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Optimal design of modular planar arrays for microwave wireless power transmission

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Microwave wireless power transmission (MWPT) is a transformative energy transfer technology that eliminates the need for physical cables, offering improved flexibility and convenience. This technology has significant potential across various applications, such as powering remote or inaccessible areas, sustaining Internet of Things (IoT) devices, enabling efficient energy transfer between satellites, and providing continuous energy to drones [1]. For drone wireless charging, lightweight and compact rectennas are crucial for optimal performance [2].

An MWPT system typically comprises two key components: a transmitting antenna and a rectenna. The overall efficiency is a critical performance indicator, influenced by three factors: DC-to-RF (direct current to radio frequency) conversion efficiency, beam collection efficiency (BCE), and RF-to-DC conversion efficiency. Improving BCE is particularly important, as it reflects how effectively microwave power is focused on the rectenna, minimizing losses outside the receiving area. To achieve this, phased arrays are commonly employed due to their superior beam steering and shaping capabilities. However, their high cost, primarily driven by the extensive use of expensive transmit modules (TMs), remains a significant barrier to widespread adoption.

To address cost challenges, unconventional phased array architectures such as sparse arrays, clustered arrays, and irregular subarray designs have been explored [3,4]. Sparse arrays strategically reduce the number of elements while maintaining low sidelobe levels, thereby lowering the costs [3]. Clustered arrays achieve similar objectives by grouping multiple elements into clusters, with each cluster powered by a single TM, thereby reducing the number of TMs required [3]. Irregular subarrays offer distinct advantages, such as suppressing grating lobes and enabling wider scanning angles, making them useful in MWPT applications [4]. However, their complex feed networks and high manufacturing costs limit their feasibility for large-scale implementation.

This study proposes an optimized design method for modular transmitting arrays in MWPT systems, aiming to enhance transmission efficiency and reduce costs. The proposed method begins with deriving an optimal continuous aperture distribution to maximize BCE. Next, a 2×2 patch subarray is designed, with excitation coefficients directly determined from this distribution. The subarrays are grouped into modules using the K-means clustering algorithm, and the excitation coefficients for each module are iteratively optimized to achieve two key objectives: maximize BCE and minimize the peak radiation level (PRL) outside the receiving area. The proposed method comprises three key steps.

Step 1. Optimization of a continuous aperture distribution. This study considers an MWPT system with circular transmitting and receiving antennas, with radii R_t and R_r, respectively, separated by a distance L. The receiving antenna is assumed to be positioned within the Fresnel zone of the transmitting antenna. The primary objective is to optimize the transmitting antenna's aperture illumination to focus maximum power on the receiving antenna, thereby enhancing the system's overall transmission efficiency.

To achieve this, the transmitting antenna is modeled with an axisymmetric aperture distribution, represented by $E_t(\rho,\psi) = f(\rho)\exp[\mathrm{j}\psi(\rho)]$, where $f(\rho)$ and $\psi(\rho)$ represent the amplitude and phase distributions of the aperture, respectively, and $\rho = r/R_t$ is the normalized radius in the transmitting aperture. The phase taper $\psi(\rho) = k\rho^2 R_t^2/2L$, where $k = 2\pi/\lambda$ is the wavenumber and λ is the wavelength, which compensates for the phase differences due to varying distances from the aperture to the focal point. Incorporating this phase taper allows the electric field in the focal plane, near the axis, to exhibit far-field characteristics, which can be expressed as $E(u) = \mathrm{j}kR_t^2\mathrm{e}^{-\mathrm{j}kL}/L \cdot F(u)$, where $F(u) = \int_0^1 f(\rho)J_0(u\rho)\rho\mathrm{d}\rho$, $u = kR_t\sin\theta$, θ denotes the subtended angle, and $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind. The BCE is calculated as

$$\mathrm{BCE} = \frac{\int_0^{u_0} F^2(u)u\mathrm{d}u}{\int_0^1 f^2(\rho)\rho\mathrm{d}\rho}, \tag{1}$$

where $u_0 = kR_t\sin\theta_0$ and $\theta_0 = \arctan(R_r/L)$ is the subtended angle at the edge of the receiving aperture. It is clear that maximizing the BCE hinges upon the optimal design

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of the aperture amplitude distribution $f(\rho)$. This distribution is represented as a linear combination of basis functions $f(\rho)=\sum_{n=1}^{N} x_n(1-\rho^2)^{n-1}$, where x_n is the coefficient and $(1-\rho^2)^{n-1}$ is the basis function. The optimization problem then reduces to finding the optimal coefficient vector $\boldsymbol{x}=[x_1,\ldots,x_N]^{\mathrm{T}}$ that maximizes the BCE. Through mathematical derivation, this optimization can be reformulated as an eigenvalue problem, where the largest eigenvalue $\lambda_{\max}$ is the optimal BCE and its corresponding eigenvector $\boldsymbol{x}^{\mathrm{opt}}$ provide the optimal amplitude distribution.

In high-power MWPT applications, radiation safety is critical, requiring control over the PRL outside the receiving region. The PRL is defined as

$$\mathrm{PRL}=20\log_{10}\frac{\max_{u\geqslant u_0}|F(u)|}{\max_u|F(u)|}. \tag{2}$$

To simultaneously maximize the BCE while ensuring that the PRL remains below a specified threshold C_0, the optimization problem is reformulated as

$$\min_{\boldsymbol{x}} -\mathrm{BCE}(\boldsymbol{x})+\aleph\cdot[\max(0,\mathrm{PRL}(\boldsymbol{x})+C_0)], \tag{3}$$

where $\aleph$ is a penalty parameter. This constrained optimization problem is solved using the grey wolf optimizer combined with Nelder-Mead (GWO-NM) algorithm [5].

Step 2. Sampling the continuous aperture distribution and optimizing module partition. Direct implementation of a specific aperture illumination in antenna design is challenging. To address this, a circular antenna array is employed to approximate the performance of the continuous aperture. The excitation coefficients of the array elements are sampled from the optimized continuous distribution $f(\rho)$ obtained in Step 1. To reduce system cost and weight, the radiating elements are grouped into subarrays, with each subarray driven by a single TM. The excitation coefficient for the pth subarray is $I_p=f(\sqrt{x_p^2+y_p^2}/R_t)$, where (x_p,y_p) represents the location of the pth subarray. By grouping these subarrays into clusters, the number of distinct TMs is minimized. The challenge then lies in partitioning the subarrays into modules, with each module comprising subarrays that share the same excitation coefficient.

The module partition problem can be formulated as an excitation matching problem, aiming to minimize the discrepancy between the reference subarray excitation vector and the corresponding module excitation vector, defined as

$$\min_{\boldsymbol{R},\boldsymbol{I}^{\mathrm{sub}}}\left|\boldsymbol{R}\cdot\boldsymbol{I}^{\mathrm{mod}}-\boldsymbol{I}^{\mathrm{ref}}\right|^2, \tag{4}$$

where $\boldsymbol{I}^{\mathrm{ref}}$ is the reference subarray excitation vector, $\boldsymbol{I}^{\mathrm{mod}}$ is the module excitation vector, and $\boldsymbol{R}$ is a binary matrix indicating subarray-module assignments.

This problem can be effectively modeled as a clustering task, with the well-known K-means algorithm employed to determine the optimal partition. The excitation coefficient for each module is approximated by the average excitation coefficient of the subarrays within that module. The K-means algorithm is applied iteratively, starting with randomly selected cluster centers. Each subarray is then assigned to the nearest cluster center, after which the cluster centroids are recalculated. This process continues until convergence, defined by a predetermined number of iterations.

To improve convergence and mitigate the risk of local minima, the K-means algorithm is executed multiple times with different initial cluster centers. The partition that achieves the lowest within-cluster variance is selected as the optimal solution. Once the optimal module partition is identified, the array's radiation pattern is computed by summing the contributions of each module, weighted by the corresponding excitation coefficients and individual subarray radiation patterns. The BCE and PRL are then recalculated based on the optimized module partition.

Step 3. Refining module excitation coefficients. Although subarray clustering effectively reduces system cost and weight, it introduces sampling errors due to large inter-element spacing. These errors can degrade performance by lowering the BCE and increasing the PRL. To address this, the module excitation coefficients are re-optimized using the GWO algorithm. The GWO algorithm is configured with a population size of 40 and a maximum of 50 iterations. The objective is to maximize the BCE while ensuring that the PRL remains below the specified threshold C_0, i.e.,

$$\min_{\boldsymbol{I}^{\mathrm{sub}}} -\mathrm{BCE}(\boldsymbol{I}^{\mathrm{sub}}) \quad \text{s.t.} \quad \mathrm{PRL}(\boldsymbol{I}^{\mathrm{sub}})\leqslant C_0. \tag{5}$$

This iterative refinement enhances transmission efficiency while ensuring compliance with safety constraints. A comprehensive overview of the proposed method is provided in Appendix A.

Numerical analysis and discussion. This section demonstrates the proposed method on a fixed point-to-point MWPT system with circular antennas. The transmitting antenna ($D_t=2.3$ m) and rectenna ($D_r=5.0$ m) are spaced 100 m apart, operating at 5.8 GHz. Numerical settings and results are detailed in Appendix B.

Conclusion. This study presents an optimal design method for modular planar transmitting arrays in MWPT systems. The approach combines aperture optimization, subarray partitioning, and excitation refinement to enable cost-effective, high-performance transmitting arrays. By maximizing BCE under PRL constraints, the method is suitable for long-range and high-power MWPT applications.

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Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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