Genetic Algorithm-Based Design of Receiving Resonator Arrays for Wireless Power Transfer via Magnetic Resonant Coupling

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***Abstract*—Resonator design methods play an important role in realizing efficient wireless power transfer via magnetic resonant coupling (WPT-MRC) systems. In WPT-MRC systems, transmitting (Tx) resonator arrays are often used to extend the range of the power supply. However, it is difficult to design a receiving (Rx) resonator that prevents significant drops in transfer efficiency across the Tx resonator array owing to the complexity that stems from fluctuating coupling coefficients. In order to resolve this difficulty, this paper proposes a genetic algorithm-based Rx resonator array design method. Using the proposed design method, the computed minimum transfer efficiency of a power supply system using a Tx resonator array increased from 3.8% to 42.6%, and the computed results were verified by simulations and measurements.**

***Index Terms*—Genetic algorithms, magnetic resonant coupling, resonator array, wireless power transfer.**

I. Introduction

Wireless power transfer via magnetic resonant coupling (WPT-MRC) has the potential to realize free-positioning power supply systems for consumer electronics such as mobile phones [1]. In order to realize such convenient wireless power supply systems, the systems must be constructed with a spatially broad power supply range that can obtain an acceptable transfer efficiency at an arbitrary position. In the study of WPT-MRC systems, considerable effort has been made to improve the transfer efficiency and extend the power supply range. Transmitting (Tx) and receiving (Rx) resonator designs are critical factors for improving the performance of WPT-MRC systems, and many design methods have been proposed to achieve various objectives. WPT-MRC systems enable efficient power supplies when the Rx resonator is near the Tx resonator. However, the transfer efficiency significantly decreases as the distance between the Tx and Rx resonators increases. Considering this characteristic of WPT-MRC systems, implementing Tx resonator arrays has proven to be a valid method for extending the power supply range [2]. However, using a single Rx resonator in conjunction with a Tx resonator array causes a significant drop in transfer efficiency near the edges of the Tx resonators owing to the magnetic flux canceling out. One of the countermeasures to this problem is to construct an Rx resonator array and dynamically select the Rx resonator to activate depending on the position of the Rx resonator array. When the number of Tx and Rx resonators in the system are m and n, respectively, there will be $m \times n$ possible pairs of Tx and Rx resonators. By selecting the pair

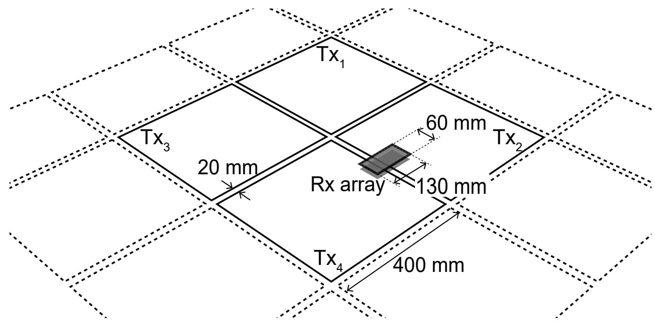


Fig. 1: Overview of the evaluated system.

of resonators that can achieve the best transfer efficiency from the $m \times n$ pairs at each position, the transfer efficiency of the whole system will not decrease unless all $m \times n$ pairs achieve a low transfer efficiency. In order to design an Rx resonator array capable of obtaining a high minimum transfer efficiency, consideration must be given to the $m \times n$ patterns of coupling coefficients at each position. However, it can be assumed that conventional resonator design methods based on experience or analysis will not meet this requirement owing to the complexity deriving from fluctuating coupling coefficients and the selection of resonator pairs. On the other hand, in the field of antenna design, methods based on genetic algorithms (GA) have proven to be valid in many complex problems [3]. GA is an algorithm based on feedback of the cost function, which can take into account any requirement that can be represented by a cost function. GA adopts mechanisms such as mutations and crossovers in order to quickly reach superior solutions without getting stuck into undesired local optimums. This paper aims to resolve the difficulty in obtaining high minimum transfer efficiency on a Tx resonator array by proposing an Rx resonator array design method based on GA. In section II, a description of the system used in this study is presented. In section III, the proposed design method is described in detail, and a WPT-MRC system operating at 6.78 MHz is actually designed. Section IV reveals the simulated and measured results of the designed Rx resonator arrays, and the paper concludes in section V.

II. Platform System

An overview of a WPT-MRC system using a Tx resonator array and an Rx resonator array is presented in Fig. 1. The Tx resonator array was composed of 400 mm × 400 mm loop resonators with a 20 mm gap, and the Rx resonator array was composed of 2 or 4 loop resonators. Considering the size of a mobile phone, the Rx resonator array was restricted to fit in a 130 mm $\times$ 60 mm rectangle. The resonators were made of copper wire with a diameter of 1 mm, and the resonant frequency of each resonator was tuned to 6.78 MHz using a series capacitor. Considering a WPT-MRC system on a table, Tx and Rx resonator arrays are always positioned facing each other, and the distance between the arrays was fixed at 10 mm. Both Tx and Rx resonators work selectively, and only one Tx resonator and one Rx resonator are activated simultaneously. In this selection process, the obtainable transfer efficiencies for every possible pair of Rx and Tx resonators are evaluated, and the pair that acquires the best transfer efficiency is activated. The selection of the Tx resonator can be realized by switching based on transfer efficiency feedback from the load, and the selection of the Rx resonator can be realized by connecting multiple full-bridge rectifiers, as shown in Fig. 2. Using m and n, defined in section I, and representing the obtainable transfer efficiency using the i-th Tx resonator and the j-th Rx resonator as $\eta_{\mathrm{Tx}i,\mathrm{Rx}j}$, the transfer efficiency of system η can be expressed as follows:

$$\eta = \max_{i,j} \eta_{\mathrm{Tx}i,\mathrm{Rx}j} \quad \left(\begin{array}{l} i = 1, 2, \cdots, m \\ j = 1, 2, \cdots, n \end{array} \right) \tag{1}$$

The transfer efficiency was computed by modeling the Tx and Rx resonators as a pair of LCR series resonant circuits in inductive coupling. The transfer efficiency was defined as the proportion of the power consumed by the load to the total power consumption. Considering conventional studies on maximum efficiency point tracking methods, transfer efficiency was calculated under the assumption that the load tracks the value that maximizes transfer efficiency [4]. For other parameters, the mutual inductance was calculated by the Neumann formula, and the copper loss of the Rx resonator was calculated as the product of wire length and resistance per unit length considering the skin effect at 6.78 MHz. The copper loss of the Tx resonator was calculated using a FEM-based electromagnetic solver (Ansoft HFSS) owing to the stationarity throughout the design process. For both Tx and Rx resonators, self inductance and capacitance were canceled out owing to series resonant conditions.

III. GA-Based Design of Rx Resonator Arrays

Using a single Rx resonator with a Tx resonator array causes a significant drop in transfer efficiency near the edges of the Tx resonators owing to the magnetic flux cancelling out. This results in a decrease in minimum transfer efficiency within the power supply range. In order to increase the minimum transfer efficiency, we propose a GA-based Rx resonator array design method. GA is an iterative optimization process that imitates the evolution of species. In order to implement GA, an encode that represents the individuals as vectors, called chromosomes, and a cost function for the evaluation of the chromosomes are required. The objective of GA is to search for the chromosome that minimizes or maximizes the cost function. The elements

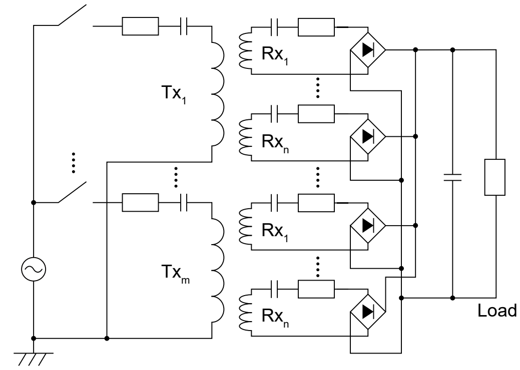


Fig. 2: Equivalent circuit of the proposed system.

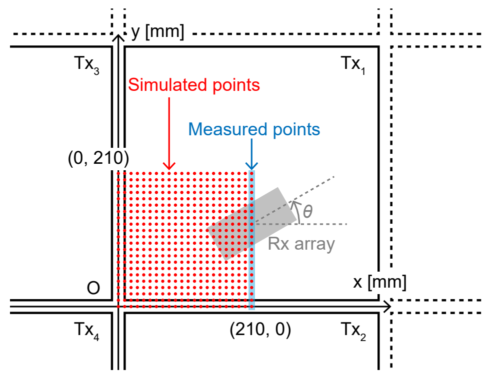


Fig. 3: Simulated and measured points.

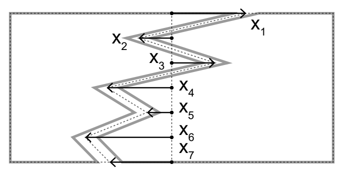


Fig. 4: Encode 1.

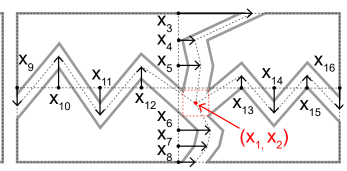
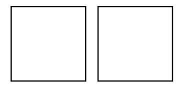
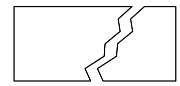
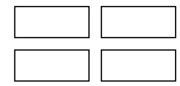
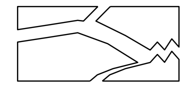


Fig. 5: Encode 2.

contained in chromosomes can be either binary, integer, real, or a mixture of all three; real numbers were used in this study. To design the Rx resonator array, the shapes of the arrays were encoded into the chromosomes by using parameters representing length, shown in Fig. 4 and Fig. 5. Encode 1, shown in Fig. 4, used 7 real parameters, $x_1, \cdots, x_7$, and encode 2, shown in Fig. 5, used 16 real parameters, $x_1, \cdots, x_{16}$. In order to prevent the intersection of the edges and to restrict the size of the Rx resonator array to the required size, the parameters were normalized to 1, and minimal exception handling was implemented. Although the objective of the design process is to increase the minimum transfer efficiency, finding the exact value of the minimum transfer efficiency is difficult. Therefore, we defined a discrete version, $\eta_{\min,\Delta d,\Delta\theta}$, as follows, and used $\eta_{\min,\Delta d,\Delta\theta}$ as the cost function. We defined the lattice points of Δd mm spacing as simulated points. The simulated points when Δd is 10 are shown in Fig. 3. We placed the Rx resonator array at each point, and varied θ in Fig. 3 from 0° to 360° with a step of $\Delta\theta$°. We then evaluated η, shown in (1), at each position. Note that the pair of Tx and Rx resonators that could obtain the highest transfer efficiency were activated at each

TABLE 1
Designed Rx Resonator Arrays and Minimum Transfer Efficiency.

	(a)	(b)	(c)	(d)	(e)
Rx Array					
Encode	–	1 (Fig. 4)		2 (Fig. 5)	
$\eta_{\min,10,15}$	3.8 %	14.3 %	32.3 %	28.7 %	42.6 %
$(x, y$ [mm], θ [°])	$(210, 0, 45)$	$(110, 0, 0)$	$(10, 40, 60)$	$(210, 210, 135)$	$(40, 210, 30)$
$\eta_{\min,5,5}$	3.8 %	14.3 %	18.7 %	28.7 %	41.8 %
$(x, y$ [mm], θ [°])	$(210, 0, 45)$	$(110, 0, 0)$	$(0, 105, 260)$	$(210, 210, 135)$	$(15, 35, 55)$

position, as described in section II. Assuming the symmetry of the Tx resonator array, the whole surface could be evaluated by the simulated points shown in Fig. 3. When the Rx resonator array was on the simulated points, Tx resonators except Tx1, Tx2, Tx3, and Tx4 were far enough compared to these four Tx resonators; therefore, the transfer efficiency using the other Tx resonators were neglected. The minimum η obtained from this operation was $\eta_{\min,\Delta d,\Delta\theta}$. By using the transfer efficiency, η, at each position shown in (1) and x, y, and θ from Fig. 3, $\eta_{\min,\Delta d,\Delta\theta}$ can be expressed as follows:

$$\eta_{\min,\Delta d,\Delta\theta} = \min_{x,y,\theta} \eta \left(\begin{array}{l} x = 0, \Delta d, \cdots, 210 \text{ [mm]} \\ y = 0, \Delta d, \cdots, 210 \text{ [mm]} \\ \theta = 0, \Delta\theta, \cdots, 360 \text{ [°]} \end{array} \right) \quad (2)$$

Using $\eta_{\min,\Delta d,\Delta\theta}$ as the cost function and encoding the shape of the Rx resonators as shown in Fig. 4 and Fig. 5, the GA-based Rx resonator array design method proposed in this study was executed. Δd and $\Delta\theta$ were set to 10 and 15, respectively, in order to strike a balance between accuracy and quick convergence. Previous studies on GA-based antenna design indicated that a relatively small population number and a relatively large mutation rate results in quick convergence [3]. In reference to this study, the population number, the mutation rate, and the number of generations were set to 30, 0.2, and 30, respectively. Rank-based selection was adopted for the selection of parent chromosomes, and the number of elites in each generation was set to 2. The design process was executed three times for each encode, and the convergence of the three trials for each encode are shown in Fig. 6 and Fig. 7. The generated arrays with the largest $\eta_{\min,10,15}$ value for each encode are presented in Table 1(c) and (e), with the $\eta_{\min,10,15}$ values of simple-shaped Rx resonator arrays shown in Table 1(a), (b), and (d). The results show that by using encode 1 and encode 2, $\eta_{\min,10,15}$ is improved to 32.3% and 42.6%, respectively, whereas a single Rx resonator showed a value of 3.8%.

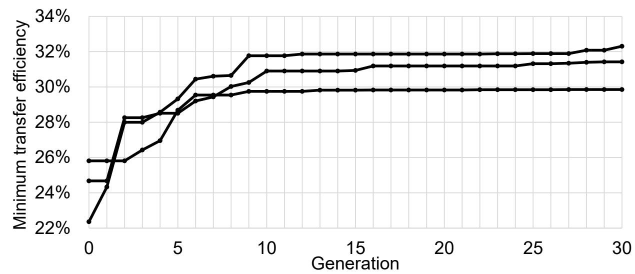


Fig. 6: $\eta_{\min,10,15}$ of each generation (Encode 1).

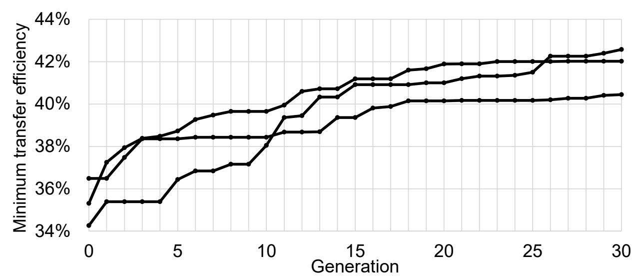
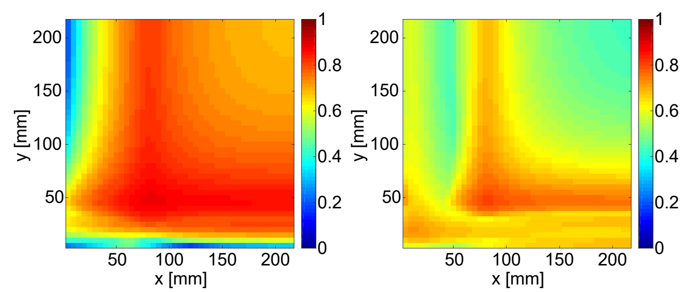


Fig. 7: $\eta_{\min,10,15}$ of each generation (Encode 2).



(a) Single Rx resonator.

(b) Encode 2.

Fig. 8: Simulated transfer efficiency at each position ($\theta = 0°$).

IV. Simulation and Measurement

For further evaluation of the proposed Rx resonator array design method, more detailed simulations and measurements were implemented. In the design process, Δd and $\Delta\theta$ for $\eta_{\min,\Delta d,\Delta\theta}$ were set to 10 and 15, respectively, for quick evaluation. For more details, an evaluation of $\eta_{\min,\Delta d,\Delta\theta}$ with the parameters respectively set to $\Delta d = 5$ and $\Delta\theta = 5$ was implemented. The resulting values of $\eta_{\min,5,5}$ are presented in Table. 1. They show that designing an Rx resonator array using $\eta_{\min,10,15}$ as the cost function also improves $\eta_{\min,5,5}$. In addition, the positional dependence of η shown in (1) for the Rx resonator arrays was investigated. To show the typical results, the η value at each position with θ fixed to 0° for a single Rx resonator shown in Table 1(a) and that for the Rx resonator array shown in Table 1(e) are presented in Figs. 8(a) and (b), respectively. Generally, η dropped at two regions: near the center and edges of the Tx resonators. As the number of Rx resonators on the array increased, η at the edges tended to increase, whereas η at the center tended to decrease. As for the single Rx resonator and the Rx resonator arrays generated using encode 1, the drop of η was significant at the edges. In contrast, as for the Rx resonator arrays generated using encode 2, the drop of η at the center and edges showed similar values.

In order to confirm the simulated results, the transfer efficiency was measured on the points extracted from the simulated points. Both the measured points and simulated points are shown in Fig. 3. The Rx resonator array with the highest $\eta_{\min,10,15}$ and $\eta_{\min,5,5}$ values, shown in Table 1(e), was fabricated by bending a 1 mm diameter copper wire. Fig. 9 shows the fabricated Rx resonator array. The transfer efficiency of each Tx and Rx resonator pair was measured on the points shown in Fig. 3. The angle θ, shown in Fig. 3, was fixed to $0°$. The experimental setup is shown in Fig. 10. When the Rx resonator array was positioned on the measured points, the simulated transfer efficiencies using Tx3 and Tx4 showed low transfer efficiency; therefore, only the transfer efficiencies using Tx1 and Tx2 were measured. For the measurement of the transfer efficiency, the S-parameters were measured by a network analyzer, R&S ZVL6. The transfer efficiency, defined as the proportion of power consumed by the load to the total power consumption, was calculated by these S-parameters under the assumption that the load impedance is optimum [4]. Fig. 11 shows the simulated transfer efficiency, and Fig. 12 shows the measured transfer efficiency. The measured copper loss of Tx, Rx1, Rx2, Rx3, and Rx4 in Fig. 9 was 0.517, 0.070, 0.060, 0.091, and 0.064 Ω, respectively, whereas the simulated copper loss was 0.410, 0.042, 0.035, 0.051, and 0.034 Ω, respectively. Considering the parasitic resistance, the measured results roughly corresponded to the simulated results.

V. Conclusion

In order to prevent significant drops in transfer efficiency across the Tx resonator array, we proposed a GA-based Rx resonator array design method. Using an Rx resonator array designed by the proposed method, the computed minimum transfer efficiency improved from 3.8% to 42.6%. The designed Rx resonator array was fabricated, and the computed results were confirmed by measurement.

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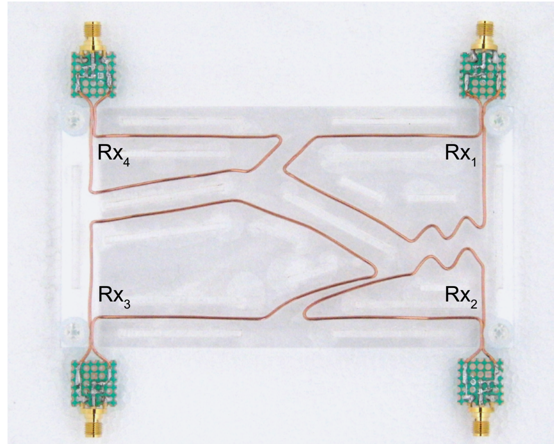

Fig. 9: Fabricated Rx resonator array.

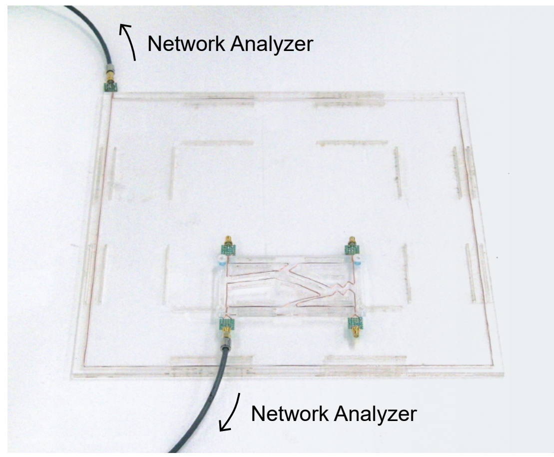

Fig. 10: Experimental setup.

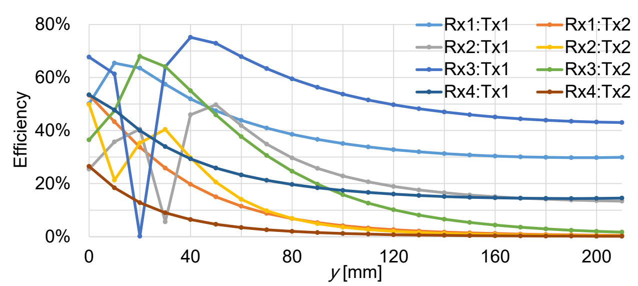

Fig. 11: Simulated transfer efficiency between pairs of Tx and Rx resonators.

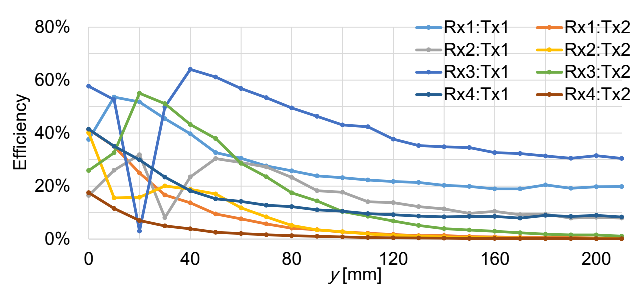

Fig. 12: Measured transfer efficiency between pairs of Tx and Rx resonators.