Efficient Microwave Wireless Power Transmission using Optimization Algorithm

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***Abstract*—In this study, we developed an efficient microwave wireless power transmission (MPT) system for multiple receivers using an optimization (OPT) technique. The optimization algorithm finds the optimal transmission signal for transferring the desired power to multiple receivers with maximum power transfer efficiency (PTE). We designed a 5 × 5 rectangular patch array antenna and patch element antenna operating at 10 GHz as the transmitter and receiver, respectively. The operating process of the MPT system using the OPT technique is analyzed. Additionally, we compared the received power of each receiver and the PTE of the OPT technique with that of the multi-receiver time-reversal (MR-TR) technique considering various scenarios. The OPT algorithm generates a multibeam to charge multiple receiver simultaneously. We validated that the OPT technique can deliver power to receivers precisely at desired ratios with greater PTE than that of the MR-TR technique in an MPT system.**

***Index Terms*—microwave wireless power transmission, array antenna, optimization algorithm.**

I. INTRODUCTION

Microwave wireless power transmission (MPT) is a position-free long-range wireless power transmission (WPT) technology that uses microwaves to transmit energy to the receivers in the radiative near-field and far-field regions. Recently, the demand for powering widespread electronic devices and sensors in homes and offices, such as the Internet of things and 5G, has increased the academic and industrial interests in MPT [1][2]. Particularly, the operating frequency has increased to the millimeter-wave (mmWave) range owing to the use of 5G and the possibility of improving the efficiency. When multiple electronic devices need to be charged through MPT, each device requires different amounts of power as it relies on the charging state of the device. Therefore, an MPT system that can obtain the maximum power transfer efficiency (PTE) and supply power to each receiver with a specified power ratio is essential. PTE is defined as ratio of received power at port of receivers and transmitted power at port of transmitter.

Various methods aimed at charging multiple receivers through MPT have been explored [3]–[9]. Studies on MPT have focused on waveform optimization for multiple rectennas that uses a multi-sine signal [3][4]. Additionally, multi-beamforming antennas and systems have been proposed for MPT [5]–[7]. However, these studies have not reported a method for achieving the maximum PTE, which is the core aspect of MPT. Moreover, the accurate charging of each receiver with the desired power has not been addressed thus far. Furthermore, although the optimization problem of MPT for multiple receivers has been solved using a scattering matrix [8] and non-convex quadratically constrained quadratic program (QCQP) [9], these methods do not ensure a general optimum solution when the desired ratio of the received power is unequal. The time-reversal (TR) technique is considered to be an effective method for maximizing PTE. However, in practical cases that focus on human safety [10] and charging multiple receivers, TR is not the ideal solution for MPT.

In this study, we developed an efficient MPT system that can charge multiple receivers using a convex optimization algorithm. An optimization (OPT) technique is proposed to design the optimal signal that can charge receivers at the maximum total PTE while simultaneously satisfying the desired charging power ratio. Initially, we formulated an optimization problem that can maximize the PTE under the constraint of charging multiple receivers with the desired received power ratio (RPR). The initial optimization problem was transformed into a convex optimization problem (CVP) using several ideas. A 5 × 5 rectangular patch array antenna and patch element antenna operating at 10 GHz were designed as the transmitter and receiver, respectively. The operation of the WPT system was analyzed using the proposed OPT technique, and the MPT system was simulated using a three-dimensional full electromagnetic simulator, namely CST Microwave Studio. We considered several scenarios with multiple receivers at various positions in the radiative near-field region of the transmitter. The electric field (E-field) distribution, which is known to indicate multi-beamforming of the MPT system, was analyzed. Furthermore, performance parameters, such as PTE, received power, and the actual RPR at the receivers of the proposed OPT technique were compared with the results of the multi-receiver TR (MR-TR) technique. Based on the experimental results, we determined that the MPT system precisely transfers power to multiple receivers using the proposed OPT technique.

II. OPTIMIZATION ALGORITHM FOR MICROWAVE WIRELESS POWER TRANSMISSION

This optimization problem is aimed to transfer power to the multiple receivers with the desired ratio and maximum power transmission to achieve maximum PTE. The problem is applied for an MPT system with N transmitting antennas at arbitrary positions and M receivers. Let a transmitted signal vector be $\mathbf{S} = [s_1, s_1 \cdots s_N]^T$. The n-th element of $\mathbf{S}$, $s_n = v_n e^{j\psi_n}$, expresses the input voltage for the n-th transmitting antenna. v_n and ψ_n are the amplitude and phase of the transmitted signal, respectively. The voltage received at the m-th receiving antenna can be obtained with $V_{Rm}(\mathbf{S}) = \sum_{n=1}^{N} h_{m,n} s_n = \mathbf{H}_m^T \mathbf{S}$. Assuming the channel response is known to the transmitter, the optimization problem aims at finding the optimal set of $\mathbf{S}$. The problem maximizes the total received power of multiple receivers subject to constraints, the limited total transmitted power and the ratio of the received power of each receiver, i.e.,

$$\max \quad P_R(\mathbf{S}), \tag{1}$$

$$\text{subject to} \quad \frac{\|\mathbf{S}\|_F^2}{R} \le P, \tag{2}$$

$$\frac{|V_{R1}(\mathbf{S})|^2}{|V_{Rm}(\mathbf{S})|^2} \le \beta_m, \; 2 \le m \le M. \tag{3}$$

The objective function, $P_R(\mathbf{S})$, is set to proportional to the total power received at multiple receivers and expressed as $\sum_{m=1}^{M} |V_{Rm}(\mathbf{S})|^2$. Under a given total transmit power condition, maximizing the total received power is equivalent to maximizing the PTE. The total transmit power of optimal signal is constrained by the inequality (2), where R and P are the port impedance and the limited transmitted power of MPT system, respectively. The received power of each receiver is expressed as its ratio to the power of the first receiver as in (4): β_m is the ratio of the received power of the m-th to the 1st receiver. The problem (1)–(3) is not convex [11]. The problem, however, can be converted into a GP, i.e. convex problem, as shown in [10].

Divide $\mathbf{S}$ into $\mathbf{S}_1, \cdots, \mathbf{S}_M$, where M is the number of the receivers, i.e., $\mathbf{S} = \sum_{m=1}^{M} \mathbf{S}_m$ and $\mathbf{S}_m = [s_{m,1}, s_{m,2} \cdots s_{m,N}]^T$. The n-th element of $\mathbf{S}_m$, $s_{m,n} = v_{m,n} e^{j\psi_{m,n}}$, expresses the input voltage for the n-th transmitting antenna, where $v_{m,n}$ and $\psi_{m,n}$ refer to the amplitude and phase of the transmitted signal, respectively. Now, we can determine the phase of the transmitting signal with the same approach used in the TR technique, i.e., $\psi_{m,n} = -\phi_{m,n}$.

The problem (1)–(3) can be transformed to the equivalent epigraph problem form. By transforming the left sides of constraints into posynomials, this optimization problem can be converted to a convex problem. $|V_{Rm}(\mathbf{S})|^2$ can be expressed as $P_m(\mathbf{S}) - N_m(\mathbf{S})$. $P_m(\mathbf{S})$ and $N_m(\mathbf{S})$ are the sums of absolute value of the positive and negative terms of polynomial, respectively, i.e., posynomials. Subsequently, $P_R(\mathbf{S})$ can be expressed as $\sum_{m=1}^{M} [P_m(\mathbf{S}) - N_m(\mathbf{S})]$, and problem (2)–(4) transform into problem (5)–(8).

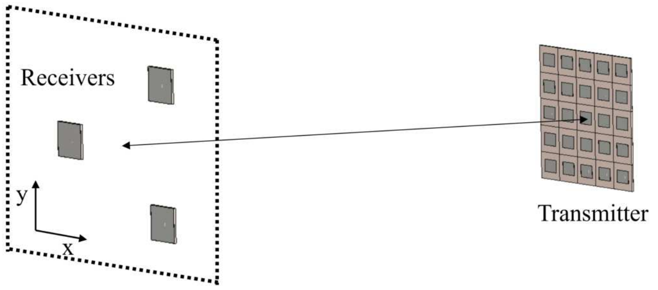


Fig. 1. Microwave wireless power transmission (MPT) system comprising a transmitter and three receivers positioned on the same plane.

$$\min \quad 1/t \tag{4}$$

$$\text{subject to} \quad \frac{\|\mathbf{S}\|_F^2}{R} \le P \tag{5}$$

$$\frac{t + \sum_{m=1}^{M} N_m(\mathbf{S})}{\sum_{m=1}^{M} P_m(\mathbf{S})} \le 1 \tag{6}$$

$$\frac{P_1(\mathbf{S}) + \beta_m N_m(\mathbf{S})}{N_1(\mathbf{S}) + \beta_m P_m(\mathbf{S})} \le 1, 2 \le m \le M \cdot \tag{7}$$

The idea is to upper bound $[t + \sum_{m=1}^{M} N_m(\mathbf{S})] / \sum_{m=1}^{M} P_m(\mathbf{S})$ by a posynomial function [12]. The upper bound is obtained with the inequality of arithmetic and geometric means. Consider $\{p_k(\mathbf{S})\}$ as a set of monomial terms in the posynomial $\sum_{m=1}^{M} P_m(\mathbf{S}) = \sum_{k=1}^{K} p_k(\mathbf{S})$. K is the number of positive terms of $\sum_{m=1}^{M} P_m(\mathbf{S})$. Because $\sum_{k=1}^{K} p_k(\mathbf{S}) \ge \prod_{k=1}^{K} \left(\frac{p_k(\mathbf{S})}{x_k}\right)^{x_k}$ with $x_k \ge 0$ and $\sum_{k=1}^{K} x_k = 1$, $[t + \sum_{m=1}^{M} N_m(\mathbf{S})] / \sum_{m=1}^{M} P_m(\mathbf{S})$ is upper bounded by a posynomial.

In this step, the above concept is applied to convert the left side of (7) into a posynomial. Consider $\{f_z(\mathbf{S})\}$ as a set of monomial terms in a posynomial $N_1(\mathbf{S}) + \beta_m P_m(\mathbf{S}) = \sum_{z=1}^{Z_m} f_z(\mathbf{S})$. Hence, for a given choice of $\{x_k\}$ and $\{x_z\}$, the initial problem is replaced by an equivalent convex problem, i.e.,

$$\min \quad 1/t \tag{8}$$

$$\text{subject to} \quad \frac{\|\mathbf{S}\|_F^2}{R} \le P \tag{9}$$

$$\left(t + \sum_{m=1}^{M} N_m(\mathbf{S})\right) \prod_{k=1}^{K} \left(\frac{P_m(\mathbf{S})}{x_k}\right)^{-x_k} \le 1 \tag{10}$$

$$\left[P_1(\mathbf{S}) + \beta_m N_m(\mathbf{S})\right] \prod_{z=1}^{Z_m} \left(\frac{f_z(\mathbf{S})}{x_z}\right)^{-x_z} \le 1, 2 \le m \le M \tag{11}$$

where $x_z \ge 0$ and $\sum_{z=1}^{Z_m} x_z = 1$. Z_m is the number of positive terms of $N_1 + \beta_m P_m(\mathbf{S})$. The transformed optimization problem (16)–(19) is the standard GP, i.e., a convex problem [11]. An iterative computation method using the approach in [13] can be used to find the sets of $\{x_k\}$ and $\{x_z\}$.

III. MPT SYSTEM WITH ARRAY ANTENNA

Fig. 1 depicts the MPT system used in this study, which comprises a 5 × 5 patch array antenna as the transmitter and

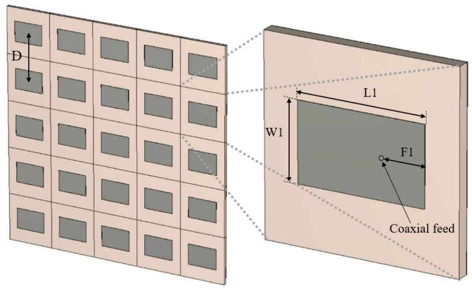


Fig. 2. Designed (a) 5 × 5 patch array antenna as transmitter and (b) the element patch antenna. D = 15 mm, W1 = 6.5 mm, L1 = 9.5 mm, F1 = 2.98 mm.

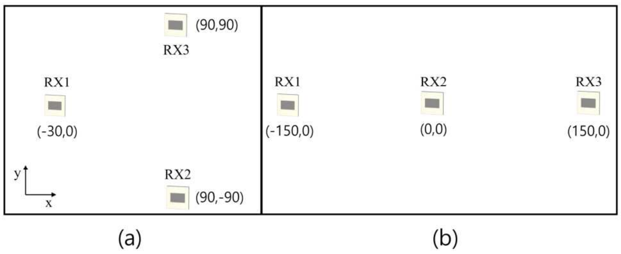


Fig. 3. Positions of the three receivers as viewed from the transmitter. Each position of the receiver is marked adjacent to the antenna relative to the origin, which is the center of the transmitter plane. (a) Scenario 1: Triangular arrangement; (b) Scenario 2: Linear arrangement. Three receivers are placed on the same plane 350 mm away from the transmitter.

several patch antennas as receivers. The antennas of the transmitter and receiver were designed using a 1-mm-thick and 15-mm-long Rogers RT/Duroid 5880 square substrate with a dielectric constant of 2.2. The single element in the patch array antenna was designed as a rectangle with dimensions of 6.5 × 9.5 mm and coaxial feed, as illustrated in Fig. 2. The dimensions of the patch array antenna were set based on the targeted operating frequency of 10 GHz, and the interval of each element is half the wavelength. The receiver was designed as a rectangular patch antenna with dimensions of 6 × 9.8 mm. These antennas were simulated using the CST Microwave Studio. The receivers were positioned on the same plane, as depicted in Fig. 1. The distance between the transmitter and receiver planes was set to 350 mm, which is the radiative near-field region of the transmitter. We considered multiple positions of the three receivers and various ratios of the received power in this study.

The proposed optimization algorithm serves as the core of the MPT system; therefore, its implementation is essential. Initially, the pilot signal is transmitted from the receiver to the transmitter, and the transmitter calculates the channel response between the receiver and transmitter based on the received pilot signal. In this study, this process was simulated using CST Microwave Studio. The optimal transmitted signals are then obtained using the proposed OPT technique via a convex optimization solver, namely CVX [14]. Finally, the transmitter transmits the optimal power signal obtained using the OPT technique. To perform a comparative analysis, the result of OPT technique was compared to that of the MR-TR technique. The transmitted signals for each receiver were obtained by pilot signal transmitted from each receiver. The total transmitted signal of MR-TR technique was calculated by summing the transmitted signals for each receiver considering desired RPR.

TABLE I. PERFORMANCE COMPARISON OF OPT AND MR-TR TECHNIQUES CONSIDERING THE SCENARIO WITH THREE RECEIVERS (FIG. 3)

Desired received power ratio			**RX1 (mW)**	**RX2 (mW)**	**RX3 (mW)**	**PTE (%)**
Scenario 1	1:1:1	TR	4.9	3.4	3.4	1.17
		OPT	4.9	4.9	4.9	1.48
	1:1:2	TR	2.3	1.0	7.9	1.11
		OPT	3.6	3.6	7.3	1.48
Scenario 2	1:1:1	TR	4.1	4.1	4.1	1.22
		OPT	4.2	4.2	4.2	1.25
	1:1:2	TR	1.9	1.9	7.5	1.13
		OPT	3.0	3.0	6.0	1.20

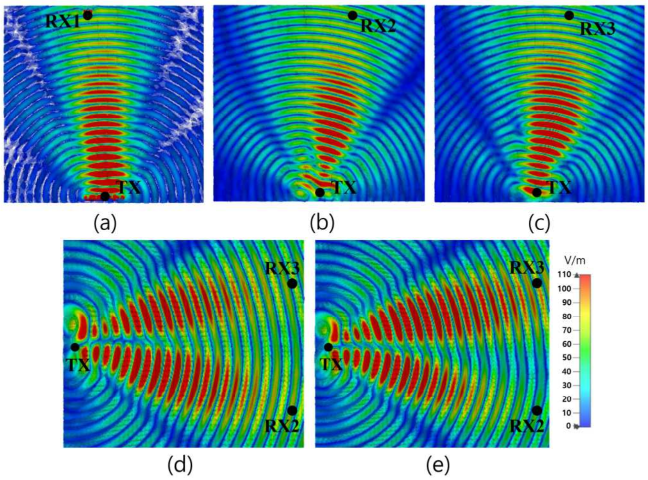
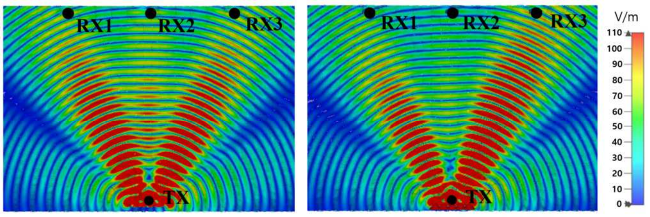


Fig. 4. Electric field distribution of scenario 1 when the optimization (OPT) technique is used. (a) y = 0 mm, (b) y = −45 mm, and (c) y = 45 mm plane when the received power ratio (RPR) is 1:1:1. x = 45 mm plane when the RPR is (d) 1:1:1 and (e) 1:1:2. The three receivers are charged simultaneously.

IV. RESULTS AND DISCUSSION

Table I summarizes the comparison of the received power and PTE considering all scenarios of the OPT and MR-TR techniques. In the OPT technique, the ratio of the received power was equal to the desired value in all cases. By contrast, large errors were observed in the desired and actual RPRs in the case of the MR-TR technique. In scenarios 1 and 2, the actual ratios of the received power were 1:0.43:3.43 and 1:1:3.95, respectively, when the desired RPR was 1:1:2 considering the MR-TR technique. Therefore, the PTE of the OPT technique was greater than that of the MR-TR technique.

Figs. 4 and 5 illustrate the E-field distributions of scenarios 1 and 2, respectively, when OPT technique is used. As depicted in Figs. 4 (a), (b), and (c), three multibeam were generated in scenario 1 when the RPR was 1:1:1. As the receiver was placed on different xz planes, we selected the planes y = 0 mm, y = −45 mm, and y = 45 mm to indicate the



(a) (b)

Fig. 5. Electric field distribution of scenario 2 on the y = 0 mm plane considering the optimization (OPT) technique with the received power ratios (RPRs) of (a) 1:1:1 and (b) 1:1:2.

beams for receivers 1, 2, and 3, respectively. Additionally, we compared the E-field distributions of different RPRs. When the RPR was 1:1 for receivers 2 and 3, the E-field magnitude of the beam was equal. Conversely, when the RPR was 1:2 for receivers 2 and 3, the E-field magnitude of the beam for receiver 3 was larger than that of receiver 2. Fig. 5 illustrates the multibeam generated in scenario 2. Herein, when the RPR was 1:1:1, two beams targeted receivers 1 and 3, whereas one beam with a smaller E-field magnitude targeted receiver 2. However, as receiver 2 was placed between receivers 1 and 3, it was also charged by the two beams that targeted receivers 1 and 3. When the RPR was 1:1:2, the beam of receiver 3 was larger than that of receiver 1. Based on the results of the scenario with three receivers, we validated that the OPT technique improves the performance of MPT for multiple receivers.

V. CONCLUSION

In this study, we developed an efficient MPT method capable of charging multiple receivers using a convex optimization algorithm. The optimization problem was formulated to maximize the PTE based on the constraint of charging multiple receivers with the desired RPR. We transformed the initial optimization problem into a CVP. Additionally, a 5 × 5 rectangular patch array antenna and patch element antenna operating at 10 GHz were designed as the transmitter and receiver, respectively. The MPT system was simulated using CST Microwave Studio and CVX. We considered multiple scenarios with three receivers arranged in linear and triangular positions. The E-field distribution was analyzed to verify the multi-beamforming of the MPT system. The performance parameters, such as the power received at each receiver and the PTE of the OPT, were compared with those of the MR-TR technique considering several scenarios with three receivers. We determined that the actual RPR was equal to the desired RPR in each scenario when the OPT technique was used. By contrast, the MR-TR technique failed to ensure the desired RPR. Therefore, we validated that the OPT technique achieves a greater PTE than the MR-TR technique. Furthermore, the E-field distribution indicates that the receivers are charged by multibeam. Consequently, the proposed OPT technique was verified to be superior to the MR-TR technique in terms of power transmission to multiple receivers. The obtained results can aid in designing improved MPT and mmWave WPT systems.

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