Implementation of Optimal Transmitting Sources for Radiative-Wireless Power Transmission Using Practical Antenna Arrays

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***Abstract*—In this study, research on the methodology that effectively implement theoretical current distributions as practical antenna arrays is described. An optimization technique using genetic algorithm is applied to sample the theoretical current distribution. As a results, the proposed thinned arrays show improved performance compared to the same number of densely arranged regular arrays. It is revealed that the use of optimization technique has advantages in cost, weight, efficiency than the same number of the regular array.**

***Index Terms*—Thinned arrray, optimal transmitting current, current realization, optimized technique, genetic algorithm, radiaitve-wireless power transmission, microwave power transmission.**

I. INTRODUCTION

In recent years, wireless power transmission (WPT) using microwave has been drag huge attention since it can provide spatial freedom of the mobile devices. In the previous works, the optimal current distributions that can maximize power transfer efficiency have been proposed [1] - [4]. Although the preceding studies can provide physical understandings of radiative-wireless power transmission (R-WPT), there is little comments on how to implement the optimal transmitting current, especially when it comes to electrically large size. In [1], the optimal transmission current distribution for lossless situations could be identified, however, the ideal current sheet should be implemented as real antennas when the system is realized as WPT system.

Research on implementing the ideal current distribution as antenna arrays have been studied and described in the array theory [5] - [8]. In [5], [6], synthesis methods of planar sources are described. They explained representative array synthesis techniques, such as Dolph-Chebyshev array synthesis, or Taylor synthesis, and Bayliss difference pattern synthesis. The techniques are useful when the pattern need to satisfies a specific side-lobe ratio (SLR), to make sum pattern, or difference pattern, respectively. Many previous works tried to find the array factors (AFs) that can make the radiation pattern of the designed array similar with the target pattern satisfying the error bound or pattern mask [7], [8]. On the other hand, the goal of this research is to figure out the efficient way to realize the optimal current distribution, so that the pattern mask method or the representative array synthesis methods are not proper to be applied to R-WPT scenario. In this study, the ways to properly implement the optimal transmitting current as real antennas are described

II. THEORETICAL APPROACH

A. Radiation Pattern Matching

The proposed study is conducted to find an array structure that can replace the optimal transmitting current sheet as shown in Fig. 1. Since the goal is to design an array that can maximize the total efficiency, the equations on the PTE in the previous study is referred [1]. Assuming that the transmitting power at the base area is set as 1, the reaction term becomes the important factor that decide the PTE. It implies the correlation between the pilot field from the receiver antenna and the transmitting current distributions. Using reciprocity, the reaction factor in terms of the efficiency can be expressed as below:

$$\eta_{field} = \left| \int (\mathbf{E_{BS}} \cdot \mathbf{J_{mb}} - \mathbf{H_{BS}} \cdot \mathbf{M_{mb}}) \; dS_{mb} \right|^2 \tag{1}$$

where $\mathbf{E_{BS}}$, $\mathbf{H_{BS}}$ are the propagating field radiated from the transmitting sources (or base station), and $\mathbf{J_{mb}}$, $\mathbf{M_{mb}}$ are the electric and magnetic currents flow at the receiver (or mobile). Since the mobile antenna and its location are already determined, the only factor that decide the efficiency is the field radiated from the base station. Therefore, it can be considered that the similarity between the field radiated from the array antennas, and the ideal optimum current sheet is crucial when it comes to the designing the transmitting array.

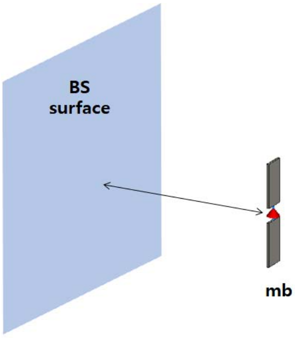
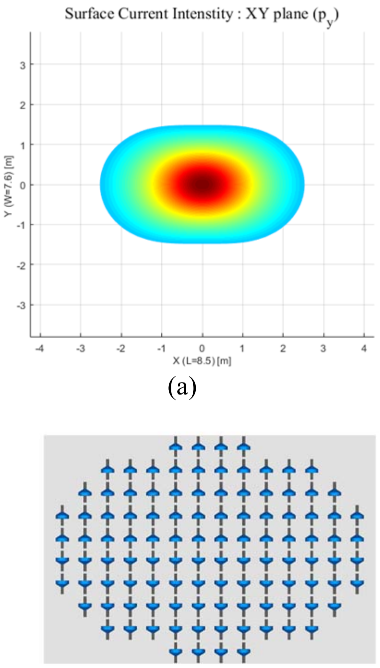


Fig. 1. Scenario for R-WPT. Assume the transmitting current that is optimal for the mobile (mb) can flow on the base (BS) surface.

Since the study is conducted in radiative region, the transmitting field should be matched at the radiative region. There are some previous studied that focus or match the target field pattern at the near-field area [9], [10]. However, near-field pattern matching requires huge field data if the real antenna is used as unit element. Referring the other research in [11] - [14], it is confirmed that the field of the near field fits well when the far-field radiation pattern is matched. In [11], [12] optimization techniques are used to match the radiation pattern of an actual antenna with ideal point source arrays. It optimized the magnitude, phase, and position of the ideal point sources using genetic algorithm (GA). The authors in [13], [14] represents spherical mode matching techniques to match the radiation pattern. It is argued that the radiation pattern of an actual antenna can be expressed as the sum of the spherical mode, and the coefficient of a specific spherical mode can be matched using a point source. In particular, after the spherical mode is matched, it is found that the field in the near-field region is also well matched since there exist same spherical modes. Therefore, the following study is conducted on the far-field pattern matching to effectively implement the ideal current sheet as practical antenna elements

B. *Optimal Excitation Coefficient*

There is recent research to be noted in order to implement an optimized transmission array. Referring to the previous study [2] - [4], the phase-conjugation of the pilot field from the mobile antenna is the way to transmit the radiative power with maximum efficiency. According to the results of this previous study, it can be understood that the optimal excitation coefficient and maximum efficiency are determined when the position of the transmission array is decided. However, little research has been conducted on how to determine the initial center position of the transmitting array, and also the arrangement of elements that composing the whole array. Therefore, finding the position and arrangement of the array that can implement the transmission current distribution most effectively is an important issue.



(a)

(b)

Fig. 2. Optimal transmitter for half-lambda dipole mobile antenna. (a) Shape of optimal transmitting current when the cut value is set as 31%. (b) Regular array following the optimal transmitting array.

III. THINNING OF TRANSMITTIG ARRAY

In fact, it can be intuitively understood that array antennas with close spacing may operate as the optimal current sheet. The following results shows the implementation of the ideal current sheet using half lambda regular array with rectangular grid. The half lambda dipole array with ground plane at quarter lambda distance is placed in the oval shaped boundary referring the optimal transmitting current as shown in the Fig. 2. However, it is great burden if the transmitting area is completely filled with the antennas. In particular, there need numerous array modules that adjust the magnitude and phase of each element, which require too much cost as well as weight and power loss. Therefore, the array thinning technique using genetic algorithm in which the efficiency is maintained to some extent while simplifying the densely arranged regular array.

First, we implemented a regular array that densely samples the ideal current distribution. A patch array is used so that only equivalent magnetic current could be considered. In order to sample the current most similarly, the patches are placed as closely as possible, and the gap between the patches (dmin) is set to be 0.5 times the length (Lp) of one side of the patch antenna as shown in Fig. 2. A 10x10 arrays are designed as a reference array structure with 500mm distance from the mobile antenna. The resonance frequency of the all antenna are set as 2.45GHz and the Rogers Duroid 5880 with 5mm thickness is used as the substrate.

Second, find the optimized excitation coefficients for all patch elements by applying the theory of the previous study [2] - [4]. According to the study, the phase-conjugation is the optimal excitation coefficient. Therefore, the voltage applied to each load of the 10x10 base array element is extracted when pilot signal from the mobile antenna is excited. The magnitude of the extracted voltage is applied with reversed phase to satisfy the phase-conjugation condition.

Third, the array thinning is conducted to reduce the number of the arrays, while efficiency of the thinned array is expected to be similar with the regular arrays. Before thinning the whole array, the phase conjugation condition is applied. Then, by turning on/off each patch element, the optimal array structure that is most similar to the radiation pattern of the regular array is searched. To find an optimal array structure, GA is used referring the previous research [15] - [17]. The on/off state of the element is expressed as binary sequences of 1 and 0. The binary 'gene' is multiplied to the magnitude of the excitation coefficient as below:

$$V_{opt} = V_{PC} \times G, \tag{2}$$

$$G = [\ 1, 0, 0, 1, \cdots, 1], \tag{3}$$

where V_{PC} is the magnitude excitation coefficient of the base array that satisfies the phase-conjugation condition. G is a binary sequence to which the GA is applied, and the thinning ratio is determined as the ratio of the number of the on state to the number of the vector elements.

All of the radiation patterns used in the GA are derived by multiplying the active element pattern (AEP) and the AF. AEP is extracted from the full-wave simulation, CST, when only the central patch is excited while other 99 elements of the regular array are terminated to 50ohm load. The reference pattern P_{ref} of the regular array is calculated considering the excitation coefficient, which is phase-conjugation, of the 10x10 patch, and the pattern of the thinned array P_{GA} is calculated excluding the excitation coefficient of the off element. The cost function of GA is expressed as the relative error of the reference pattern at phi=0 and phi=90 plane, as shown below:

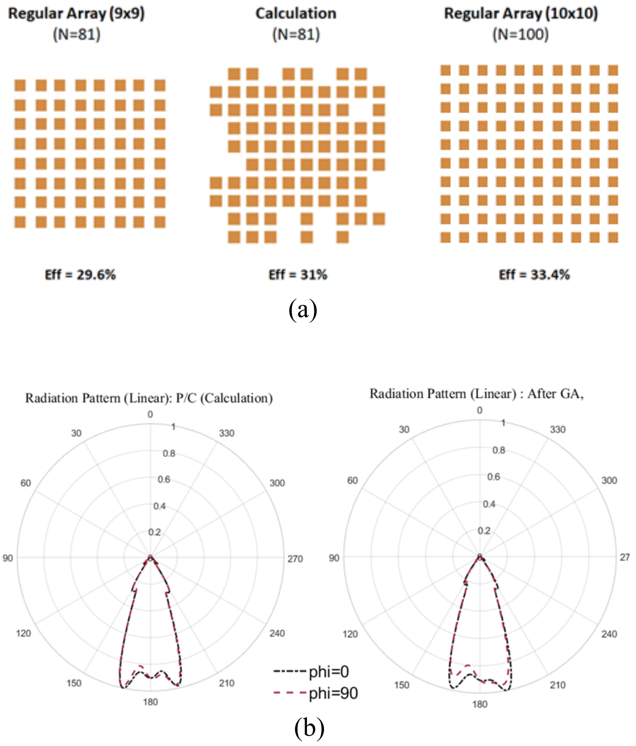
$$Y = \frac{P_{ref_0} - P_{GA_0}}{P_{ref_0}} + \frac{P_{ref_{90}} - P_{GA_{90}}}{P_{ref_{90}}} \tag{4}$$

The radiation pattern is normalized in the optimization code to effectively perform the optimization.

IV. RESULTS AND DISCUSSION

The thinned array by applying GA algorithm to a 10x10 regular array is conducted with 81% of thinning ratio to the regular array. Genetic algorithm is performed using built in functions in MATLAB. The resultant cost function in (4) is 0.1370. The optimized configuration of the thinned array is shown in the Fig. 3. It can be seen that the elements in the periphery are removed compared to the regular array. The regular array is compared in terms of the same number, and same array size with the thinned array.

The efficiency is extracted for each array structures using full-wave simulation, CST. Reciprocal situation is considered to simply check the efficiency. The efficiency is defined as a ratio of the power received at 50ohm termination of the base array to the transmitting power at the mobile antenna. Following the Fig. 3(a), it can be shown that the efficiency of the thinned array is improved compared to the same number of regular array. On the other hand, the efficiency is dropped compared to the same size of the regular array, which might be originated from the pattern errors. Indeed, the radiation pattern of the regular array and the thinned array in the Fig. 3(b) show some differences. Note that the radiation patterns are plotted in linear scale.



(a)

(b)

Fig. 3. Optimized transmitting arrays. (a) Configuration and efficiency results of the regular arrays and thinned arrays. (b) Radiation pattern of the 10x10 regular array and the thinned array.

The results are well matched with expectations. The thinned array reduced the number of elements by 19% compared to using the regular array, while the relative efficiency decreased by about 7%. Additional comparison is conducted with same number of regular arrays (9x9) to propose the effects of thinning. It is shown that the efficiency of the thinned array is increased by about 4.7% compared to that of the regular array, while the number of patch elements is the same

V. CONCLUSION

This study describes the implementation of the ideal optimal current distribution as real antenna arrays. The way to improve the efficiency while maintaining the number of arrays is proposed using the pattern matching method is performed by applying a genetic algorithm with binary sequence gene, which means the on/off state of each element. The results show improved efficiency compared to the same number of regular arrays. Using the methodology presented in this study, it is possible to design a transmitter array that is lighter, cheaper than densely arranged regular array. It is expected that the proposed array thinning can be useful in actual implementation of a WPT system.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2016R1E1A1A01943375).

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