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Multi-Target Microwave Power Transmission With Maximum Efficiency and Allocable Power Proportion

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Abstract

Low wireless power transmission efficiency (PTE) and uncontrollable power proportion among multiple receiving targets often lead to the great waste of energy and extremely low received power. Therefore, multi-target microwave power transmission (MPT) with high PTE and allocable power proportion is critical for current MPT systems. In this work, optimal designs for multi-target MPT based on the weighted and constrained method of the maximum power transmission efficiency (WCMMPTE) are proposed to solve these two problems at the same time. Several receiving terminals represented by test antennas surrounded by 40-element transmitting antenna array are modeled to build a multiple-input multiple-output MPT system and the corresponding full-wave simulations are conducted to validate the proposed theory. By optimizing the distribution of excitations for the transmitting array antenna through WCMMPTE, the maximal PTE is guaranteed while the different proportions of power received by terminals are simultaneously achieved.

1 Introduction

Microwave power transmission (MPT) is a current popular technology to wirelessly deliver power at microwave frequencies from an antenna array to several receiving terminals, which plays an indispensable role in internet of things, radio frequency identification and other wireless communication applications [1]-[3]. The distribution of excitations for the transmitting array antennas affects the overall power transmission efficiency (PTE) and the power level eventually received by each terminal. Therefore, many optimization methods (e.g., time reversal) [4] [5] and optimization algorithms (e.g., genetic algorithm, simulated annealing and particle swarm optimization) are applied to seek the better excitations, leading to the relative higher PTE. However, except for the failure to reach the highest PTE, these methods are hardly to achieve the arbitrary power proportion for multiple terminals.

In this work, the weighted and constrained method of the maximum power transmission efficiency (WCMMPTE) is proposed to optimize the excitations for the transmitting array antenna. By setting PTE as the optimization target and adding constraints on the received power of the terminals as the, the optimized distribution of excitations can ensure the maximal PTE and the desired power proportion for the terminals at the same time. The MPT system consisted of a 40-element transmitting antenna array and three terminals represented by receiving antennas in the near-field is built and the full-wave simulation is conducted to validate the proposed method. In the end, the received power ratio of 1:1:1 and 1:2:3 are obtained respectively while the maximal PTE is guaranteed.

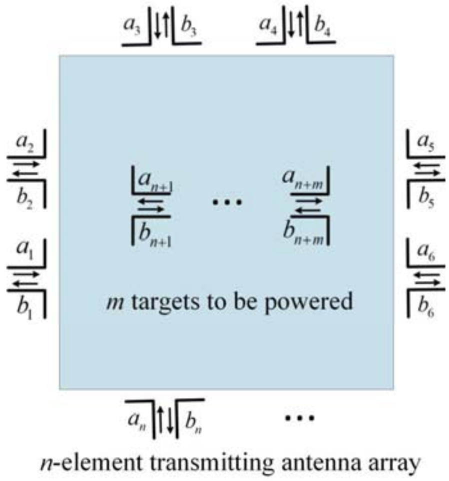

Figure 1. General MPT system consisted of n-element transmitting antenna array to be designed and m potential targets.

2 Operational Mechanism

As shown in Fig.1, let us consider a general MPT system consisted of an n-element transmitting array to be designed and m receiving terminals. The whole system can be viewed as an (n+m)-port network and characterized by scattering parameters. The PTE η between the n-element transmitting antenna array and the receiving targets can be expressed as

$$\eta = \frac{\boldsymbol{x}^H \boldsymbol{A}\boldsymbol{x}}{\boldsymbol{x}^H \boldsymbol{x}}, \tag{1}$$

where $\boldsymbol{x} = [a_1, a_2, ..., a_n]^T$ denotes the normalized incident wave for the transmitting antenna array and $\boldsymbol{A} = [S_{rt}]^H [S_{rt}]$. The superscripts '$T$' and '$H$' stand for the transpose and Hermitian operation, respectively. $[S_{rt}]$ is the scattering matrix and the subscript 'r' and 't' represent the receiving antennas and the transmitting array, respectively. In order to control the received power ratio of each target, here we assume that the m receiving targets represented by m receiving antennas are randomly distributed in space. We divide the m receiving targets into two different sets—— set P denotes the targets needed to be wirelessly powered with desired proportion, and the set Q are the rest of targets whose received power must be minimized to ensure the microwave radiation security and reduce the waste of power. Hence, the optimal design of the transmitting antenna array becomes a quadratically constrained quadratic programing problem expressed as

$$\begin{aligned} \max \quad & \frac{\boldsymbol{x}^H \boldsymbol{A}\boldsymbol{x}}{\boldsymbol{x}^H \boldsymbol{x}} \\ \text{s.t.} \quad & |\boldsymbol{b}_i|^2 = c_i, \quad i \in P, \\ & |\boldsymbol{b}_j|^2 = c_0, \quad j \in Q, \end{aligned} \tag{2}$$

where $[\boldsymbol{b}_r] = [\boldsymbol{S}_{rt}] \cdot \boldsymbol{x}$, and $|\boldsymbol{b}_i|^2$ denotes the power received by ith test receiving antenna. For each c_i and c_0 in (2), there should be always c_i ? c_0, which implies that the radiated power is forced to be transmitted to the antennas needed to be powered. However, for each receiving target, the desired received power can be different by adjusting the corresponding c_i. By applying the Lagrangian multiplier method, the optimal solution of (2) is uniquely given by

$$\boldsymbol{x}^* = \boldsymbol{A}^{-1}\boldsymbol{S}^H(\boldsymbol{S}\boldsymbol{A}^{-1}\boldsymbol{S}^H)^{-1}\boldsymbol{W}\boldsymbol{y}, \tag{3}$$

where $\boldsymbol{S} = [S_{rt}]$, $\boldsymbol{y}$ represents an m-dimensional vector whose element values are real constants, and $\boldsymbol{W} = diag(w_1, w_2, ..., w_m)$ is a weighted diagonal matrix where $w_1, w_2, ..., w_m$ are influenced by c_i and c_0. Consequently, the analytical expression (3) explicitly gives the optimal distribution of excitations for the transmitting antenna array, which ensures the maximum PTE and the required power proportion at the same time.

3 Validations and Results

In this work, an MPT system consisted of a 40-element transmitting antenna array and 18 potential targets is built at 2.45 GHz in Fig. 2. In order to prove the generality of the method, three of the 18 potential targets are selected to be wirelessly powered and the positions of these three targets are also randomly selected. It can be seen from Fig. 2 that one of the targets is selected at the bottom-left corner of the upper plane while the other two targets are arranged at the upper-left corner and bottom-right corner of the lower plane. The receiving antennas at the other 15 receiving locations are evenly distributed in space to suppress the power density at these locations expected to be zero-field points. While the MPT scheme is determined, the S-parameters used later in (3) are obtained by full-wave

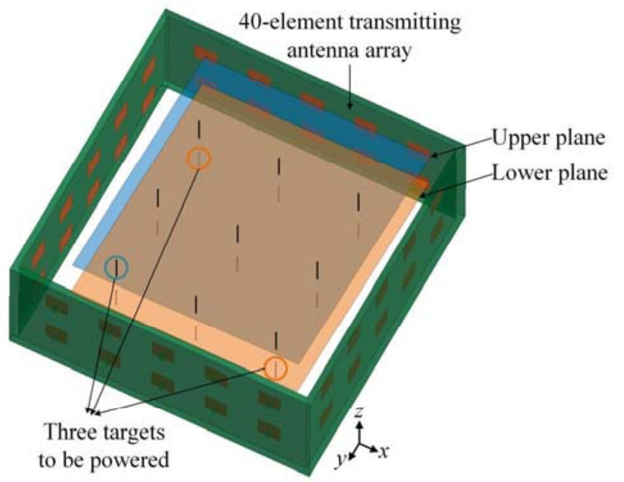

Figure 2. The proposed 40-to-3 MPT scheme.

Table I. Values for Different Power Proportions

Weight	1:1:1	1:2:3	Weight	1:1:1	1:2:3
w_1	100	100	w_{10}	1	1
w_2	1	1	w_{11}	1	1
w_3	1	1	w_{12}	100	141.4
w_4	1	1	w_{13}	1	1
w_5	1	1	w_{14}	1	1
w_6	1	1	w_{15}	1	1
w_7	1	1	w_{16}	100	173.3
w_8	1	1	w_{17}	1	1
w_9	1	1	w_{18}	1	1

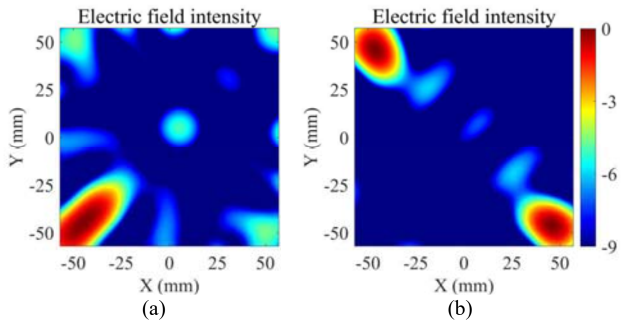

Figure 3. Contour plots of the simulated E-field intensities of upper plane and lower plane for the case of 1:1:1. (a) Upper plane. (b) Lower plane.

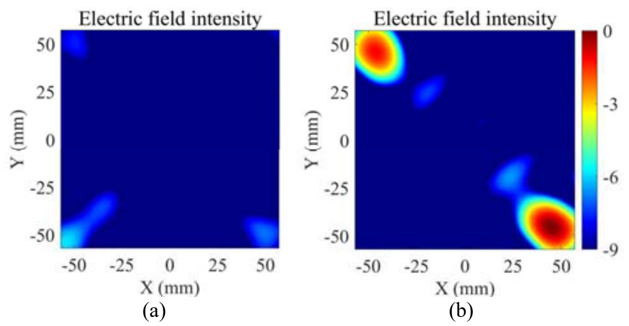

Figure 4. Contour plots of the simulated E-field intensities of upper plane and lower plane for the case of 1:2:3. (a) Upper plane. (b) Lower plane.

simulation in ANSYS HFSS (High Frequency Structural Simulator) software. Two different power proportions of 1:1:1 and 1:2:3 for the same three targets are separately designed. Following the optimization procedure mentioned in operational mechanism, the values of weights are shown in Table I. The optimal excitations for these two cases can be calculated by (3) and then realized by two feeding networks or radio frequency boards with phase shifters and attenuators.

The normalized electric field distributions of both upper plane and lower plane for different power proportions have been plotted in Fig.3 and Fig.4. It can be seen from Fig.3(a) and Fig.3(b) that the electric field intensities at the three receiving antenna positions are almost equal, while the electric field intensities at the rest of the space are kept below a very low level. The PTEs for each receiving target are 6.7%, 6.7% and 6.7%, which is consistent with the preset proportion of 1:1:1. Fig.4(a) and Fig.4(b) show the simulated results of the upper plane and lower plane of the 1:2:3 case. The spot at the bottom-left corner related to the first target in Fig.4(a) is in light-blue because Fig. 4(a) and Fig. 4(b) share the same scale. The received power should be 3dB and 4.8dB smaller than the second target and third target in terms of numerical value. Except for these three positions of targets, the electric field intensities at other positions are very low. The PTEs for the three targets are 3.1%, 6.2% and 9.2%, which is also well-matched with the desired power proportion of 1:2:3. Further antenna manufacture, field experiments and PTE measurement will be carried out later.

4 Conclusion

A method for optimal designs of multi-target microwave power transmission is proposed. Based on WCMMPTE, the optimal distribution of excitations for the transmitting antenna array given in the form of an analytical solution not only ensures the maximum power transmission efficiency but also meets the required power proportion. A 40-to-3 microwave power transmission system is built and validations have been performed to achieve the different power proportions of 1:1:1 and 1:2:3 while the corresponding system power transmission efficiencies are 20.1% and 18.5%, respectively.

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