA, and may be its only practical modeling solution. In essence, pattern improvements in the Hybrid Edge-Periodic method are generally attributed to the choice of optimal total number of edge rings and overlapping, which serve as important simulation criteria.

VII. ACKNOWLEDGEMENTS

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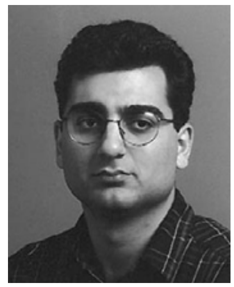

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