A DECOMPOSE-SOLVE-RECOMPOSE (DSR) TECHNIQUE FOR LARGE PHASED ARRAY ANALYSIS

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1. 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 the 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 presented for a uniform and non-uniform 24x24-element LPA, 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 Moment (MoM) technique, and a simpler approximation approach using the periodic array windowing approach, are employed for comparisons.

2. HYBRID EDGE-PERIODIC DSR TECHNIQUE

A 2D spatial DSR analysis, using the Hybrid Edge-Periodic DSR technique, is employed for the modeling 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 periodic array block, 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. Mathematically, this method may also be considered as a form of matrix decomposition technique, with its methodology based on physical 2D spatial decomposition.

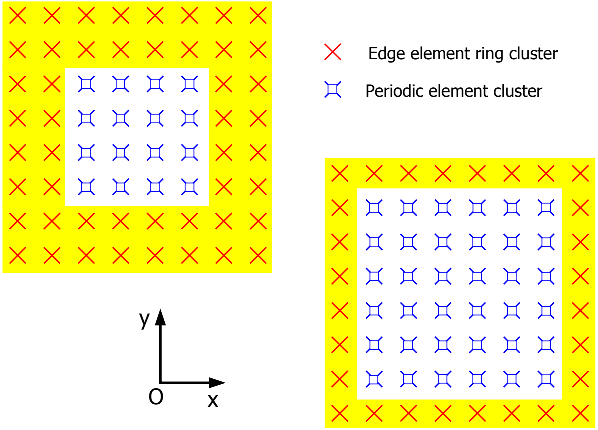


Fig. 1: Discarding an edge element ring for an 8x8 planar array using the Hybrid Edge-Periodic DSR technique. The original edge element ring cluster (top left) is 2 rings wide, and with the second ring in the cluster discarded (i.e. overlapped by the periodic element cluster), only the first ring is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

Additional improvements of the Hybrid Edge-Periodic DSR technique may be achieved through the use of region "overlapping" between the 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,

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

These discarded rings actually served as "pawns" for approximating the mutual coupling effects on the rings retained. Nevertheless, the discarding of edge element rings is generally more expensive since more rings are necessary and the computation cost increases with increasing number of total rings (due to the use of full-wave numerical methods for the edge array computation).

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 2, the Hybrid Edge-Periodic DSR technique will 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, since their radiation behaviors are generally well understood.

The accuracy of this spatial DSR technique over the traditional periodic array windowing approach is 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 solutions are computed using *EM*PiCASSO, a well-established commercial EM CAD software tool from EMAG Technologies.

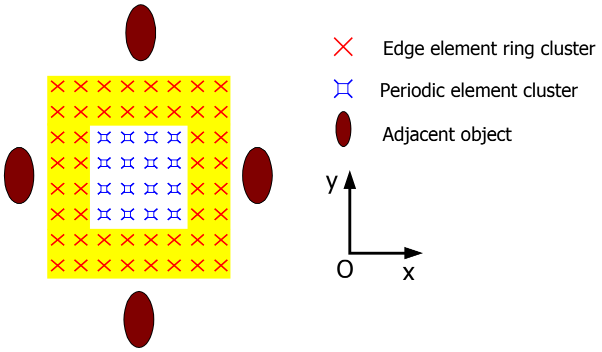


Fig. 2: Schematic of a Hybrid Edge-Periodic DSR model for the analysis of an LPA in the vicinity of other objects.

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, as depicted in Fig. 3. A similar DSR procedure is then utilized for this non-uniform case.

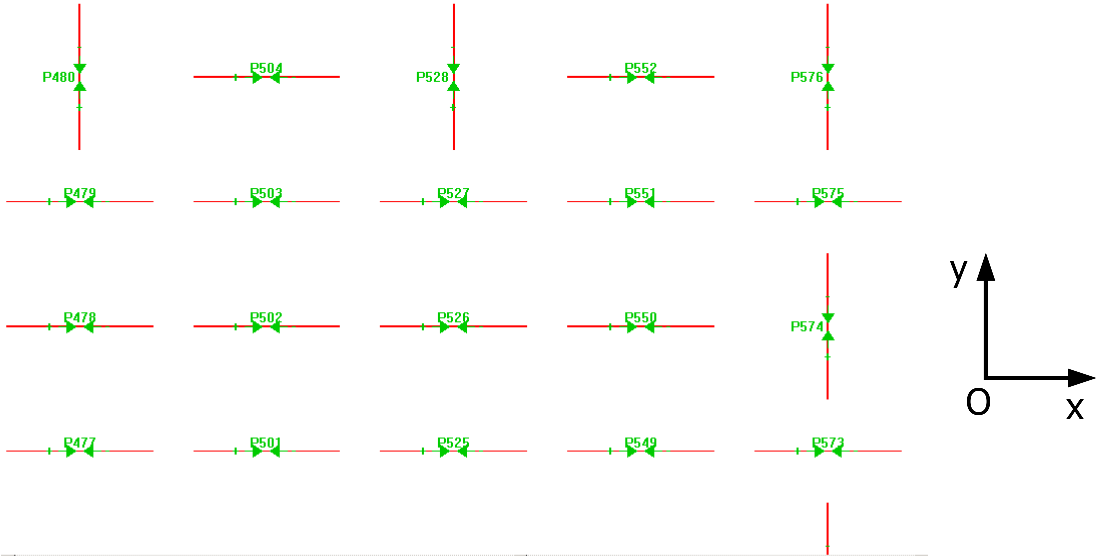
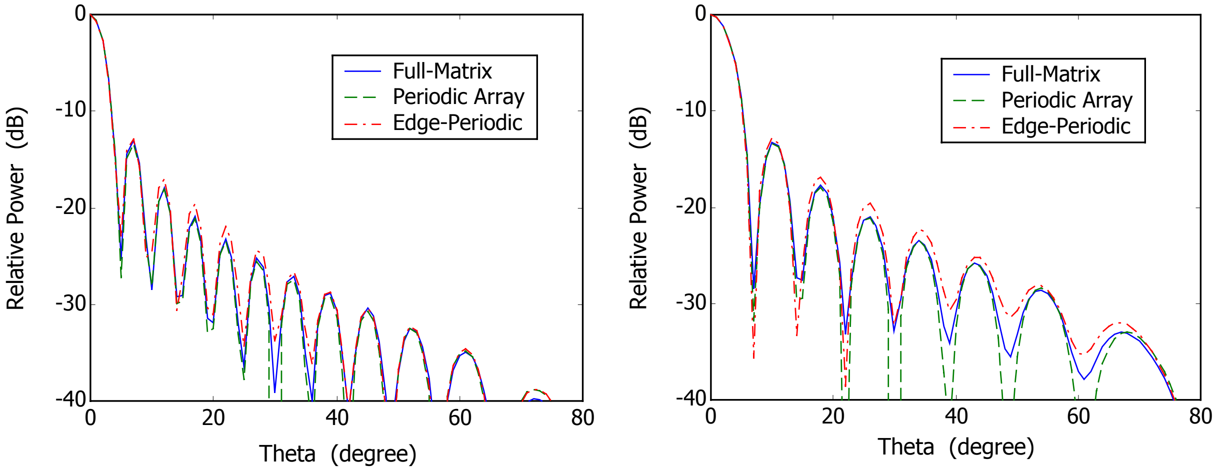


Fig. 3: A snap-shot of EMP*iCASSO GUI showing the top-right corner of a non-uniform 24x24-element microstrip dipole LPA configuration. A total of 48 y-polarized dipoles, arranged alternately, are utilized on the first edge ring only.*

3. FAR-FIELD RADIATION CHARACTERISTICS

Far-field radiation patterns for the uniform 24x24-element LPA are computed using the full-matrix (full-wave solution), periodic array windowing and Hybrid Edge-Periodic DSR techniques, and are shown in Fig. 4. Their corresponding directivities are 30.89dBi, 30.94dBi and 30.87dBi, respectively. For the DSR 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 side-lobe patterns with good accuracy. More accurate side-lobe levels (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.

In addition, the Hybrid Edge-Periodic DSR technique is capable of accurately predicting far-field radiation characteristics of the non-uniform 24x24-element LPA, as illustrated in Fig. 5. 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) and 18.49dB (for Hybrid Edge-Periodic) below their co-polarized counterparts, respectively. Fig. 5 also demonstrates that very accurate cross-polarization results can be achieved through the DSR technique. This is attributed to the cross-polarized fields, which are contributed only by the y-directed dipoles at the array edge, 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 field patterns can be further improved as well.



(a) (b)

Fig. 4: 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 DSR results are computed using a total of 7 edge element rings with a 4-ring overlap.

4. 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 both uniform and non-uniform 24x24-element LPAs provide very good results. Although the periodic array windowing approach yields acceptable accuracy for a uniform LPA, the 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 DSR method are generally attributed to the choice of optimal total number of edge rings and overlapping, which will be further discussed during presentation.

5. ACKNOWLEDGEMENTS

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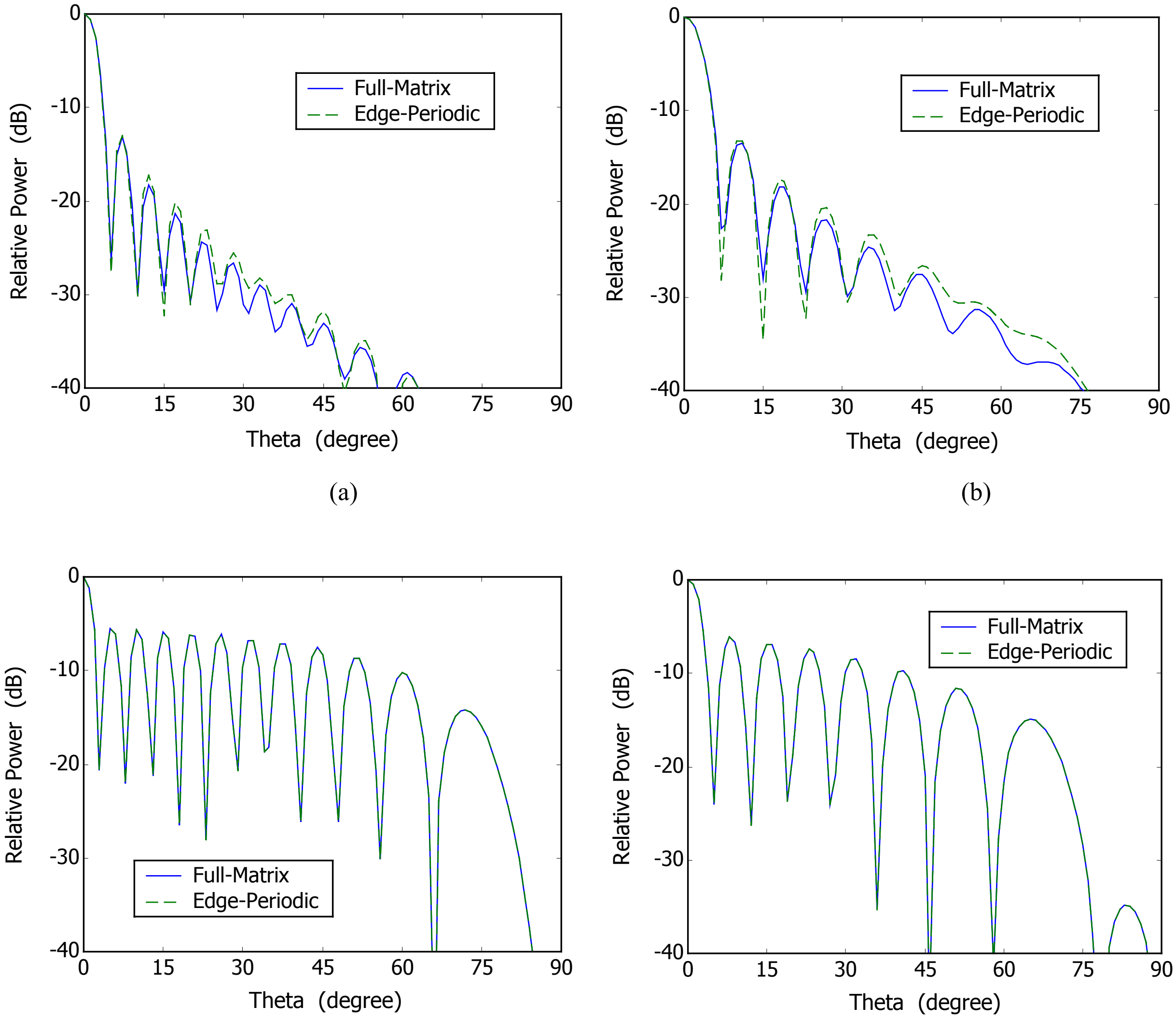

(a)

(b)

(c)

(d)

Fig. 5: Far-field radiation patterns of a non-uniform 24x24-element array of microstrip dipoles: (a) E-plane co-polarization, (b) H-plane co-polarization, (c) E-plane cross-polarization, and (d) H-plane cross-polarization. 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. 4.

6. REFERENCES

[1] Filippo Capolini, Matteo Albani, Stefano Maci and Leopold B. Felsen; "Frequency-domain Green's function for a planar periodic semi-infinite phased array -- Part I: Truncated Floquet wave formulation"; *IEEE Trans. Antennas and Propag.*, vol. 48, no. 1, January 2000; pp. 67-74.

[2] Filippo Capolini, Matteo Albani, Stefano Maci and Leopold B. Felsen; "Frequency-domain Green's function for a planar periodic semi-infinite phased array -- Part II: Diffracted wave phenomenology"; *IEEE Trans. Antennas and Propag.*, vol. 48, no. 1, January 2000; pp. 75-85.

[3] F. Mariottini, F. Capolino, S. Maci and L. B. Felsen; "High frequency Green's function for a rectangular array of dipoles with weakly varying tapered excitation", *2001 IEEE Antennas and Propag. Society International Symp.*, vol. 3, Boston, MA; July 2001; pp. 796-799.

[4] Hsi-Tseng Chou, Hsien-Kwei Ho, P. H. Pathak, P. Nepa and O. A. Civi; "A hybrid Discrete Fourier Transform – Moment Method for the fast analysis of large rectangular phased arrays", *2001 IEEE Antennas and Propag. Society International Symp.*, vol. 4, Boston, MA; July 2001; pp. 314-317.

[5] Do-Hoon Kwon, Robert J. Burkholder and Prabhakar H. Pathak; "Efficient method of moments formulation for large PEC scattering problems using asymptotic phasefront extraction (APE)"; *IEEE Trans. Antennas and Propag.*, vol. 49, no. 4, April 2001; pp. 583-591.

[6] H.-T. Chou; "Extension of the forward-backward method using spectral acceleration for the fast analysis of large array problems"; *IEE Proc. Microwaves, Antennas and Propag.*, vol. 147, no. 3; June 2000; pp. 167-172.

[7] K. Y. Sze, K. F. Sabet, T. Ozdemir and D. Chun; "A spatial decompostion technique for large phased arrays using region overlap"; *2002 Symp. on Antenna Technology and Applied Electromagnetics (ANTEM 2002)*, Montréal, Canada; July/August 2002; pp. 502-505.

[8] K. Y. Sze, K. F. Sabet, T. Ozdemir and D. Chun; "A PNM implementation for large phased arrays"; *2002 Symp. on Antenna Technology and Applied Electromagnetics (ANTEM 2002),* Montréal, Canada; July/August 2002; pp. 514-517.

[9] L. Shafai; "A progressive numerical method and its application to large field problems in antennas and electromagnetic scattering"; *Can. J. Elect. Eng*., vol. 2, no. 4; 1977; pp.17-23.

[10] Qiubo Ye; "Electromagnetic scattering by numerical methods applicable for large structures"; *Ph. D. Thesis*; University of Manitoba, Winnipeg, Manitoba; July 2000.

[11] Hung-Yu David Yang and Jianpei Wang; "Surface waves of printed antennas on planar artificial periodic dielectric structures"; *IEEE Trans. on Antennas and Propag.*, vol. 49, no. 3; March 2001; pp. 444-450.

[12] Hung-Yu David Yang; "Theory of microstrip lines on artificial periodic substrates"; *IEEE Trans. Microwave Theory and Techn.*, vol. 47, no. 5; May 1999; pp. 629-635.

[13] B. A. Munk and G. A. Burrell; “Plane-wave expansion for arrays of arbitrarily oriented piecewise linear elements and its application in determining the impedance of a single linear antenna in a lossy half-space”; *IEEE Trans. on Antennas and Propag.*, vol. AP-27, no. 3; May 1979; pp. 331-343.

[14] V. Galindo; “A generalized approach to a solution of aperiodic arrays and modulated surfaces”; *IEEE Trans. on Antennas and Propag.*, vol. AP-16, no. 4; July 1968; pp. 424-429.