Study on Efficiency Maximization of Wireless Power Transmission in Fresnsel Region

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Abstract—**In this presentation, the maximum efficiency for radiative wireless power transmission is analyzed. Power transfer efficiency is formulated and analytically studied to find the optimal transmitting current for radiative power transmission for mobile antennas. The maximum power transfer efficiency when the size of transmitting area is limited is described. Comparison between previous works and the proposed work are described. In addition, discretization errors are presented to realize the ideal current.**

Keywords—Wireless Power Transfer, Microwave Power Transmission, Power Transfer Efficiency, Transmitting Array Antennas, Optimum Transmitting Current, Indoor Wireless Power Transfer

I. INTRODUCTION

Nowadays, wireless power transmission (WPT) has drag huge attention as a method to supply power for numerous sensor networks of Internet of Things (IoT) environment. There are three ways to transfer wireless power to mobile devices: Inductive coupling, magnetic coupling, microwave power transmission (MPT). Major of recent technologies uses inductive coupling or magnetic coupling, which are based on non-radiating near-fields. They can transfer high power to the mobile devices, however, the mobile devices should be placed at close distance to receive wireless power from the transmitter. On the other hand, microwave power transmission, which are based on propagating field of antennas, can provide further operating distance, although power transfer efficiency (PTE) is rather degraded. Compared to the techniques such as inductive coupling and magnetic coupling, there are little research on WPT using propagating waves. Most of the works on MPT focuses on long distance WPT, which uses far-field region. However, Friis equation could not be applied when the distance between the transmitter and receiver is not far enough, which is exactly indoor MPT scenario. Therefore, studies on MPT in radiative near-field region or mid-field region should be conducted to apply MPT for practical mobile devices in our daily lives.

There are some previous works on MPT in radiative near-field region since late 20th century [1-5]. Brown reported the experimental results using large arrays [1, 2]. Goubau and Borgiotti shows analytical studies on MPT in radiative near-field region [3, 4]. Shinohara continues their works as experiments in Fresnel region and designed rectifiers for MPT [5, 6] . The previous works have presented great works on the MPT in radiative near-field region, resulting that beam waist of Gaussian beam is the best way to transfer wireless power. The previous works assume an ideal receiving aperture, which can capture all of the incident Gaussian beam. However, the receiving antennas of practical indoor WPT scenarios are usually compact mobile antennas and they cannot receive all

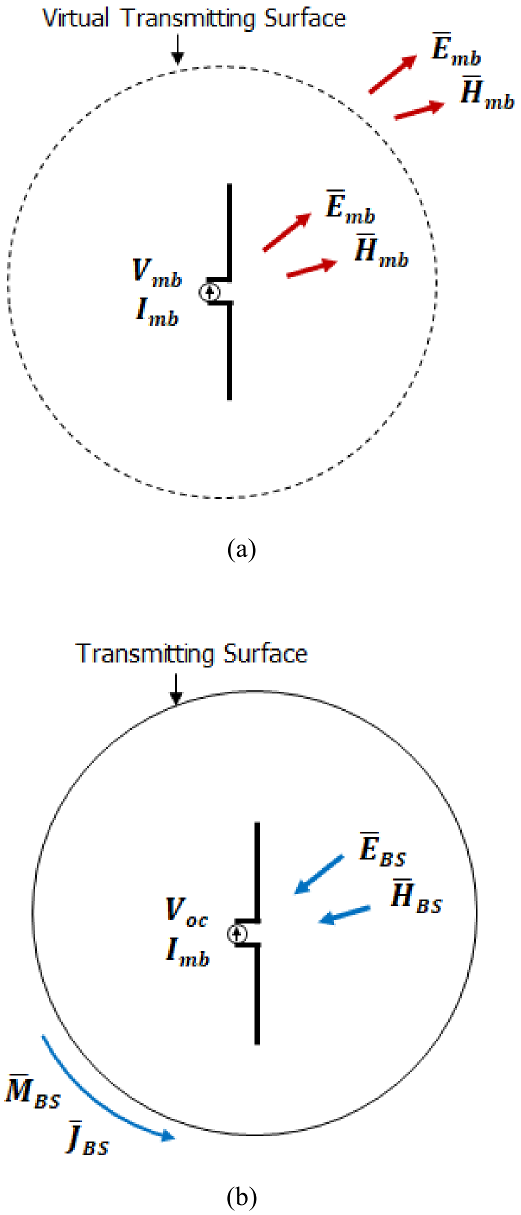


Figure.1. Scenario for the radiative wireless power transmission where the base station and the mobile antennas are placed in Fresnel region. (a) The mobile antenna transmits pilot signal. (b) The current on the base surface emits transmitting fields.

power passing through them. Therefore, we proposed the MPT in radiative near-field region especially for practical receiving antennas such as dipole, patch and horn antennas.

II. THORETICAL APPROACH

Receiving power of the mobile antenna by base currents can be obtained by using an equivalent model of lossless receiving antenna. To find out the maximum receiving power, the receiving power (P_r) delivered to the load of mobile antenna is defined as (1) in terms of open circuit voltage (V_{oc}):

$$P_r = \frac{1}{8}\frac{|V_{oc}|^2}{R_L} \tag{1}$$

where R_L is the load resistance, set to antenna resistance.

The V_{oc} can be obtained using reaction theorem which denotes correlation of radiating field ($\bar{E}_{BS}, \bar{H}_{BS}$) from base currents and currents ($\bar{J}_{mb}, \bar{M}_{mb}$) on mobile receiving antenna. Reciprocity theorem is then applied to simplify the calculation since the radiated field ($\bar{E}_{BS}, \bar{H}_{BS}$) from base currents is complex to compute. The calculation of V_{oc} is then,

$$V_{oc} = -\frac{1}{I_{mb}} \int \bar{E}_{mb} \cdot \bar{J}_{BS} - \bar{H}_{mb} \cdot \bar{M}_{BS} \, dV_{BS} \tag{2}$$

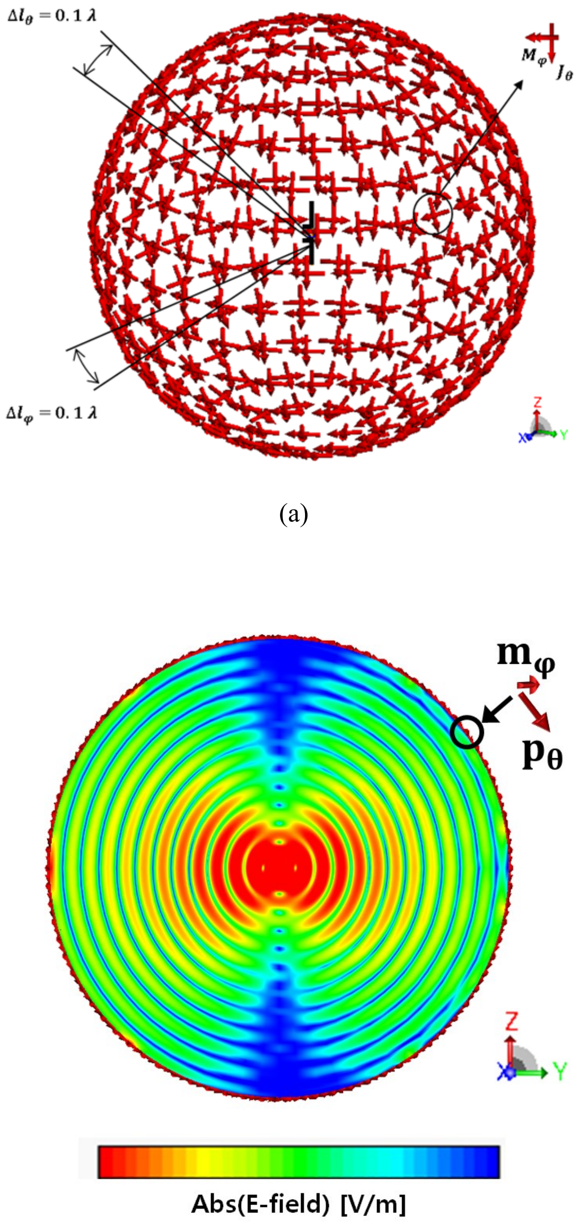
where I_{mb} is the receiver current of mobile current source. The integral is conducted on a closed surface as shown in Fig.1. Assume the input power for the pilot signal (Fig.1 (a)) is 1 W. Then the power transfer efficiency can be expressed using (2). The equation in (2) can be solved using Cauchy-Schwartz inequality and the solutions are [7]:

$$\bar{J}_{BS\_opt} = k\frac{1}{Z_0}(\hat{r}\cdot\hat{n})\,\bar{E}_{mb}{}^{*}, \tag{3a}$$

$$\bar{M}_{BS\_opt} = -kZ_0\,(\hat{r}\cdot\hat{n})\bar{H}_{\text{mb}}{}^{*}. \tag{3b}$$

III. RESULTS

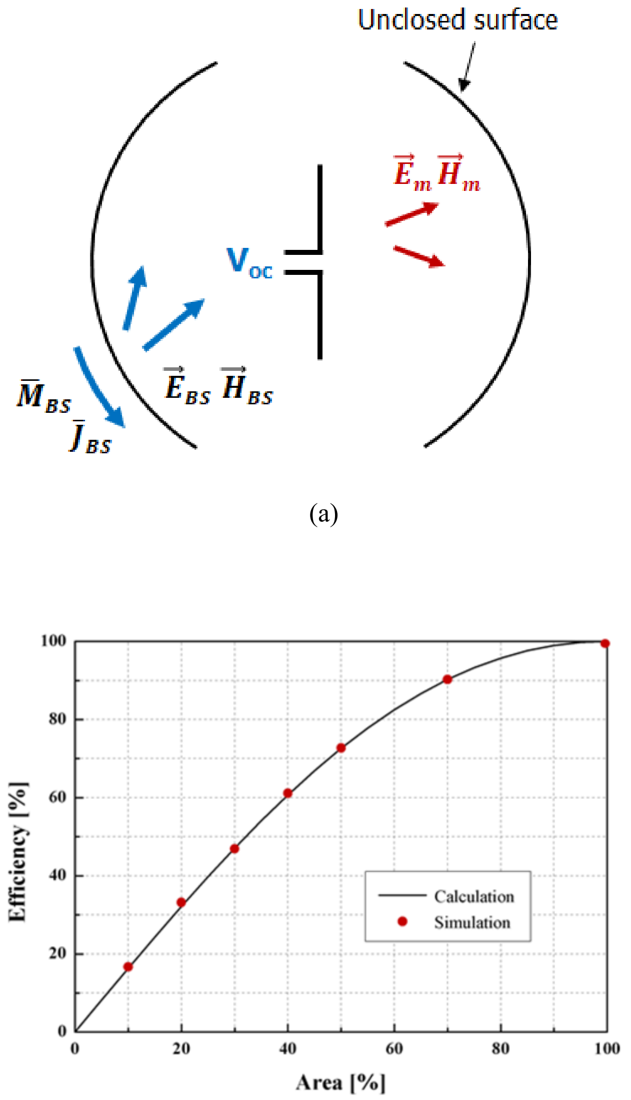
The purpose of this study is to derive the maximum PTE for a given transmitting area. For this purpose, the optimal base current below a certain value is removed, and the maximum PTE is calculated in the limited transmitting area. The scenario with spherical base surface, which is the simplest case, and its theoretical result is plotted in Fig. 2. A full wave simulator, FEKO, is used to confirm the proposed theory. Since it is impossible to simulate continuous current sheet in the simulator, the optimal base current sheets are modeled as numerous infinitesimal point electric and magnetic dipoles which assigned the calculated current density values at each points. For the simulation, the radius of the spherical surface is 6.4 λ and the distance of the point sources are 0.1 λ to theta and phi direction as shown in Fig. 2 (b). The mobile antenna which is half lambda dipole is placed at the center of the spherical surface. Operating frequency is simply set as 1 GHz and it can be scalable for specific application. Note that for the spherical base surface, the phase of the optimal transmitting current becomes uniform, and only the magnitude of the transmitting current varies. Since there is no phase variation, the distance between the point sources can be sparser than 0.1 λ. However, if the base surface is planar shape, there must exist phase variation of the optimal base current. Therefore, the point sources should be carefully implemented for the planar base surface.



(a)

(b)

Figure.2. Results of the spherical base surface. (a) Configuration of simulation using numerous point sources (101160 sources). The black dipole is a mobile antenna and red arrows are infinitesimal dipoles. (b) Resultant E-field distribution of the optimal transmitting current at the baes surface.



(a)

(b)

Figure.3. (a) Configuration of the unclosed transmitting surface. The transmitting surface can be minimized while the efficiency drop is minimized. (b) Results of the spherical base surface. The graph with black line indicates the theoretical maximum PTE with limited transmitting. The red points show the simulated points with FEKO using numerous electric and magnetic point sources.

The resultant electric field distribution inside the spherical surface is described in the Fig. 2(b). The point sources at the spherical surface are excited when the half-lambda mobile antenna is placed at the middle of the spherical space. Since the optimal electric current flows in theta direction and the optimal magnetic current flows in the phi direction, the electric and magnetic point sources are located with proper alignment. The optimal transmitting current emits spherical waves toward inside of the spherical surface, which are very similar shape to the radiating field patterns of the mobile antenna. Note that it explains the meaning of the mathematical results in (3), indicating that the reconstruction of the radiating field from the mobile antenna is the most important thing in terms of the power transfer efficiency. Following the proposed theory, the electric field distribution by the optimal transmitting currents will not change, even though the shape of the transmitting base surface varies.

In Fig. 3(a), the unclosed transmitting surface is described. Since the whole area of the closed surface cannot be used as a transmitter, the transmitting surface should be properly minimized. Considering the equations in (2) and (3), the receiving power can be still maximized when a part of optimal current is used as transmitter. It should be noted that the magnitude of the optimal current is directly related with the receiving power. Therefore, the area where the optimal current is weak should be removed, so that the transmitting area can be effectively used. The efficiency bound in terms of the transmitting area can be found by cutting off the weak parts of the optimal current first.

In Fig. 3(b), the theoretical efficiency in terms of the area of the transmitting area is plotted. The black line indicated the theoretical efficiency bound, while the red circles in Fig. 2 (a) indicate the simulated efficiency values. The power transfer efficiency in the FEKO simulator is defined as a ratio of the receiving power at the mobile load to the total input power of infinitesimal sources. Relative errors between the calculated and simulated values of all 7 points are less than 3.1 % which are caused by discretization of continuous current distribution. The results of theory and simulation are in good agreement, confirming the proposed theory.

IV. CONCLUSION

We have studied the maximum PTE for radiative WPT using optimization technique. The results are described as the relation of the maximum PTE and limited area of the transmitting surface. The simulation using numerous infinitesimal point sources which mimic continuous current sheet proves the proposed theory. This work suggests the calculated PTE bound of radiative-WPT when the area is limited. Also it provides a guideline for a design of radiative-WPT system using compact mobile devices.

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