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Analysis of Received Power in RF Wireless Power Transfer System With Array Antennas

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ABSTRACT In this paper, a method for calculating the received power in a radio-frequency wireless power transfer system with array antennas is proposed. The received power is derived based on the superposition of the electric fields that radiate from individual transmitter (Tx) elements and are captured by each receiver (Rx) element. That is expressed in a finite series form with the radiation patterns of an element considering mutual coupling in the array and corresponding distances between the elements of Tx and Rx. Unlike conventional methods (such as the Friis and Goubau formulas), this approach is able to calculate the received power precisely in both Fresnel and far-field regions. It is also efficiently applicable to various cases, such as those involving beamforming and with varying positions of Rx. The calculated results using this method are applied to a 5.2 GHz WPT system with array antennas and verified through comparisons with both simulation and experimental results.

INDEX TERMS Array antenna, beamforming, Fresnel region, Friis formula, received power, wireless power transfer, power transmission efficiency.

I. INTRODUCTION

Wireless power transfer (WPT) technology has been used recently in various applications, such as mobile devices, wearable devices, implantable medical devices, and electrical vehicles. However, most of these applications adapt stationary wireless charging methods based on inductive coupling or resonant coupling [1], [2], meaning that there remains some inconvenience for users. On the other hand, radio-frequency (RF) WPT, sometimes referred to as microwave power transmission (MPT), can transfer wireless energy to a receiver (Rx) over a long and wide range. Even with low WPT efficiency, defined as the ratio of the total received power (P_R) reaching the Rx antenna to the total transmitted power (P_T) radiated from the transmitter (Tx) antenna, it is possible to increase the WPT efficiency by applying an array with multi-elements as Tx or Rx antenna. In addition, beamforming technology with an array antenna ensures wireless power transfers in specific directions [3]–[5]. Accordingly, many studies related to array antennas and beamforming have been conducted in an effort to improve the RF WPT efficiency [6]–[10]. RF WPT technology based on beamforming also enables immediate responses to changes in the position of Rx and transmits the wireless power to a number of devices with a single Tx system. This is why it is suitable for charging various low-power devices and is utilized for wireless sensor networks (WSNs) with Internet of things (IoT) devices [11]–[16].

The WPT efficiency is a key indicator for estimating the performance of a RF WPT system. Specifically, P_R is directly related to the circuit performance of the Rx applications. Hence, before designing a WPT system, it is important to predict the WPT efficiency and P_R to determine the goals of the system and their applications. When carrying out an experiment after implementing an actual system, accurately calculated result data must be obtained to verify the experimental result. The Friis formula [17] is the most well-known formula for obtaining the P_R. It is composed of a simple

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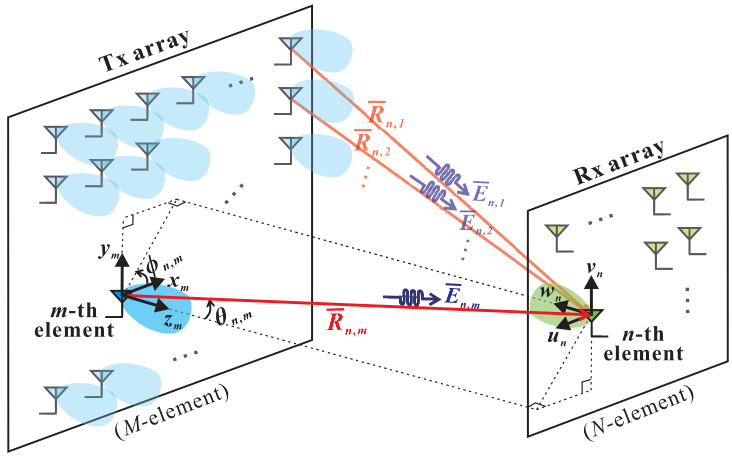


FIGURE 1. RF wireless power transfer (WPT) system with array antennas.

proportional expression and therefore makes it easy to calculate P_R intuitively. However, because this is a valid formula in the far-field region, considerable errors occur in near-field regions relative to the size of the Tx antenna (such as Fresnel and reactive regions [18]). For example, the WPT efficiency result by Friis formula has a value of more than 100% if the power transmission distance is very close to the wavelength. In the 1960s, Goubau [19] developed a WPT efficiency formula that complements this Friis formula [20]. This formula does not yield results that exceed 100% WPT efficiency regardless of the distance value, meaning that the Goubau formula can determine a more accurate P_R compared to the Friis formula. These two formulas have been widely used because they are simple; nevertheless, they result in significant errors in the Fresnel and reactive region. Therefore, various methods of analysis of the WPT efficiency or P_R have been investigated to secure more accurate results in the Fresnel region [21]–[26].

Modified Friis and Goubau formulas with correction terms have also been proposed [21], [22], respectively. In one study [23], in order to decrease the difference between the theoretical and calculated results, the WPT efficiency reflecting the synthesis loss in an Rx array was introduced. These studies could yield improved accuracy of the results in the Fresnel region but require the radiation patterns of the Tx and Rx antennas. Therefore, they are limited because the simulation or measurement of the array pattern is also difficult if the array antenna is large. In other works [24]–[26], methods by which to predict the WPT efficiency were introduced based on the relative distances between individual elements. These approaches make efficient assessments because they do not require simulations or measurements for a large array antenna. However, cases involving beamforming by adjusting the magnitude or phase of the feed signal were not addressed.

Using commercial EM simulation tools results in very accurate outcomes, as doing so makes it possible to model the configuration of Tx and Rx antennas and the channel environments and to simulate the WPT. However, depending on the computer specifications, the size of the analytical model that can be simulated is limited. If the size of the antenna compared to the wavelength is large or the power transmission distance is long, an EM simulation takes a long time and occasionally such a simulation may be impossible. Because most RF WPT systems utilize large array antennas to achieve high WPT efficiency and aim to transmit power over long distances, it is quite restrictive to apply this method to various WPT scenarios. Therefore, it is necessary to develop a simple as well as accurate method to calculate the WPT efficiency and the P_R value for scenarios such as those with beamforming and changes of the Rx position.

In this paper, a method by which to calculate P_R and the WPT efficiency for a RF WPT system with array antennas is proposed. In Section II, the principle of the proposed method is explained. The formulas with which to determine P_R and the WPT efficiency are derived by analyzing electromagnetic interactions based on the superposition of the electric fields radiated from individual Tx elements and captured at each Rx element. Section III applies the proposed method to a variety of WPT scenarios while varying the transmission distances, the type of antenna, the number of array elements, the Rx positions, and the beamforming directions and compares these results to those by the Friis and Goubau formulas and an EM simulation. Measurement results are also shown to verify the results derived when using the proposed method, with an analysis of the results also carried out in Section IV.

II. PRINCIPLE OF THE PROPOSED METHOD

Fig. 1 shows a RF WPT system with a Tx array antenna and an Rx array antenna. Here, it is assumed that no obstacles exist around the Tx antenna and the Rx antenna or between the two. The numbers of the array elements in Tx and Rx are M and N, and the indexes of the elements in Tx and Rx array are expressed as m and n, respectively. In this figure, $\overline{E}_{n,m}$ is the electric field radiated from the m-th Tx element and delivered to the n-th Rx element, and $E_{n,m}$ is the magnitude of $\overline{E}_{n,m}$. $\overline{R}_{n,m} = \hat{a}_{n,m}R_{n,m}$ is the position vector of the n-th Rx element based on the (x_m,y_m,z_m) coordinate system with the center of the m-th Tx element as the origin. When E is the electric field and η is the wave-impedance, the time-averaged magnitude of the Poynting vector in free space is expressed as the power density $W = |E|^2/2\eta$ [27]. Accordingly, $E_{n,m}$ in Fig. 1 is

$$E_{n,m} = \sqrt{2\eta W_{n,m}} e^{-j(kR_{n,m}-\beta_m)}. \quad (1)$$

In (1), k is the wave-number and β_m denotes the excited phase of the m-th Tx element. $e^{-j(kR_{n,m}-\beta_m)}$ shows the phase of the electric field according to the distance ($R_{n,m}$) and initial phase (β_m). $W_{n,m}$ is the received power density from the m-th Tx element to the n-th Rx element and is therefore expressed as follows (2), as shown at the bottom of the next page: If $R_{n,m}$ is in the far-field region of the m-th Tx element, the Friis formula can be applied to calculate the received power from the m-th Tx element to the n-th Rx element [17], [18]. Thus, the denominator of (2) is

$$\frac{\lambda^2 P_{t_m} G_{t_m}\left(\theta_{n,m}, \phi_{n,m}\right) G_{r_n}\left(\theta_{m,n}, \phi_{m,n}\right)}{\left(4\pi R_{n,m}\right)^2}. \quad (3)$$

Here, λ is the wavelength and P_{t_m} is the excited power to the m-th Tx element. $G_{t_m}(\theta_{n,m},\phi_{n,m})$ is the realized gain of the co-polarization of the m-th Tx element in the direction of the n-th Rx element and $G_{r_n}(\theta_{m,n},\phi_{m,n})$ is the realized gain of the co-polarization of the n-th Rx element in the direction of the m-th Tx element. Consequently, (2) is derived as follows:

$$W_{n,m} = \frac{\lambda^2 P_{t_m} G_{t_m}\left(\theta_{n,m}, \phi_{n,m}\right) G_{r_n}\left(\theta_{m,n}, \phi_{m,n}\right)}{\left(4\pi R_{n,m}\right)^2 4\pi R_{n,m}{}^2} \quad (4)$$

Both $G_{t_m}(\theta_{n,m},\phi_{n,m})$ and $G_{r_n}(\theta_{m,n},\phi_{m,n})$ are determined by the relative location and direction between the Tx m-th element and the Rx n-th element according to the spacing and the position of the element in the array. According to (1) and (4), $E_{n,m}$ of the electric field based on the response of the n-th Rx element to individual Tx elements is finally derived as

$$E_{n,m} = \sqrt{2\eta \frac{P_{t_m} G_{t_m}\left(\theta_{n,m}, \phi_{n,m}\right) G_{r_n}\left(\theta_{m,n}, \phi_{m,n}\right)}{4\pi R_{n,m}{}^2}} \times \frac{\lambda}{4\pi R_{n,m}} e^{-j\left(kR_{n,m}-\beta_m\right)}. \quad (5)$$

Based on the definition of the power density which can be obtained by $W = |E|^2/2\eta$, the power of the electric field (E) at distance R away from the source is $P = 4\pi R^2|E|^2/2\eta$. Because the total electric field delivered to the n-th Rx element is expressed as the superposition of the electric field ($E_{n,1}$, $E_{n,2}$, $\cdots$, $E_{n,M}$) radiated from the M-elements of the Tx array, the received power P_{r_n} of the n-th Rx element can be derived as (6)–(9), as shown at the bottom of the next page.

According to (5) and considering that $\theta_{m,n} = \theta_{n,m}$, $\phi_{m,n} = -\phi_{n,m}$, (6) is expressed in a finite series form, as follows (7), with the radiation patterns of Tx and Rx single elements. Given that this principle is equally applicable to all N-elements in the Rx array, the total received power (P_R) can be expressed as (8), assuming that each instance of individual power received is synthesized without loss. The total transmitted power (P_T) radiated from the Tx array is then $\sum_{m=1}^{M} P_{t_m}$. Finally, in the RF WPT system with the Tx array and the Rx array, as shown in Fig. 1, the WPT efficiency can be derived as follows (9).

Because this proposed formula (9) originates from the power relationship between the Tx and Rx elements based on the gain (G_{t_m}, G_{r_n}) of the single antenna, it is valid in the far-field of the single array element. When the largest dimension of an array antenna is D_a and the largest dimension of the single antenna element of the array is D_e, D_a is generally much longer than D_e such that $2D_e{}^2/\lambda \ll 2D_a{}^2/\lambda$, meaning that the proposed formula (9) can be utilized if the power transmission distance is in the far-field region of the single antenna element, regardless of whether or not it is in the far-field region of the array antenna. Also, G_{t_m} and G_{r_n} in (9) can be used in this condition because they are gains of the single antenna element. Therefore, the proposed method can be applied even in the near-field region (such as Fresnel region) of the array antenna if the condition of the transmission distance being in the far-field region of the single Tx element ($> 2D_e{}^2/\lambda$) is met.

Theoretically, the proposed formula (9) can utilize to a WPT system based on an array antenna with a metamaterial or metasurface if the radiation pattern of the individual radiating elements in the array can be obtained (by measurement or a simulation). In contrast, it is not appropriate to apply the proposed method to a WPT systems which is difficult to derive the radiation patterns of radiating elements as they have the variable performance depending on the situation. For examples, in a reflective array antenna with a metasurface [28], the radiation pattern of the individual radiating elements of the reflective array varies according to the direction of the feed antenna. In other case, it is difficult to apply the proposed calculation method to the Rx metasurface array antenna with active elements [29], because the radiation pattern of the individual radiating elements in the Rx array could change depending on the performance of the diodes for the variable input power.

III. VERIFICATION OF THE PROPOSED METHOD

In this section, the proposed method derived from Section II is applied for a variety of WPT scenarios while varying the transmission distances, Rx positions, and the beamforming directions. Results from the method are compared with that of an EM simulation and conventional formulas. Here, we assume a WPT system with a Tx 8 × 8 array and a Rx 2 × 2 array, as shown in Fig. 2, as an example. The Tx array and the Rx array are both composed of simple patches operating at 5.8 GHz with a $0.5\lambda_0$ spacing, and λ_0 is the wavelength of the operating frequency. The Fresnel region ($0.62\sqrt{D^3/\lambda_0} <$ and $< 2D^2/\lambda_0$, where D is the longest length

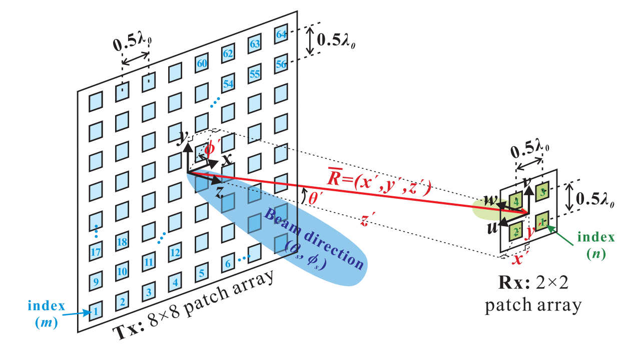


FIGURE 2. WPT system with a transmitter (Tx) of 8 × 8 array and a receiver (Rx) of 2 × 2 array.

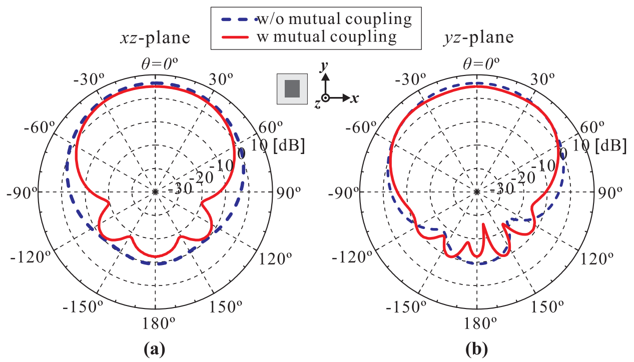


FIGURE 3. 2D radiation patterns of a single patch element on the (a) *xz*-plane and (b) *yz*-plane.

of the antenna) of this Tx antenna is from 0.43 to 3.3 m [18]. The Rx 2 × 2 array is located at (x', y', z') as the origin of the Tx center.

Fig. 3 shows the 2D radiation patterns for co-polarization of the single patch element of the Tx and Rx array according to whether mutual coupling is considered. The radiation pattern without mutual coupling refers to the pattern when the single patch stands alone in free-space. On the other hand, the radiation pattern with mutual coupling is the pattern when the patch is within the array, considering mutual interference with neighboring patch elements in the array. As shown in Fig. 3, distortion of the radiation pattern arises due to the mutual coupling.

A. NON-BEAMFORMING (Uniform EXCITATION)

Fig. 4 shows the WPT efficiency results when using the proposed method with (9), the conventional methods, and the EM simulation. It is assumed that a uniform signal is fed to each Tx antenna and that the main beam is formed in the $+z$-direction. For the position of Rx (x', y', z'), x' and y' are 0 and only z' (the transmission distance in this case) is changed. CST Microwave Studio Software is used in the simulation. The conventional methods in this paper are the Friis formula [17] of (10) and the Goubau formula [19], [20] of (11). G_t is the gain of the Tx 8 × 8 array antenna, G_r is the gain of the Rx 2 × 2 array antenna, and the values are 22.86 dBi and 10.75 dBi, respectively. Here, the R is the distance between the centers of Tx and Rx, and in this case $R = z'$. In (11), A_t and A_r correspond to the aperture area of the Tx antenna and to that of the Rx antenna, respectively. These values can be correspondingly expressed as G_t and G_r by $A = G\frac{\lambda^2}{4\pi}$ [18].

$$\frac{P_R}{P_T} = G_t(\theta', \phi')\, G_r(\theta', -\phi')\left(\frac{\lambda}{4\pi R}\right)^2 \tag{10}$$

$$\frac{P_R}{P_T} = 1 - e^{-\frac{A_t A_r}{(\lambda R)^2}} \tag{11}$$

As the power transmission distance exceeds 0.052 m $(=2D_e{}^2/\lambda)$, the WPT efficiency in Fig. 2 is able to be calculated by the proposed formula (9). Here, $M = 64$, $N = 4$, $P_{t_1} = P_{t_2} = \cdots = P_{t_{64}}$, and $\beta_1 = \beta_2 = \cdots = \beta_{64}$. The values of $\theta_{n,m}$, $\phi_{n,m}$, and $R_{n,m}$ are determined by the

$$W_{n,m} = \frac{\text{the received power from } m\text{-th Tx element to } n\text{-th Rx element}}{4\pi R_{n,m}{}^2} \tag{2}$$

$$P_{r_n} = \frac{4\pi}{2\eta}\left|R_{n,1}E_{n,1} + \ldots + R_{n,m}E_{n,m} + \ldots + R_{n,M}E_{n,M}\right|^2. \tag{6}$$

$$P_{r_n} = \left(\frac{\lambda}{4\pi}\right)^2 \left|\sum_{m=1}^{M} \sqrt{P_{t_m} G_{t_m}(\theta_{n,m}, \phi_{n,m})\, G_{r_n}(\theta_{n,m}, -\phi_{n,m})}\, \frac{e^{-j(kR_{n,m}-\beta_m)}}{R_{n,m}}\right|^2 \tag{7}$$

$$P_R = \sum_{n=1}^{N} P_{r_n} = \left(\frac{\lambda}{4\pi}\right)^2 \sum_{n=1}^{N} \left|\sum_{m=1}^{M} \sqrt{P_{t_m} G_{t_m}(\theta_{n,m}, \phi_{n,m})\, G_{r_n}(\theta_{n,m}, -\phi_{n,m})}\, \frac{e^{-j(kR_{n,m}-\beta_m)}}{R_{n,m}}\right|^2 \tag{8}$$

$$\frac{P_R}{P_T} = \left(\frac{\lambda}{4\pi}\right)^2 \frac{\sum_{n=1}^{N} \left|\sum_{m=1}^{M} \sqrt{P_{t_m} G_{t_m}(\theta_{n,m}, \phi_{n,m})\, G_{r_n}(\theta_{n,m}, -\phi_{n,m})}\, \frac{e^{-j(kR_{n,m}-\beta_m)}}{R_{n,m}}\right|^2}{\sum_{m=1}^{M} P_{t_m}} \tag{9}$$

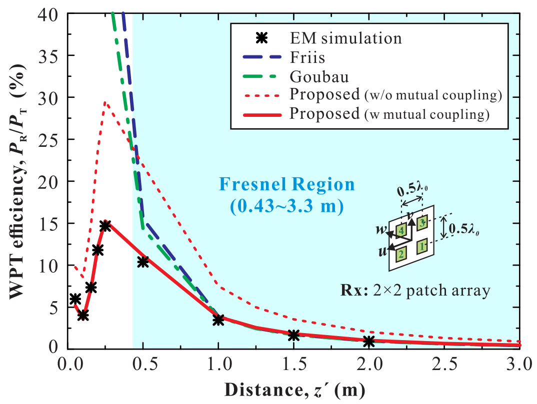


FIGURE 4. WPT efficiency with respect to the distance between Tx and Rx.

relative locations and directions of the Tx and Rx elements. Here, $G_{t_m}(\theta_{n,m},\phi_{n,m})$ and $G_{r_n}(\theta_{n,m},-\phi_{n,m})$ in (9) are obtained from the radiation patterns of their corresponding elements depending on the $\theta_{n,m}$ and $\phi_{n,m}$.

As shown in Fig. 4, the results calculated using the proposed method are in good agreement with the EM simulation results. Note that the accuracy of the derived result is guaranteed by applying the radiation pattern considering the mutual coupling in Fig. 3. On the other hand, in the Fresnel region (especially when the distance < 1 m), the results by the Friis formula have a large error with the EM simulation result. The Goubau results produce values that are smaller than those by Friis, but the errors are also significant.

Figs. 5(a) and (b) show the results of the WPT efficiency when the Rx is a 4 × 1 dipole array and an 8 × 1 dipole array, respectively. It is assumed that the Tx antenna is the 8 × 8 patch array, identical to the Tx in Fig. 2, and that the Rx dipole arrays of 4 × 1 and 8 × 1 are composed of 5.8 GHz half-wavelength dipole elements whose gain are 2.2 dBi. As when calculating (9) for the case of Fig. 4, the radiation patterns applied to the calculation consider the mutual coupling of the each array element (Tx: patch, Rx: dipole). In these cases, the results of the proposed calculation method are in good agreement with the EM simulation results, much more than the conventional calculation method. As shown in Fig. 4 and Fig. 5(a), even with an identical number of Rx array elements, it can be seen that the received power can change depending on the arrangement of the array or the type of antenna element used. According to the calculated and simulated results in Figs. 5(a) and (b), when the number of Rx elements is doubled, the received power increases, but does not double. This occurs because the received power of the individual Rx elements according to their positions in the array differs. As a result, regardless of the type or number of array antennas, it can be seen that the proposed calculation method is useful for analyzing various WPT scenarios.

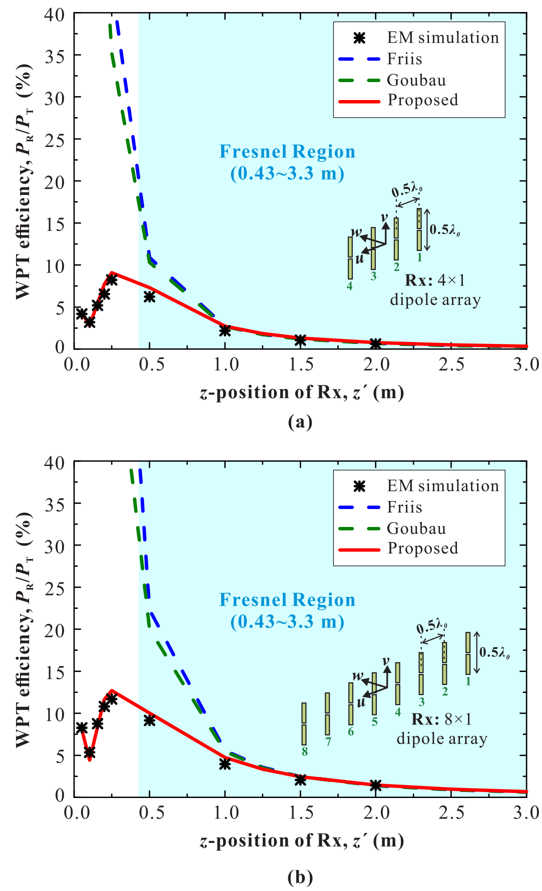


FIGURE 5. WPT efficiency with respect to the distance between Tx and Rx when the Rx is (a) a 4 × 1 dipole array and (b) an 8 × 1 dipole array.

B. BEAMFORMING

Array technology is often used with Tx antennas in a WPT system because this technology facilitates beamforming in a desired direction with a desired beam-shape by adjusting the magnitude and phase of the signal fed to each array element. In this section, the WPT efficiency is calculated according to Rx position, considering for beamforming in a specific direction. Fig. 6 presents the information of the phase of the signal and the power excited to each of the Tx 8 × 8 array elements in Fig. 2. Fig. 6(a) shows the excited phase-set (β_m) for steering the main beam in the direction of $\theta_s = 30°$ and $\phi_s = 0°$, and Fig. 6(b) is the excited power-set (P_{t_m}) when applying -18 dB Taylor weighting for side-lobe reduction, leading to the formation of a beam pattern such as that in Fig. 6(c).

When Rx is placed at two different positions, Fig. 7 displays the result after calculating the WPT efficiency with respect to the z-position (z') of Rx. Fig. 7(a) shows a case in which Rx is located in the beamforming direction ($\theta' = \theta_s = 30°$, $\phi' = \phi_s = 0°$). Fig. 7(b) presents the results when Rx is placed in front of Tx ($\theta' = 0°$, $\phi' = 0°$); consequently, $\theta_s \neq \theta'$ and $\phi_s \neq \phi'$. Even when considering the phase and power fed to the Tx-elements, the results by the

Tx: 8×8 patch array

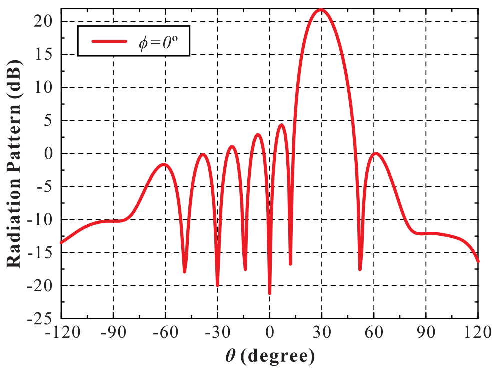
0°	270°	180°	90°	0°	270°	180°	90°
0°	270°	180°	90°	0°	270°	180°	90°
0°	270°	180°	90°	0°	270°	180°	90°
0°	270°	180°	90°	0°	270°	180°	90°
0°	270°	180°	90°	0°	270°	180°	90°
0°	270°	180°	90°	0°	270°	180°	90°
0°	270°	180°	90°	0°	270°	180°	90°
0°	270°	180°	90°	0°	270°	180°	90°

(a)

Tx: 8×8 patch array

0.14W	0.20W	0.29W	0.37W	0.37W	0.29W	0.20W	0.14W
0.20W	0.28W	0.41W	0.53W	0.53W	0.41W	0.28W	0.20W
0.29W	0.41W	0.62W	0.79W	0.79W	0.62W	0.41W	0.29W
0.37W	0.53W	0.79W	1.00W	1.00W	0.79W	0.53W	0.37W
0.37W	0.53W	0.79W	1.00W	1.00W	0.79W	0.53W	0.37W
0.29W	0.41W	0.62W	0.79W	0.79W	0.62W	0.41W	0.29W
0.20W	0.28W	0.41W	0.53W	0.53W	0.41W	0.28W	0.20W
0.14W	0.20W	0.29W	0.37W	0.37W	0.29W	0.20W	0.14W

(b)



(c)

FIGURE 6. Excitation information and radiation pattern of the Tx 8 × 8 array in Fig. 2: (a) excited phase-set, (b) excited power-set, and (c) 2D radiation pattern on the $\phi = 0°$ plane.

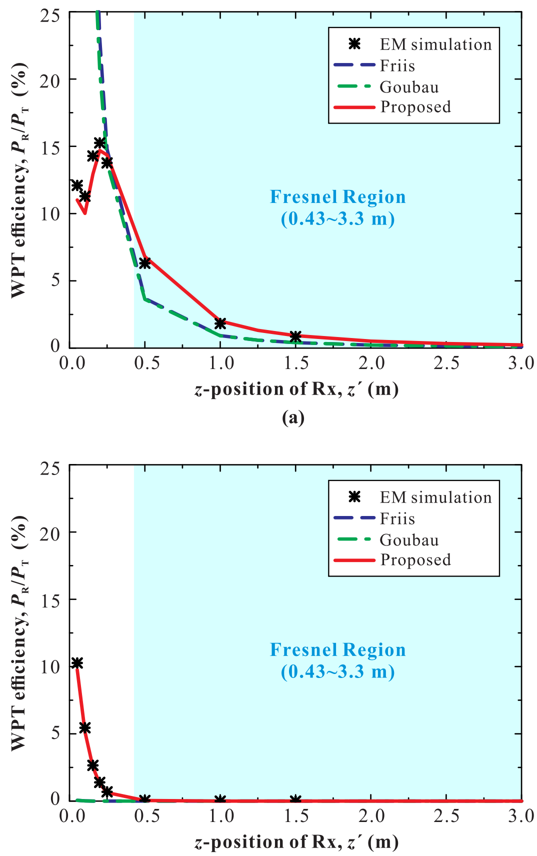


FIGURE 7. WPT efficiency for beamforming in the $\theta_S = 30°$ and $\phi_S = 0°$ direction when Rx is (a) located in the direction of ($\theta' = 30°$, $\phi' = 0°$) and is (b) not located in the direction of ($\theta' = 0°$, $\phi' = 0°$).

proposed method are more consistent with the EM simulation results than those by the conventional methods. In particular, according to Fig. 7(b), the WPT efficiency results when using the Friis and Goubau formulas are close to 0% in both the near- and far-field regions. Nevertheless, as shown in the EM simulation results, in the Fresnel and reactive regions, little power is received even if the Rx is not located in the direction of the main beam; this is also confirmed by the results of the proposed method.

Hence, the proposed method is shown to be effective when used to calculate the WPT efficiency in both far-field and Fresnel regions, and it is suitable when applied in the WPT scenarios of beamforming and in various Rx positions. Moreover, although the simulation results are reliable, conducting EM simulations for all WPT scenarios is very time-consuming work. On the other hand, the proposed method requires no additional EM simulations or measurements to obtain the gain or radiation pattern of an array antenna if the WPT scenario is changed, and it is a reasonable and efficient method for obtaining results for various WPT scenarios.

IV. EXPERIMENTAL VERIFICATION

A. EXPERIMENT SETUP

To verify the proposed method experimentally, 5.2 GHz left-handed circular polarization (LHCP) patch arrays were designed and fabricated to implement an actual WPT system, as shown in Fig. 8. The Tx system of the WPT system consists of Tx circuits, a micro-controller (MCU), and an 8 × 4 patch array antenna. The single Tx circuit includes a phase-shifter, an attenuator, and a power amplifier and is connected to the single patch element. The MCU controls the phase of the signal fed to the Tx antenna for beamforming in the desired direction. The Tx 8 × 4 array is composed of patch elements that operate with LHCP forming at 5.2 GHz (in Fig. 8(b)). The spacing between the patch elements is 34 mm ($0.59\lambda_0$), and the overall size of the array is 272 mm × 136 mm. The Fresnel region of this 5.2 GHz Tx array is from 0.43 to 3.2 m. A Rx 2 × 3 array is also designed with 5.2 GHz LHCP patch elements (in Fig. 8(c)), but its geometry differs from the patch element of the Tx array. It has a total size of 72 mm × 135 mm, with a horizontal spacing of $0.63\lambda_0$ and a vertical spacing of $0.78\lambda_0$. Fig. 9 displays the simulated results of each Tx and Rx element. When considering the mutual coupling within each array, the radiation patterns of the Tx and Rx patches are shown in Fig. 9(a) and Fig. 9(b), respectively, and their corresponding gains are approximately 6.15 dBic and 5.7 dBic.

The WPT experiment was performed changing the Rx positions (x', y', z'). In order to focus the wireless power on the Rx positions, phase-sets for beam-focusing were applied

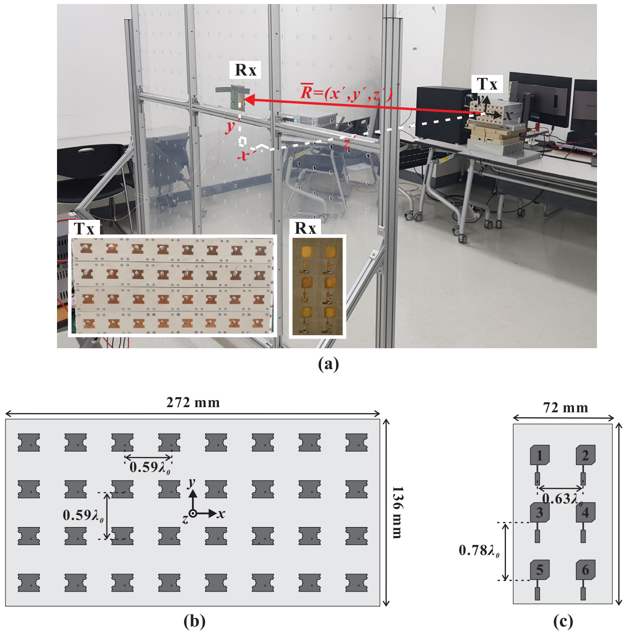


FIGURE 8. 5.2 GHz WPT experiment: (a) experimental setup, (b) Tx 8 × 4 array, and (c) Rx 2 × 3 array.

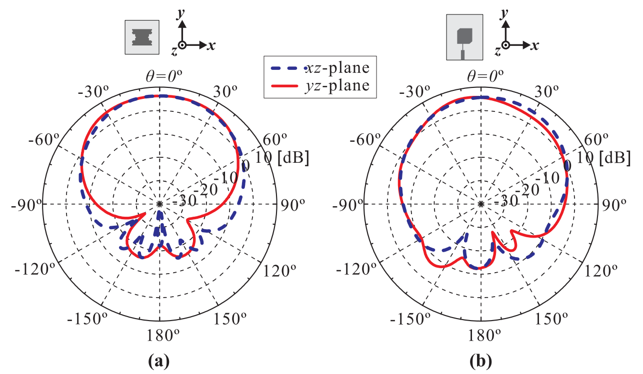


FIGURE 9. 2D radiation patterns of a single element at 5.2 GHz in (a) the Tx array and (b) the Rx array.

to the Tx array in each WPT scenario. Uniform power of 0.5 W is supplied to each Tx patch element, and the total transmitted power (P_T) is 16 W.

B. RESULTS AND ANALYSIS

The received power by the third element in Rx as shown in Fig. 8(c) was measured with a spectrum analyzer (Agilent E4440A). The results are described in Fig. 10 and Fig. 11. When the Tx and Rx are in the line-of-sight (LOS) ($x'=y'=0$), Fig. 10(a) shows the experimental results of the received power according to the power transmission distance (z') and the value of WPT efficiency in Fig. 10(b) was calculated based on Fig. 10(a). As shown in Fig. 10, the received power decreases as the distance (z') increases and the range of the measured received power was from 9.8 dBm to 22.5 dBm. As a result, it is apparent that the experiment was well

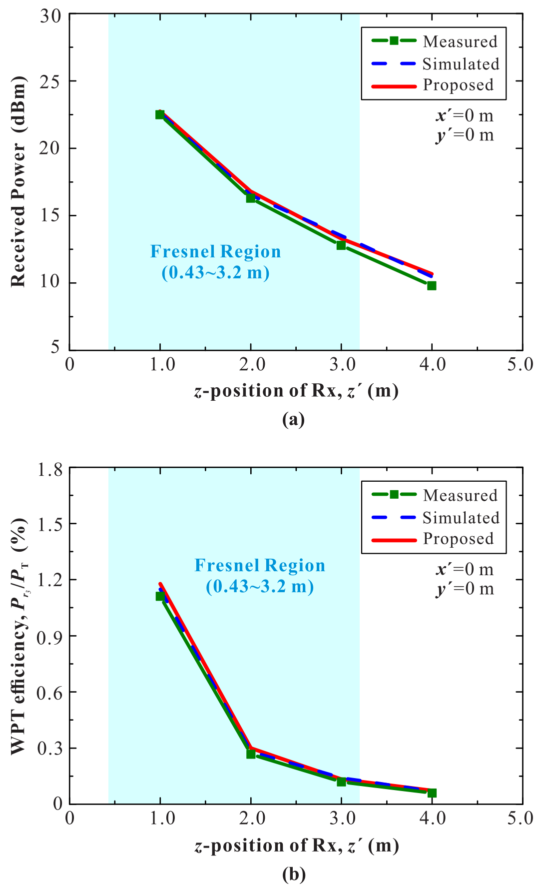


FIGURE 10. Comparison of the results according to the power transmission distance (z'): (a) received power of the third element in Rx and (b) WPT efficiency of the third element in Rx.

performed because the experimental results are in good agreement with the calculation results as well as the EM simulation results. It indicates that the proposed method in this paper is valid to calculate the WPT efficiency in both Fresnel region (0.43 m–3.2 m) and far-field region (> 3.2 m). In addition, Fig. 11 depicts the experimental results of the received power according to the position of Rx (x', y', z') in the off-axis ($x' \neq 0$). As the position of the Rx deviates from the center, the measured power decreases, and this can also be seen in the results of the calculations and simulations. Accordingly, it proves that the proposed method is quite accurate and applicable to both Fresnel regions and beamforming in various directions. There are small mismatches between the calculated and measured results, because the experimental setup was constructed in a laboratory as shown in Fig. 8(a).

Table 1 shows the time taken to derive the EM simulation and calculation results in Fig. 11. All EM simulations were run on a computer with an Intel Core i7-7820X 3.6 GHz CPU and 128 GB of RAM integrated with two NVIDIA Quadro P6000 GPUs. Calculations with the proposed method are carried out by utilizing MATLAB. As a result, using an EM simulation is found to be accurate, but it takes a considerably long time to derive the result. As the

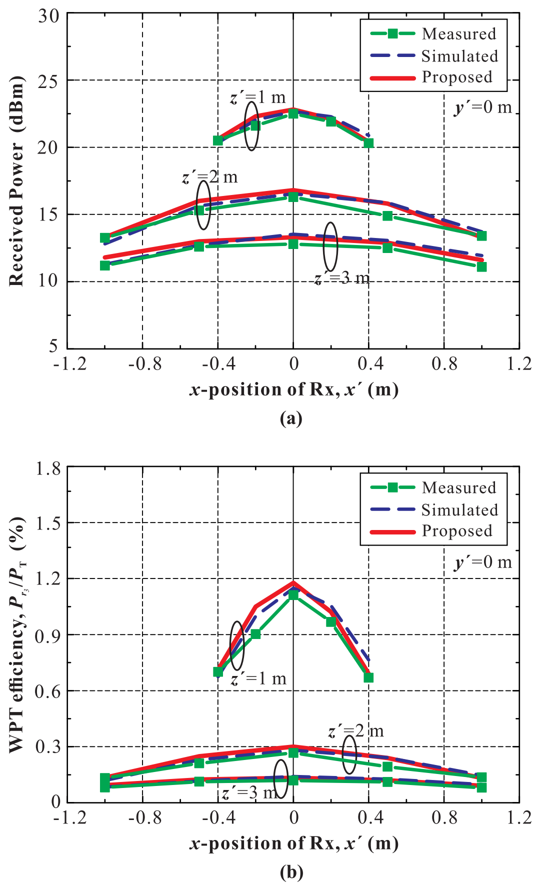


FIGURE 11. Comparison of the results according to the position of Rx (x', y', z'): (a) received power of the third element in Rx and (b) WPT efficiency of the third element in Rx.

transmission distance increases, the EM simulation time increases sharply. If the structure of antenna become more complex, the simulation time can be increased dramatically. On the other hand, the proposed method is able to obtain accurate results equal to those of the EM simulation, but the time required for the calculation was only 0.8 seconds regardless of the transmission distance. For the nine WPT scenarios shown in Table 1, a total time of approximately 62 hours was required for the EM simulation. In contrast, by using the proposed formula (9), the time required to derive the equivalent results was only eight seconds.

In conclusion, the method proposed in this paper can derive the received power not only as accurately as an EM simulation but also much faster than an EM simulation. It is a simple as well as accurate method for calculating the WPT efficiency and received power for various scenarios, such as those with varying transmission distances, different types of antennas, different numbers of array elements, different Rx positions, and different beamforming directions. Therefore, the proposed method is more efficient than an EM simulation when used to predict and analyze the received power in a WPT system with array antennas.

TABLE 1. Comparison of EM simulation and calculation times required to obtain the results of P_R for the WPT system in Fig. 8.

Rx positions (x', y', z')	(0 m, 0 m, 1 m)	(0.2 m, 0 m, 1 m)	(0.4 m, 0 m, 1 m)
EM Simulation	2h 56m 53s	2h 58m 46s	3h 48m 55s
Proposed Method	0.78s	0.77s	0.78s
Rx positions (x', y', z')	(0 m, 0 m, 2 m)	(0.5 m, 0 m, 2 m)	(1 m, 0 m, 2 m)
EM Simulation	3h 10m 24s	3h 53m 13s	4h 49m 13s
Proposed Method	0.77s	0.78s	0.78s
Rx positions (x', y', z')	(0 m, 0 m, 3 m)	(0.5 m, 0 m, 3 m)	(1 m, 0 m, 3 m)
EM Simulation	5h 0m 23s	10h 54m 51s	23h 54m 45s
Proposed Method	0.78s	0.78s	0.78s

V. CONCLUSION

In this paper, a method by which to calculate the received power and WPT efficiency based on wireless power interactions between individual Tx and Rx array elements in a WPT system with array antennas is investigated. The accuracy of its calculation is ensured given the use of radiation patterns distorted by mutual coupling in the array. While applying the well-known Friis or Goubau formula produces a large error for the WPT in a near-field region, such as Fresnel and reactive regions, the proposed method yields reliable results in both near- and far-field regions. The results calculated by applying this method to various 5.8 GHz RF WPT scenarios were in good agreement with the results from an EM simulation. When compared to experimental results with a 5.2 GHz WPT system, the measured and calculated results showed good agreement. In addition, only a few seconds were needed to calculate all cases, unlike in the EM simulation. Accordingly, the proposed method can produce exact results with rapid calculations. Therefore, it is expected to be actively utilized during the development of RF WPT systems given that it reduces the EM simulation time and was verified experimentally. This will be very helpful to those involved in developing energy harvesting and power management schemes for IoT technology based on wireless sensors. Moreover, the proposed method can be applied to a phased array system and a MIMO (multiple-input and multiple-output) antenna system, such as radar and 5G communications.

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