Planar arrays synthesis for optimal wireless power transmission

Xun Li[1,3a)], Jinzhu Zhou[1b)], and Xiaolin Du[2]

[1] *Key Laboratory of Electronic Equipment Structure Design, Ministry of Education, Xidian University, Xi'an 710071, P. R. China*

[2] *National Laboratory of Radar Signal Processing, Xidian University, Xi'an 710071, P. R. China*

[3] *Collaborative Innovation Center of Information Sensing and Understanding, Xidian University, Xi'an 710071, P. R. China*

a) *alixun2008@163.com*

b) *xidian_jzzhou@126.com*

Abstract: This paper describes the synthesis method of uniformly excited unequally spaced planar array with maximum beam collection efficiency (BCE, i.e., the ratio between the power radiated over a target region and the whole transmitted power) using Particle Swarm Optimization (PSO) algorithm. Based on this method, feeding network of the arrays becomes simple and compact and is easy to implement. And here the multiple optimization constrains include the number of elements, and the array aperture. Comparison of representative example is presented, and the results show that an enhancement of BCE and a depression of the sidelobe level outside of the receiving region (CSL) can be obtained through the proposed method.

Keywords: antenna array, array synthesis, wireless power transmission (WPT), particle swarm optimization, space solar power satellite (SSPS)

Classification: Electromagnetic theory

References

[1] P. E. Glaser: Science **162** (1968) 857. DOI:10.1126/science.162.3856.857

[2] W. C. Brown and E. E. Eves: IEEE Trans. Microw. Theory Techn. **40** (1992) 1239. DOI:10.1109/22.141357

[3] C. Bergsrud and J. Straub: Acta Astronaut. **103** (2014) 193. DOI:10.1016/j.actaastro.2014.06.033

[4] J. O. McSpadden and J. C. Mankins: IEEE Microw. Mag. **3** (2002) 46. DOI:10.1109/MMW.2002.1145675

[5] W. C. Brown: Proc. IEEE **62** (1974) 11. DOI:10.1109/PROC.1974.9380

[6] A. Massa, G. Oliveri, F. Viani and P. Pocca: Proc. IEEE **101** (2013) 1464. DOI:10.1109/JPROC.2013.2245491

[7] S. Prasad: IEEE Trans. Antennas Propag. **AP-30** (1982) 1021. DOI:10.1109/TAP.1982.1142900

[8] G. Oliveri, L. Poli and A. Massa: IEEE Trans. Antennas Propag. **61** (2013) 2490. DOI:10.1109/TAP.2013.2241714

[9] A. K. M. Baki, N. Shinohara, H. Matsumoto, K. Hashimoto and T. Mitani: IEICE Trans. Commun. **E90-B** (2007) 968. DOI:10.1093/ietcom/e90-b.4.968

[10] A. K. M. Baki, K. Hashimoto, N. Shinohara, T. Mitani and H. Matsumoto: IEICE Trans. Commun. **E91-B** (2008) 527. DOI:10.1093/ietcom/e91-b.2.527

[11] N. Shinohara, B. Shishkov, H. Matsumoto, K. Hashimoto and A. K. M. Baki: IEICE Trans. Commun. **E91-B** (2008) 286. DOI:10.1093/ietcom/e91-b.1.286

[12] T. Moriyama, L. Poli and P. Rocca: IEICE Electron. Express **12** (2015) 20150028. DOI:10.1587/elex.12.20150028

[13] J. Robinson and Y. Rahmat-Samii: IEEE Trans. Antennas Propag. **52** (2004) 397. DOI:10.1109/TAP.2004.823969

[14] M. M. Khodier and C. G. Christodoulou: IEEE Trans. Antennas Propag. **53** (2005) 2674. DOI:10.1109/TAP.2005.851762

1 Introduction

Space solar power satellite (SSPS) is a green and renewable energy system that converts solar energy to electricity in the geostationary orbit (GEO) and transmits the electricity energy to the earth via microwave. It is regarded as one of the most promising energy system in the future, and obtaining more and more attention since proposed by Peter Glaser in 1968 [1]. Wireless power transmission (WPT) is one of the key technologies of the SSPS, and has extensive application both in terrestrial and space scenarios [2, 3, 4]. Transmitting antenna and rectifying antenna or the so-called rectenna are the two key components of WPT systems. Transmitting antenna is used to concentrate the radiated power to the rectenna, and rectenna is used to capture the impinging microwave and convert it to DC. Therefore, the concept of WPT is, to some degree, similar to the traditional communication and radar systems. However, it is must be addressed that the objective of WPT systems is to optimally transfer microwave energy rather than information, and in many cases the efficiency of WPT should be larger than 90 percents [5]. Moreover, the collection and conversion of impinging microwave power to DC power is a unique technique which has little relation to traditional methods of receiving and processing microwave in communication applications.

Because of high requirement on WPT efficiency, transmitting antenna need to be designed to have the ability of radiating as much energy as possible to the rectenna. A comprehensive review of long-distance WPT array techniques is presented in [6]. Beam collection efficiency, defined as the ratio between the power radiated over the receiving region and the total transmitted power [7, 8] is one of the key indexes of WPT system. Recently, the problem of maximizing BCE of planar array antennas has been theoretically studied and simplified as the solution of a generalized eigenvalue problem [8]. The optimal tapering is found to be "quasi-Gaussian" distribution. However, the feeding network is complicated to fabricate and maintain, owing to its "smooth nature" of "quasi-Gaussian" distribution. To reduce the complexity of feeding network, edge tapering methods [9, 10] were proposed. In these methods, the innermost elements of the array are fed with constant amplitudes, while a small number of edge elements need different amplitudes. In [11] stochastic algorithm was developed for the optimization of side lobes and grating lobes in antenna arrays for WPT applications. Additionally, another novel method based on the concept of sub-arrayed architecture was

investigated in [12], the feeding network of these arrays is greatly simplified since the number of amplifiers required is equal to the number of sub-arrays. In conclusion, up to now, the existing papers are mainly concerned with finding the best tapering to maximize BCE and the optimal tapering are always nonuniform. Therefore, they all share the drawbacks of complexity feeding network and low utilization of antenna surface.

In this letter, uniformly excited, unequally spaced planar array synthesis method aimed at maximizing the BCE is proposed. Due to the property of uniformly excited, feeding network of these arrays becomes simple and compact and is easy to fabricate. Synthesis of this array comprises a non-convex and multidimensional optimization problem, and evolutionary algorithms are best suited to find the global optimal solution. Here, a synthesis method of planar array geometry with maximum BCE using PSO algorithm is proposed.

2   Problem formulation for WPT

Consider a planar array of square shape consisting of $4N$ radiating elements and, suppose that they are located in the XOY plane as shown in Fig. 1. The effect of mutual coupling among elements is ignored and the element patterns in the array are assumed to be isotropic. The array factor can be expressed as

$$F(u, v) = \sum_{n=1}^{4N} I_n \exp[jk(ux_n + vy_n + \phi_n)] \tag{1}$$

where I_n, ϕ_n, and (x_n, y_n) are respectively the amplitude, phase, and position of the nth radiating element, k is the wave number, $u = \sin\theta\cos\varphi$, $v = \sin\theta\sin\varphi$, θ and φ are the elevation angle and azimuth angle, respectively. If we further assume that the amplitude and phase of the excitation is uniform, that is, $I_n = 1$, $\phi_n = 0$, the array factor can be simplified as

$$F(u, v) = \sum_{n=1}^{4N} \exp[jk(ux_n + vy_n)] \tag{2}$$

Suppose that the array is symmetrical about the x-axis and the y-axis, then the array can be divided as four symmetrical sub-arrays, and Eq. (2) becomes

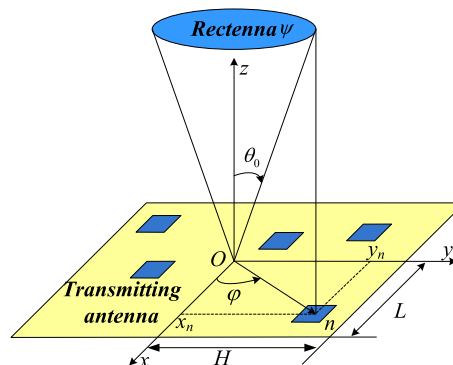$$F(u, v) = 4\sum_{n=1}^{N} \cos(kux_n) \cdot \cos(kvy_n) \tag{3}$$

Fig. 1.   Geometry of transmitting antenna and rectenna

the corresponding power pattern can be formulated as

$$P(u,v) = |F(u,v)|^2 = 16 \left\{ \sum_{n=1}^{N} [\cos(kux_n) \cdot \cos(kvy_n)] \right\}^2 \qquad (4)$$

Assume that the target area (the rectenna location) is in the far-field region, and has a circular shape, then the BCE can be written as [8], i.e.,

$$
BCE = \frac{P_\psi}{P_\Omega} = \frac{\displaystyle\int_0^{2\pi}\int_0^{\theta_0} P(u,v)\sin\theta d\theta d\varphi}{\displaystyle\int_0^{2\pi}\int_0^{\pi} P(u,v)\sin\theta d\theta d\varphi}
$$

$$
= \frac{\displaystyle\int_0^{2\pi}\int_0^{\theta_0} \left\{ \sum_{n=1}^{N}[\cos(kux_n)\cdot\cos(kvy_n)] \right\}^2 \sin\theta d\theta d\varphi}{\displaystyle\int_0^{2\pi}\int_0^{\pi} \left\{ \sum_{n=1}^{N}[\cos(kux_n)\cdot\cos(kvy_n)] \right\}^2 \sin\theta d\theta d\varphi} \qquad (5)
$$

where P_ψ and P_Ω denote the power radiated over the angular region ψ and the total transmitted power over the visible region Ω, respectively, θ_0 is the inception angle of the rectenna as in Fig. 1.

Therefore, for the given problem above, to maximize the BCE is to find the optimal radiating element positions (x_n, y_n), $n = 1, 2, \ldots, N$ that maximizes Eq. (5). The mathematical optimization model is established as PI.

PI :   Find $X = (x_1, x_2 \ldots, x_N, x_{N+1}, \ldots, x_{2N})^T$ (6)

Min. $f(X) = -BCE(X)$ (7)

S.T. $l_0 \leq x_n \leq L$ (8)

$h_0 \leq x_{N+n} \leq H$ (9)

where the design variable $X = (x_1, x_2 \ldots, x_N, x_{N+1}, \ldots, x_{2N})^T$ represents the position coordinates of the array elements in the first quadrant, x_n and x_{N+n} are the x and y coordinates of the nth element ($n = 1, 2, \ldots N$), respectively, as shown in Fig. 1. The objective function $f(X)$ is the negative BCE for the purpose of making it a minimization problem. l_0 and h_0 are pre-given spacing values to keep the neighboring elements of the sub-arrays apart, and L and H are the length and width of the sub-arrays, respectively.

It must be addressed that, the optimization problem is solved using the PSO algorithm in this letter. Due to space limit, PSO algorithm is not introduced. The reader is referred to [13, 14] and the references therein for a detailed understanding of the concept of PSO algorithm and how it works.

3 Numerical analysis and discussion

The purpose of this section is twofold. Firstly, to investigate the effectiveness of the proposed method, and then compare the results obtained through this method with the results achieved in [8], which optimizes the BCE through optimizing the array tapering. The numerical experiment is concerned with a square transmitting array with 100 elements, and the aperture size is constrained by $2L = 2H = 5.5\lambda$, the receiving region ψ is supposed to be circular and defined as

$$\Psi = \left\{ (u,v) : \sqrt{u^2 + v^2} = \sin\theta_0 \le r_0 \right\} \tag{10}$$

As mentioned in the previous section, θ_0 denotes the inception angle of the receiving region, the operation frequency is set to be 5.8 GHz. The circular collection region is set as $r_0 = 0.2$. Through the method proposed in [8], the optimal radiating power pattern is shown in Fig. 2, and the maximum beam collection efficiency obtained equals to $BCE^{opt} = 86.48\%$ [8], with a corresponding CSL (maximum sidelobe level outside of the receiving region) equals to CSL = -7.78 dB. CSL is another key factor need to be considered for the purpose of safety concern, and defined as

$$CSL(\text{dB}) = 10\lg \frac{\max_{u,v \notin \psi} P(u,v)}{\max_{u,v} P(u,v)} \tag{11}$$
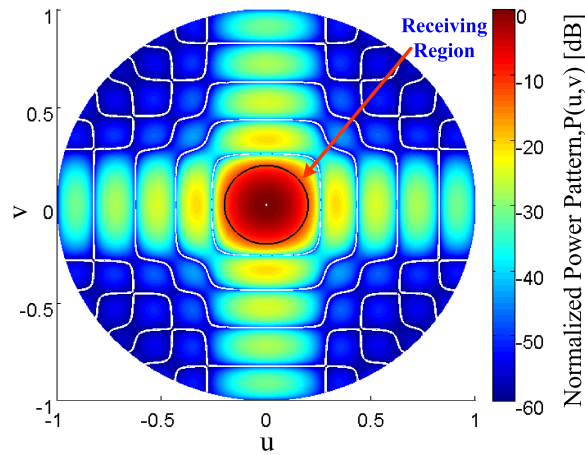

Fig. 2. Normalized power pattern (Reference method [8])

Based on the proposed method in this letter, the optimal elements distribution in the first quadrant is illustrated in Fig. 3. Obviously, they are located randomly in the constrained aperture due to stochastic nature of the PSO algorithm. Due to the symmetric distribution of the array elements, the obtained power pattern exhibits a symmetrical property, and is shown in Fig. 4. Two conclusions can be drawn by comparing Fig. 4 with Fig. 2.

(1) More energy is focused on the receiving region through the proposed method, this is numerically confirmed by the maximum BCE achieved ($BCE^{opt} = 94.01\%$ vs. $BCE^{opt} = 86.48\%$ [8]).

(2) The CSL can be suppressed, which is confirmed by (CSL = -16.84 dB vs. CSL = -7.78 dB [8]).

Comparison of the results is shown in Table I. The maximum BCE is 7.61% higher than and the CSL is 9.06 dB lower than the reported results in [8].

Table I. Results comparison

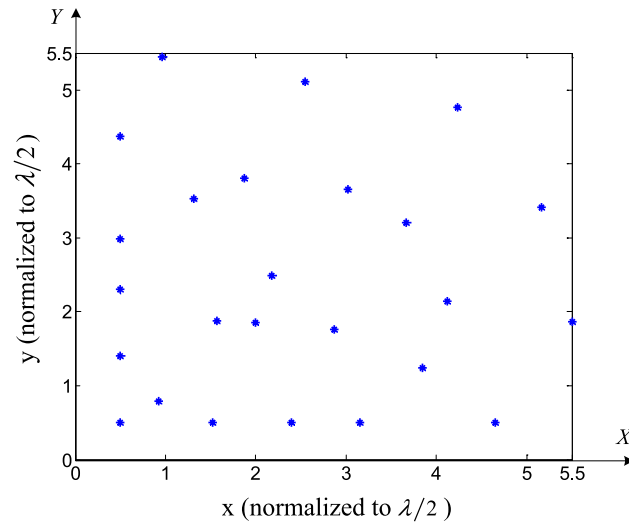|	Ref. [8]	This method	Comparison
Maximize BCE	86.4%	94.01%	7.61%
CSL	-7.78 dB	-16.84 dB	-9.06 dB

Fig. 3. The distribution of the first quadrant elements
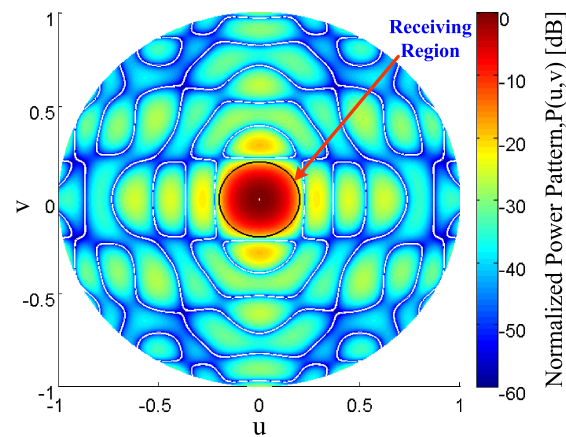

Fig. 4. Normalized power pattern (proposed method)

4 Conclusion

An approach based on particle swarm optimization algorithm has been proposed for the synthesis of uniformly excited unequally spaced planar array for the purpose of obtaining maximum BCE. Through the proposed method, feeding network becomes simple and compact and is easily to implement. Moreover, beam collection efficiency can be enhanced and the maximum sidelobes outside of the receiving region can be reduced, which shows the effectiveness of the proposed method.