Array Antenna Architectures for Solar Power Satellites and Wireless Power Transmission

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Abstract

An analytical technique for the synthesis of planar arrays for wireless power transmission is proposed whose aim is to maximize the ratio between the power collected at the receiver to the total transmitted power. The array weights are optimized through an analytical methodology which formulates the synthesis process as a generalized eigenvalue problem. The methodology can be applied for arbitrary geometries of the transmitter array and whatever the rectenna shape. A preliminary numerical validation is presented to assess the flexibility and potentialities of the method.

1. Introduction and Motivation

The idea of placing solar power satellites (SPSs) in space represents one of the most promising future options to provide renewable electrical power on a large scale [1-3]. These systems are based on the concept of collecting sunlight through huge solar panel placed in geostationary Earth orbit, and then transmitting such power to the ground through a microwave beam [4]. Accordingly, one of the key technologies to enable the future feasibility of SPSs is represented by the wireless power transmission (WPT) [4, 5].

A WPT system essentially consists of a transmitting antenna, aimed at concentrating the microwave beam towards the collection area, and the *rectenna*, which is devoted to receive and to rectify the incident power [1]. Due to the large amount of power to be dealt with, as well as to the extremely narrow beamwidths which have to be synthesized, large antenna *arrays* are usually considered for the realization of these components [1]. While rectenna elements are usually not tapered to maximize their power conversion (since the incident wave is rectified at each radiator and then summed in *DC*), the concentration of the transmitted power towards the collection area requires careful weighting of the transmitting array elements [1]. Accordingly, synthesis techniques able to achieve high transmission efficiency are of interest for the design of cost-effective WPT systems [4]. In this framework, several weighting methods aimed at maximizing the ratio of the microwave energy which actually impinges on the rectenna over the total radiated power (called *beam collection efficiency*, BCE) have been introduced [6-10]. Among these, edge tapering techniques have been proposed due to their numerical efficiency when applied to the design of large layouts and to their predictable radiation performances [6]. Such techniques have also been enhanced through the exploitation of randomly deployed non-equal element spacings [9]. Moreover, the application of stochastic optimization methods has been discussed, although they are expected to yield to low convergence rates when applied to large layouts [10].

However, despite the good performances of the above methodologies, they actually turn out sub-optimal in terms of BCE. Indeed, if a linear arrangement is at hand the optimal array tapering for maximizing the BCE can be computed as the solution of an eigenvalue problem which yields the so-called *Discrete Prolate Spheroidal Sequences* (DPSSs) [11, 12]. Unfortunately, such tapering windows have been extensively studied in the literature only for the linear case, while theoretical results on continuous apertures are available to the best of the author's knowledge if planar WPT arrays are at hand, despite their expected importance in SPS.

As a consequence, this contribution is aimed at presenting the technique for the closed-form computation of the optimal tapering window when planar WPT arrays are of interest. Towards this end, the antenna synthesis problem is formulated and solved Sect. 2, and a preliminary numerical validation is presented in Sect. 3 regarding rectangular structures. Finally, some conclusions are drawn (Sect. 4).

2. Planar Array Synthesis Methodology

Assume that a planar array displaced on a rectangular lattice of $P \times Q$ positions with spacing d_x, d_y (in wavelength) radiates a microwave beam towards a rectangular collection area $C \equiv \{|u| \le u_M, |v| \le v_M\}$.

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The BCE of such a layout is mathematically defined as

$$BCE \equiv \frac{\int_{u=-u_M}^{u=u_M} \int_{v=-v_M}^{v=v_M} |W_{AF}(u,v)|^2 dudv}{\iint_{\Omega} |W_{AF}(u,v)|^2 dudv} \quad (1)$$

where Ω is the 'visible range' and

$$W_{AF}(u,v) = \sum_{p=1}^{P} \sum_{q=1}^{Q} w_{pq} \exp[j2\pi(pud_x + qvd_y)] \quad (2)$$

is the array factor [13]. To deduce the weights w_{pq} (p=1,…,P, q=1,…,Q) which maximize (1) for a given C, $W_{AF}(u,v)$ is firstly rewritten in matrix form as $W_{AF}(u,v) = \mathbf{w}^H \mathbf{b}(u,v)$, where

$$\mathbf{w}^H = [w_{11} \ \cdots \ w_{1Q} \ \cdots \ w_{P1} \ \cdots \ w_{PQ}] \quad (3)$$

and

$$\mathbf{b}(u,v) = \left[e^{-j2\pi(ud_x + vd_y)} \ \cdots \ e^{-j2\pi(ud_x + Qvd_y)} \ \cdots \ e^{-j2\pi(Pud_x + vd_y)} \ \cdots \ e^{-j2\pi(Pud_x + Qvd_y)}\right]^H \quad (4)$$

Through simple manipulations, Eq. (1) can then be rewritten as

$$BCE \equiv \frac{\mathbf{w}^H \left[\int_{u=-u_M}^{u=u_M} \int_{v=-v_M}^{v=v_M} (\mathbf{b}(u,v)\mathbf{b}^H(u,v)) dudv\right] \mathbf{w}}{\mathbf{w}^H \left[\iint_{\Omega} \mathbf{b}(u,v)\mathbf{b}^H(u,v) dudv\right] \mathbf{w}}. \quad (5)$$

which represents the ratio of two hermitian positive-definite quadratic forms for the matrices $\Phi \equiv \int_{u=-u_M}^{u=u_M} \int_{v=-v_M}^{v=v_M} [\mathbf{b}(u,v)\mathbf{b}^H(u,v)] dudv$ and $\Psi = \iint_{\Omega} \mathbf{b}(u,v)\mathbf{b}^H(u,v) dudv$. According to a widely known theorem in matrix theory [14], it is then possible to deduce that the weight vector that maximizes the ratio (5) is the eigenvector corresponding to the maximum eigenvalue of

$$\Phi \mathbf{w} = \eta \Psi \mathbf{w}. \quad (6)$$

It is worth observing that, unlike the linear case [11], the problem to be solved is a *generalized* eigenvalue one. In the following, such a problem will be solved by exploiting the Jacobi-Davidson method [15] after having numerically computed the entries of Ψ and Φ.

3. Numerical Results

This section is aimed at presenting a preliminary numerical assessment of the features of the proposed approach as an optimal synthesis tool for WPT planar arrays. Towards this end, a set of simulations have been carried out assuming d_x=d_y=0.5, P=Q/2 (rectangular layouts) and u_M= v_M =0.2 (square collection area).

The first numerical experiment deals with the synthesis of a P=5 layout. The plot of the obtained optimal pattern [Fig. 1(*a*)] suggests that, despite the small and non-symmetric nature of the aperture ($2\lambda \times 4.5\lambda$), the transmitted power is mainly concentrated towards the receiver area, while only a small portion is "lost" in other angular directions. This is actually confirmed by the corresponding *BCE* value (*BCE*=76.9%), as well as by the small sidelobes outside the receiver region [Fig. 1(*a*)].

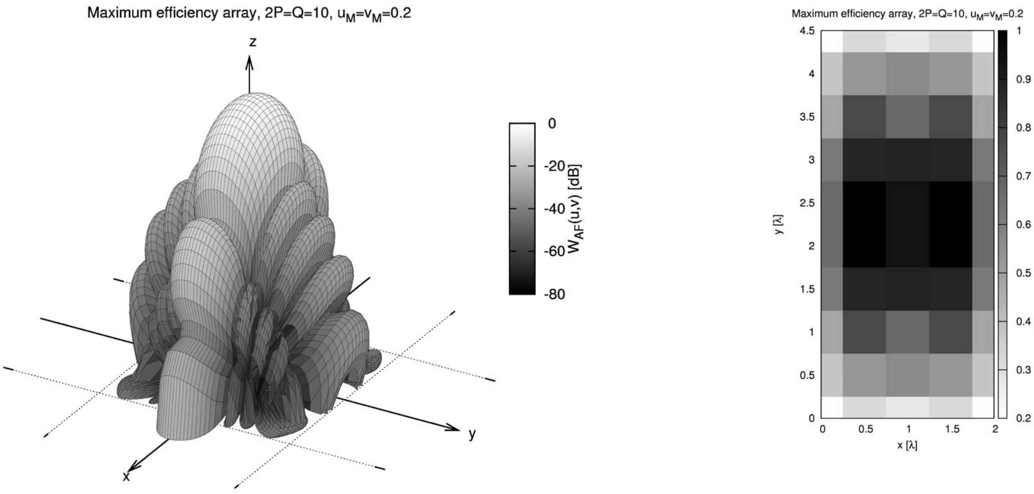
Of course, higher *BCE*s can be achieved if wider apertures are at hand. Indeed, the next numerical experiment, which deals with a 2P=Q=20 layout [Fig. 2(*b*)] shows that a more focused beam pattern is achieved in this case [Fig. 2(*a*)]. This is confirmed by the arising collection efficiency (*BCE*=98.20%), which turns out close to 1 notwithstanding the asymmetric nature of the layout, as shown by the arising pattern [Fig. 2(*a*)].

The increased *BCE* with respect to the previous case is actually related to the lower sidelobes which appear outside the receiver region [Fig. 2(*a*)]. Indeed, this is confirmed by the values of

$$ESL \equiv \frac{\max_{(u,v)\notin C} W_{AF}(u,v)}{\max_{(u,v)} W_{AF}(u,v)} \quad (7)$$

which turn out close to -12.3 [dB] for P=10 while were above -3.2 dB for the P =5 case [Fig. 1(*a*) vs. Fig. 2(*a*)].

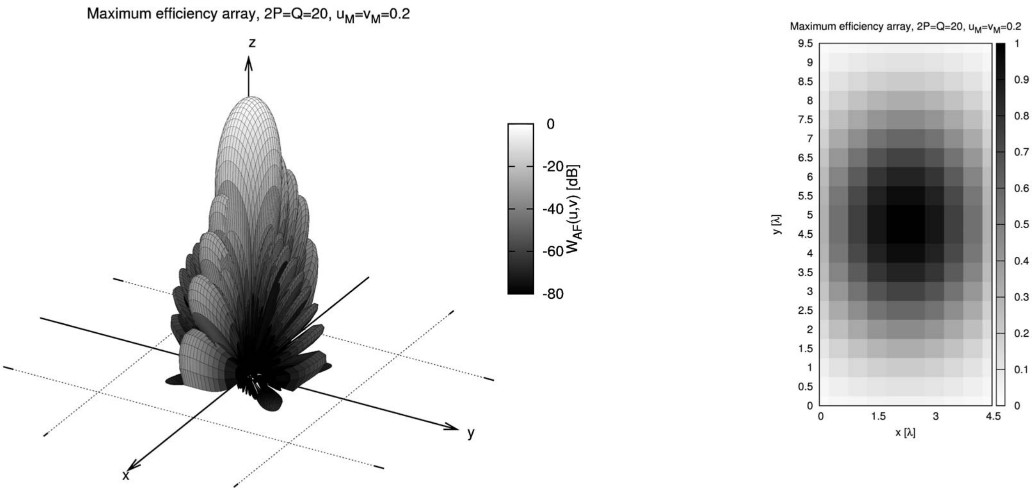
Moreover, it is worth noticing that, as expected from the continuous aperture theory [14], maximum efficiency large planar layouts tend to exhibit a 'Gaussian-like' weight profile [Fig. 2(*b*)], which instead is badly approximated by small architectures [Fig. 1(*b*)].



(*a*) (*b*)

Figure 1. [$2P$=Q=10, u_M=v_M=0.2] Optimal radiation power pattern (*a*) and associated weight coefficients (*b*).

Finally, as regards the computational complexity of the synthesis method, it is worth pointing out that both synthesis required less than 1 second on a 2.1 GHz laptop, therefore confirming the efficiency of the proposed tapering approach. Moreover, such a computational time could be even reduced by observing that only the eigenvector corresponding to the largest eigenvalue in Eq. (7) is of interest for the synthesis, thus enabling specific iterative approaches to be employed. Such computational solutions, together with the design non-regular [16] as well as multi-beam [17] *WPT* arrays are currently under investigation.



(*a*) (*b*)

Figure 2. [$2P$=Q=20, u_M=v_M=0.2] Optimal radiation power pattern (*a*) and associated weight coefficients (*b*).

5. Conclusions

The synthesis of planar arrays for wireless power transmission has been performed through an analytical methodology aimed at maximizing the ratio between the power collected at the receiver to the total transmitted power. Towards this end, the synthesis procedure has been recast as the solution of a generalized eigenvalue problem, which has been carried out through a Jacobi-Davidson method. A preliminary numerical validation has been presented pointing out the capability of the proposed technique to achieve high *BCE* values as well as its numerical efficiency.

6. References

1. W. C. Brown and E. Eves, "Beamed microwave power transmission and its application to space," *IEEE Trans. Microwave Theory Tech.*, **40**, (6), June 1992, pp. 1239-1250.

2. N. Shinohara and H. Matsumoto, "Microwave power transmission system with phase and amplitude controlled magnetrons," *Proc. 2nd International Conference on Recent Advances in Space Technologies* (RAST), Istanbul, Turkey, 2005, pp. 28-33.

3. W. C. Brown, "The technology and application of free-space power transmission by microwave beam," *Proc. IEEE*, **62**, (1), Jan. 1974, pp. 11-25.

4. J. O. McSpadden and J. C. Mankins, "Space solar power programs and microwave wireless power transmission technology," *IEEE Microw. Mag.*, **3**, (4), Dec. 2002, pp. 46-57.

5. J. O. McSpadden, T. Yoo, and K. Chang, "Theoretical and experimental investigation of a rectenna element for microwave power transmission," *IEEE Trans. Microw. Theory Tech.*, **40**, (12), Dec. 1992, pp. 2359-2366.

6. A. K. M. Baki, N. Shinohara, H. Matsumoto, K. Hashimoto, and T. Mitani, "Study of isosceles trapezoidal edge tapered phased array antenna for solar power station/satellite," *IEICE Trans. Comm.*, **E90-B**, (4), Apr. 2007, pp. 968-977.

7. A. K. M. Baki, N. Shinohara, H. Matsumoto, K. Hashimoto, and T. Mitani, "Isosceles-trapezoidal-distribution edge tapered array antenna with unequal element spacing for solar power station/satellite," *IEICE Trans. Comm*., **E91-B**, (2), Feb. 2008, pp 527-535.

8. A. K. M. Baki, K. Hashimoto, N. Shinohara, T. Mitani and H. Matsumoto, "New and improved method of beam forming with reduced side lobe levels for microwave power transmission," *5th Int.l Conf. on Electrical and Computer Engineering* (ICECE 2008), Dhaka, Bangladesh, 2008, pp. 773-777.

9. B. Shishkov, N. Shinohara, K. Hashimoto, and H. Matsumoto, "On the optimization of sidelobes in large antenna arrays for microwave power transmission," *IEICE Technical Report,* **SPS 2006-11**, Oct. 2006, pp. 5-11.

10. N. Shinohara, B. Shishkov, H. Matsumoto, K. Hashimoto, and A. K. M. Baki, "New stochastic algorithm for optimization of both side lobes and grating lobes in large antenna arrays for MPT," *IEICE Trans. Comm.*, **E91-B**, (1), Jan. 2008, pp 286-296.

11. S. Prasad, "On an index for array optimization and the discrete prolate spheroidal functions," *IEEE Trans. Antennas Propag*., **AP-30**, (5), Sep. 1982, pp. 1021-1023.

12. D. Slepian and H. O. Pollack, "Prolate spheroidal wave functions, Fourier analysis, and uncertainty," *Bell Syst., Tech. J.*, **40**, Jan. 1961, pp. 43-64.

13. C. A. Balanis, *Antenna Theory: Analysis and Design*, 2nd ed., Wiley, New York, 1997.

14. F. R. Gantamacher, *The Theory of Matrices*, Chelsea, New York, 1959.

15. E. Anderson *et al.*, *LAPACK Users' Guide*, 3rd. Ed., Society for Industrial and Applied Math., Philadelphia, 1999.

16. G. Oliveri and A. Massa, "Bayesian compressive sampling for pattern synthesis with maximally sparse non-uniform linear arrays," *IEEE Trans. Antennas Propag.*, **59**, (2), Feb. 2011, pp. 467-481.

17. L. Manica, P. Rocca, A. Martini, and A. Massa, "An innovative approach based on a tree-searching algorithm for the optimal matching of independently optimum sum and difference excitations," *IEEE Trans. Antennas Propag.*, **56**, (1), Jan. 2008, pp. 58-66.