Open-Circuit to Embedded Pattern Approach with Harmonic Optimization in ESPAR

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***Abstract*—The radiation characteristics of Electronically Steerable Parasitic Array Radiators (ESPAR) can be modified by changing the loads attached to the parasitic radiators. The open-circuit pattern to embedded pattern approach is employed to compute the radiation pattern, when dynamic loads are attached to the parasitic radiators. It provides results exactly matching to those of full-wave simulations without any approximation and it is computationally highly efficient in the optimization phase. The weighted mean squared error is used as a cost function for optimization to obtain the objective radiation pattern. The optimization is carried out using a harmonic decomposition of load values versus the position index of parasitic elements and it provides results within a minute with an average error below 1dB between objective radiation pattern and obtained radiation pattern within the main lobe.**

I. Introduction

Antenna arrays consisting of parasitic elements [1] are becoming popular these days as they are much cheaper than conventional fully active phased arrays. In the latter all antennas require separate expensive circuitry to control the relative phase and amplitude to steer the beam. Passive arrays or Electronically Steerable Parasitic Array Radiators (ESPAR) consist of one or more active antennas and multiple passive antennas placed in the near field of active radiators; the beam steering is implemented by varying the loads attached to the parasitic antennas [1]-[2]. Parasitic antennas are placed in close proximity to the active antennas to exploit the mutual coupling for beam steering. Mutual coupling depends on the structure of the array and also on the loads attached to the parasitic radiators. When the impedances attached to the parasitic radiators are varied, the boundary conditions at the parasitic ports are changed, so the parasitic elements scatter differently and in turn the radiation pattern of the whole array is modified. Varactor diodes can be used as dynamic loads, which can be controlled electronically [2].

The conventional phased array theory cannot be applied directly to the ESPAR antenna given the presence of mutual coupling and direct connection of variable loads to passive radiators. A previous approach consisted of modeling the currents on all antennas as a function of loads attached to the parasitic radiators. However such a model, expressed in [2]-[4], only holds for single-mode antennas i.e. antennas for which the current distribution may be considered constant, within a multiplying factor [11]-[12]. Only few antenna types satisfy this condition, for instance thin dipole antennas, except when placed in very dense arrays (spacing less than about $\lambda/4$). In [5] the developed array model works in agreement with the Method of Moments (MoM) simulations but the array model is specific to the IFA antenna array and cannot be applied to different types of antennas. Another approach could consist of performing the full-wave simulation in conjunction with the optimization algorithm [6] to find the optimized loads. In [3] the full-wave simulation is used but at each iteration the radiation pattern is represented by quadratic approximation. However the full-wave simulation for different combinations of loads makes the optimization process very time consuming.

The approach presented in this paper consists of using a model for parasitic arrays that does not entail any underlying approximation, such that it can be applied to any passive antenna array while preserving ultra-fast evaluation for efficient optimization. The open-circuit to embedded pattern model has been used here to express the radiation pattern of the ESPAR antenna in terms of loads attached to the parasitic radiators. A similar theory has been mentioned in [1] but the implementation is carried out using a single-mode approximation. In [7], outside the framework of arrays with parasitic elements, a similar approach has been used to compute the currents instead of computing directly the radiation patterns, for the case of loaded wire antennas.

The optimization problem faced here is a non-linear problem and different algorithms like genetic algorithm [6] or Hamiltonian dynamics [2] can be used to optimize the loads. The optimization technique proposed here uses the harmonic decomposition of loads and turns out to be very efficient.

The remainder of this paper is organized as follows: Sections II and III describe the fast full-wave analysis and optimization approach, respectively. The synthesized patterns are shown in Section IV and concluding comments are made in Section V.

978-1-5090-4837-3/17/$31.00

II. Open-Circuit To Embedded Pattern Approach

If MoM is used for the full-wave simulation, for each set of parasitic loads the exact currents on all the antennas need to be computed to calculate the radiation pattern. This approach is time consuming, since the MoM involves the computation of the inverse (or LU decomposition) of the impedance matrix, which can be very large. The optimization of parasitic loads becomes very tedious because for different combination of loads, the system of equations needs to be solved again. Therefore, in order to immensely speed up the computation without any approximation, open-circuit pattern to embedded pattern transformation is employed. The open-circuit pattern of an antenna in an array does not depend on the loads while the embedded element pattern does. So, the open-circuit patterns of all antennas (active or passive) are computed once and for all. Then all the embedded patterns for a given set of loads can be computed using the following relation [10]-[11]:

$$\bar{f}^e = (\bar{Z}^a + \bar{Z}^L)^{-1} \bar{f}^{O.C.} \quad (1)$$

Here $\bar{f}^e$ are the embedded patterns, $\bar{f}^{O.C.}$ are the open-circuit patterns, $\bar{Z}^L$ is the diagonal matrix containing the load impedances attached to the active and parasitic antennas, $\bar{Z}^a$ is the N-port impedance matrix containing mutual coupling information. In $\bar{f}^e$ and $\bar{f}^{O.C.}$ matrices each row corresponds to a given antenna and each column corresponds to a given direction. One should underscore that $\bar{Z}^a$ does not contain all the mutual coupling information, the missing information being provided by the open-circuit patterns. Equation 1 is used for computation of embedded patterns for all the antennas, for each polarization separately. After computing the embedded patterns the superposition of embedded patterns of only the active antennas, for each polarization is performed separately, which by definition gives the radiation pattern of the array for each polarization, knowing that the parasitic elements are not excited. Then the magnitude of radiation pattern of the array is computed from both polarizations. The matrix $(\bar{Z}^a + \bar{Z}^L)$ has dimensions equal to the number of loads, so its inverse can be computed much faster than that of MoM impedance matrix. Since the open-circuit patterns are computed only once, the computation of embedded patterns for different set of loads $\bar{Z}^L$ is extremely quick and simple.

III. Harmonic Optimization

Considering $\bar{f}(\theta, \phi)$ as the ESPAR antenna radiation pattern, $\bar{f}_{obj}(\theta, \phi)$ as the objective radiation pattern and $a(\theta, \phi)$ a weighting function, the cost function corresponding to the weighted mean square error is given below:

$$arg \min_{\bar{Z}_1,..\bar{Z}_N} \int_0^{2\pi}\int_0^{\pi} a(\theta,\phi)[|\bar{f}(\theta,\phi)| - |\bar{f}_{obj}(\theta,\phi)|]^2 sin\theta d\theta d\phi$$

The loads optimization is a non-linear problem, different algorithms can be used to find the set of loads that gives the radiation pattern close to the objective pattern. Here a different optimization approach has been utilized in which sweeping is done for a small subset of the combination of loads to minimize the cost function. The parasitic load values are decomposed into spatial harmonics according to the position of parasitic elements (supposing they are distributed along a line). For each harmonic, amplitudes and phases of loads are determined such that the sum of harmonics minimizes the cost function. The harmonics are optimized one-by-one starting with the lowest-order. This idea of harmonic decomposition of loads originates from the intuition that the slow variations of currents on the antenna affect the main beam while the fast variations affect the side lobes of the radiation pattern.

IV. Simulations

Simulations have been carried out, the bow-tie log antenna operating at 1.8 GHz (with 10:1 bandwidth) as an active element while 30 parasitic dipoles (3 rows and 10 columns) are placed in front of it and a back reflector is used as shown in Fig. 1. The parasitic dipoles of length $3\lambda/4$ with diameter of 0.06λ and 0.24λ spacing among them, are placed at a λ distance from the bow-tie log antenna. Each dipole has a load attached to its terminals. In case of only azimuthal beam steering, it makes sense to have the same load at the parasitic dipoles in one column. So, there are 10 different loads attached to 30 dipoles.

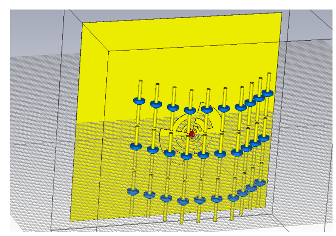
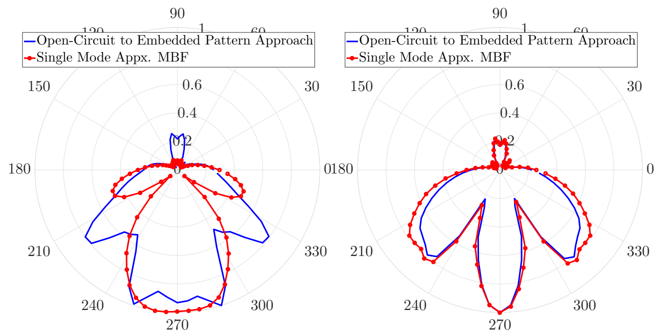


Fig. 1: ESPAR Antenna.

First a comparison between open-circuit to embedded pattern approach and single-mode approximation is made, the best available single-mode approximation is used for parasitic dipoles by using macro-basis functions (MBF) [9] with only one MBF per parasitic element. The comparisons for the cases of open-circuited parasitics and short-circuited parasitics are shown in Fig. 2 (no optimization is carried out at this point). The difference between the results obtained with those two approaches is larger for the case of open-circuited parasitics than for the case of short-circuited parasitics. This depicts the shortcomings of the single-mode approximation.

A comparison between computation time is made for the full-wave simulation and the open-circuit to embedded pattern approach to show its computational advantage during load optimization, keeping in mind that, down to machine precision, both approaches provide the same result. The simulations are executed on an i7 PC with 3.40 GHz processor, 16 GB RAM and 64-bit operating system.

It can be seen from Table I that the open-circuit pattern computation time is similar to that of the full-wave simulations (order of half an hour) but the embedded pattern computation time is order of milliseconds. With the full-wave simulation, the computation of the cost function would take



(a) (b)

Fig. 2: E-field radiation pattern of array with (a) open-circuited parasitics (b) short-circuited parasitics at 1.8 GHz.

TABLE I: Computation Time Comparison

Full-wave simulation computation time (sec)	Open-circuit pattern computation time (sec)	Embedded pattern from open-circuit pattern, computation time (sec)
$1.804\text{x}10^3$	$1.858\text{x}10^3$	0.0048

the same time for each set of loads. For instance, if 1000 combinations of loads are tried to reach the optimum set of loads, with the full-wave simulation the total computation time would be $(1.804\text{x}10^3)1000=1.804\text{x}10^6$ secs. While with the open-circuit to embedded pattern approach it would take $(1.858\text{x}10^3)+1000(0.0048)=1.863\text{x}10^3$ secs. The gain in computation time can be seen easily (here about 1000 times faster). This computation gain depends on the ratio of total number of basis functions (MoM) to the number of loads, and the number of iterations tried before the problem converges. By combining the proposed approach with the harmonic optimization described in Section III, it took less than a minute to find the optimum loads which produce the ESPAR antenna pattern closer to the objective pattern, with an average error of less than 1dB, within the main lobe. These patterns are shown in Fig. 3. The objective radiation patterns considered here are 2D azimuthal, therefore $\theta = 90°$ is used for computation of the cost function.

V. Conclusion

For ESPAR antennas, the open-circuit to embedded pattern approach is a very fast way to compute the exact radiation pattern with the dynamic parasitic loads, without any approximation. Regardless of the optimization algorithm, this approach immensely accelerates the optimization process to find the set of loads producing a radiation pattern as close as possible to a given objective pattern. The harmonic optimization is a fast method for optimizing the loads in the ESPAR antenna and when it is used with the open-circuit to embedded pattern approach, it gives results in less than a minute, with an average error smaller than 1dB between objective radiation pattern and obtained radiation pattern, within the main lobe.

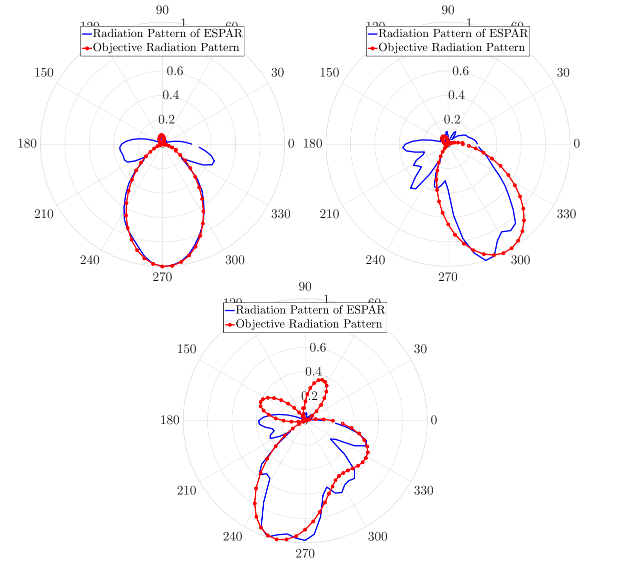


Fig. 3: Objective E-field radiation patterns vs obtained E-field radiation patterns of ESPAR utilizing open-circuit to embedded pattern approach combined with harmonic optimization.

Acknowledgement

This research has been financially supported by “Régions Wallonne et Bruxelloises” through the B-WARE project. The objective radiation patterns used to produce Fig. 3 are provided by Quentin Gueuning, from UCL/ICTEAM.

References

[1] R. Harrington, “Reactively controlled directive arrays,” *IEEE Trans. Antennas Propag.*, vol. 26, no. 3, pp. 390-395, May 1978.

[2] T. Ohira and K. Iigusa, “Electronically steerable parasitic array radiator antenna,” *Electronics and Comm. in Japan (Part II: Electronics)*, vol. 87, no. 10, pp. 25-45, 2004.

[3] R. Islam and R. Adve, “Beam-forming by mutual coupling effects of parasitic elements in antenna arrays,” *IEEE Antennas Propag. Soc. Int. Symp.*, vol. 1, San Antonio, Texas, Jun. 2002.

[4] B. Schaer, K. Rambabu, J. Bornemann, and R. Vahldieck, “Design of reactive parasitic elements in electronic beam steering arrays,” *IEEE Trans. Antennas Propag.*, vol. 53, no. 6, pp. 1998-2003, Jun. 2005.

[5] M. Ohira, A. Miura, M. Taromaru, and M. Ueba, “Efficient gain optimization techniques for azimuth beam/null steering of inverted-F multiport parasitic array radiator (MuPAR) antenna,” *IEEE Trans. Antennas Propag.*, vol. 60, no. 3, pp. 1352-1361, Mar. 2012.

[6] Z. Li, E. Ahmed, A. M. Eltawil, and B. A. Cetiner, “A beam-steering reconfigurable antenna for WLAN applications,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 1, pp. 24-32, Jan. 2015.

[7] Z. Altman, R. Mittra, and A. Boag, “New designs of ultra wide-band communication antennas using a genetic algorithm,” *IEEE Trans. Antennas Propag.*, vol. 45, no. 10, pp. 1494-1501, 1997.

[8] G. Hennaux, “Auxiliary radiators for human exposure reduction in cellular networks,” *Master Thesis*, Université catholique de Louvain, 2014-2015.

[9] E. Suter and J. R. Mosig, “A subdomain multilevel approach for the efficient MoM analysis of large planar antennas,” *Microwave and Optical Techn. Lett.*, vol. 26, no. 4, pp. 270-277, 2000.

[10] D. F. Kelley, “Relationships between active element patterns and mutual impedance matrices in phased array antennas,” *IEEE Antennas Propag. Soc. Int. Symp.*, vol. 1, pp. 524-527, June 2002.

[11] C. Craeye and D. Gonzlez-Ovejero, “A review on array mutual coupling analysis,” *Radio Science*, vol. 46, no. 2, Apr. 2011.

[12] I. Gupta and A. Ksienski, “Effect of mutual coupling on the performance of adaptive arrays,” *IEEE Trans. Antennas Propag.*, vol. 31, no. 5, pp. 785-791, Sep. 1983.