Master's Thesis
석사 학위논문

Transceiver Optimization of Wireless Power Transfer System with Multiple Transmitters to Single Receiver

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Department of Information and Communication Engineering
정보통신융합공학전공

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Co-advisor: Professor Hongsoo Choi
By

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics[1]

26. 12. 2017

Approved by

Professor Ji-Woong Choi (Advisor)	(signature)
Professor Hongsoo Choi (Co-Advisor)	(signature)

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[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Transceiver Optimization of Wireless Power Transfer System with Multiple Transmitters to Single Receiver

Kyungtae Kim

Accepted in partial fulfillment of the requirements for the degree of
Master of Science.

26. 12. 2017

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Abstract

While many companies have launched various wireless chargers in mobile industries, conventional wireless power transfer (WPT) technologies are available only for a very short distance due to large attenuation of the magnetic fields. A magnetic beamforming WPT system achieves an enhanced power transfer efficiency (PTE) with a longer wireless charging distance by focusing the magnetic fields to the receiver. However, conventional magnetic beamforming scheme needs complex calculation for optimal input voltage due to the magnetic couplings between multiple transmitters. Additionally, these couplings diminish the PTE of the WPT system.

This paper presents the maximum performance of the WPT system with multiple transmitters to the single receiver by transceiver optimization. In the transmitter side, a magnetic beamforming with a non-coupling coil pattern is introduced. Our proposed optimization in the transmitter side can achieve the enhanced PTE by controlling the only magnitude of the voltage source compared to the conventional magnetic beamforming. In the receiver side, a load optimization is introduced. The method for finding the optimal load impedance value is derived. After optimization in both sides, the WPT system can achieve a maximum performance under any circumstances. The improvement is verified via circuit simulation.

Keywords : Wireless power transfer (WPT), Power transfer efficiency (PTE), Magnetic beamforming, Non-coupling coil pattern, Load optimization,

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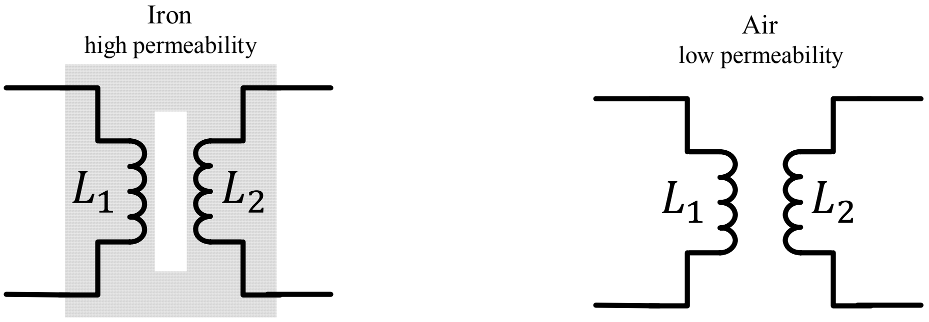
Ⅰ. INTRODUCTION

In these days, many consumers use and carry lots of mobile devices such as mobile phones, tablets, smart-watches, and so on. Even though these devices offer lots of conveniences to the users, the user should remember that these devices to be frequently charged, and it is very cumbersome. To solve these inconveniences, a wireless power transfer (WPT) technology has been developed and some electronic companies such as Samsung, LG and Huawei have released the wireless charger on the market since the early of 2010 as shown in Fig. 1. The users expected that their devices could be charged anywhere without the charging cable when they encounter the WPT technology firstly. They hoped that the device can be charged wirelessly anytime and anywhere without worrying about the charging status of their device. Ultimately, they dreamed all of charging cable in the home are eliminated perfectly! However, the current WPT technology cannot achieve this hope due to the fatal disadvantages such as a highly limited wireless charging distance and no flexibility. To charge the device successfully by the wireless charger, the device should be placed near the charger and placed with a careful alignment as shown in Fig. 1 [1]. The charging distance by this wireless charger is under few millimeter. When the device is detached more than a few millimeter from the charger, a power transfer efficiency (PTE) drops dramatically and the charging procedure stops soon [2]. The only difference from a wired-charging is placing the device on the wireless charger, instead of plugging the charging cable to the device. In other words, the users should find the wireless charger in place of the charging cable for charging procedure. Unfortunately, the WPT technology has not been much progressed from when the wireless charger was firstly released on the market from the early of 2010. These disadvantages are caused by the characteristic of the magnetic field, which is used to transfer an electrical power wirelessly.

The procedure how the wireless charger transfers the power is as follows. When an AC current flows through the coil in the transmitter, the magnetic field is induced and propagated. If this induced vibrating magnetic field from the transmitter coil penetrates the receiver coil, the magnetic coupling between both coils is generated,

Fig. 1. Variety of wireless charger



(a) Transformer (b) Magnetic inductive WPT

Fig. 2. Basic scheme of transformer and magnetic inductive WPT

which generates the current in the receiver and transfers the electrical power to the device. The magnitude of current in the receiver side is proportional to the intensity of the magnetic field penetrating the receiver's coil [3]. This scheme is called ‘magnetic inductive WPT’, and has been used for many years owing to an easy implementation [4]. The magnetic inductive WPT is similar to the principle of the transformer, which is able to convert the voltage to high or low amplitude by using the magnetic field. The only difference from the transformer is a medium between both coils [4, 5]. Fig. 2 illustrates the basic scheme of transformer and magnetic inductive WPT. L_1 and L_2 indicate the primary and secondary coil of both transformer and wireless charger. As shown in Fig. 2 (a), most of transformers use iron, which is a ferromagnetic substance, as a medium between both coils. This iron makes a high permeability path and confines the magnetic field from the primary coil, no leakage. Almost all of the magnetic fields from the primary coil traverse to the secondary coil, the amount of magnetic coupling is over 95%. Such a transformer is called ‘iron-core transformer’ [6]. However, as shown in Fig. 2 (b), the wireless charger seems an ‘air-core transformer’ compared to Fig. 2 (a). The air is a diamagnetic substance with a very low permeability, which is not able to make a path between both coils as shown in Fig. 2 (a). Because of this, lots of leakage magnetic field propagates to the air, not to the secondary coil L_2. The magnetic coupling is 10% practically, which implies only around 10% of the magnetic field from primary coil L_1 penetrates the secondary coil L_2 [5]. Unfortunately, the intensity of penetrating magnetic field decreases dramatically when the secondary coil moves away from the primary coil. This is due to the characteristic of the magnetic field, which drops sharply with distance and directionality in the air [3]. As the distance between both coils is farther, the magnetic coupling decreases sharply, finally reaching 0%. This phenomenon causes some fatal disadvantages such as a highly limited charging distance and low flexibility as explained before. As expected, increasing the performance of the wireless charger including the charging distance and PTE, it is able to provide a great convenience to the users. Over the past years, lots of researchers have tried to overcome the

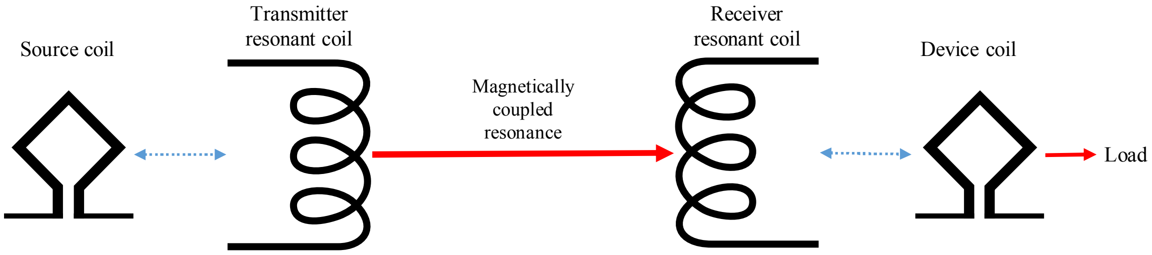


Fig. 3. Mid-range four-coil wireless power transfer system with magnetic resonance proposed in 2007 [7]

disadvantages as expressed above. In 2007, M. Soljacic, who is a professor of MIT, attracted the world's attention by developing a mid-range high efficiency WPT system with magnetic resonance [7]. His team succeeded in wirelessly transferring 60W over 2m. Their proposed WPT system consists of four coils, such as a source coil, transmitter resonant coil, receiver resonant coil and device coil as shown in Fig. 3. As explained in [3, 8], an impedance matching, which diminishes the reflected magnetic field, should be performed to improve the performance of the WPT system. The source and device coil can be used to realize the impedance matching and make both transmitter and receiver be resonated. By adjusting the magnetic coupling between both source/transmitter and receiver/device coil, this WPT system can achieve the impedance matching and maximum performance. Additionally, this WPT system can achieve an extremely high quality factor compared to the magnetic inductive WPT as shown in Fig. 2 (b). The quality factor indicates how much the energy is stored well [1, 9]. Owing to the high quality factor, the WPT system can overcome the fatal disadvantages of the inductive WPT system to some extent as explained above. This approach is usually called 'magnetic resonance WPT'. However, in spite of the better performance of the proposed magnetic resonance WPT, the system is not suitable for applications such as a mobile industry because it requires lots of space. It is difficult to reduce the size since it needs space between source/transmitter and receiver/device coil [10]. Besides, it is difficult to calculate and adjust the optimal magnetic coupling between source/transmitter and receiver/device coil automatically [9].

There is another way to achieve the magnetic resonance WPT by two coils simply as shown in Fig. 4. By adding external series capacitors C_1 and C_2 to both circuits, the two-coil WPT becomes magnetic resonance state. The difference between two-coil and four-coil WPT is a matching network, which indicates whether the WPT can tune the impedance matching or not [1]. D. W. Seo ascertained that in a particular situation, both two and four-coil schemes have the identical performance [11]. Owing to the simple configuration, many other researches are also based on the two-coil magnetic resonance WPT [2, 12-13].

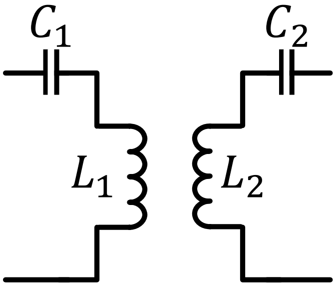


Fig. 4. Basic scheme of two-coil magnetic resonance WPT

Many researchers have tried to overcome the disadvantages in other ways, such as magnetic relay [14], magnetic array [15], and magnetic beamforming [2, 12]. Among them, the magnetic beamforming is a promising scheme which is firstly introduced in 2014 by J. Jadidian, who was a researcher at MIT. The research group extended the principle of MIMO beamforming which was already used in wireless communication to the magnetic fields [2]. MIMO beamforming in wireless communication implies that the multiple-input antennas and multiple-output antennas to achieve the improved performance, such as longer transfer distance and various directionality [16]. Similarly, the magnetic beamforming scheme makes a magnetic beam by adjusting the currents flowing in the transmitter sides, which makes a constructive interference of the magnetic fields at a one spot. The magnitude and phase of the currents are determined according to the mutual inductance between each coil located in the transmitter and receiver side. That group verified this magnetic beamforming scheme can achieve longer charging distance and various directionality in multiple transmitters and single receiver WPT system (i.e., M to 1 WPT system) by simulation and implementation [2]. In 2015, the researcher of the same group, L. Shi expanded the magnetic beamforming from single receiver to multiple receivers (i.e., M to M WPT system) and derived a general solution of the voltage sources by using a linear algebra [12]. However, the inevitably appearing magnetic couplings between multiple transmitter coils are not considered. These couplings make degradation of the WPT system [17-18].

On the other hand, some researchers provided different perspectives to overcome the disadvantages, optimization in the receiver side. D. W. Seo derived an optimal load impedance in two-coil magnetic resonance WPT system by applying a maximum power transfer theorem and referring to the configuration of four-coil WPT system [11]. Q. T. Duong derived the optimal load impedance in multiple transmitters and single receiver WPT system [19]. However, some preconditions to derive the optimal load impedance were not handled in detail. M. Fu derived the optimal load impedance in the single transmitter and multiple receiver WPT system [13].

This paper aims at providing optimization in both transmitter and receiver side of the WPT system to enhance the performance. In the transmitter side, an enhanced magnetic beamforming with a non-coupling coil pattern is introduced. In the receiver side, a load optimization is introduced. The remainder of the paper is organized as follows. In section II, a basic circuit analysis of the WPT system is introduced firstly, and a principle of conventional magnetic beamforming is provided. In section III, optimization in the transmitter side is provided. In our proposal, the non-coupling coil pattern is applied to the coils in the transmitter side for the magnetic beamforming. Owing to this coil pattern explained in [20], our proposal has some advantages compared to the conventional magnetic beamforming. Next, in section IV, the load optimization is introduced for optimization in the receiver side. We derive a general solution of the optimal load impedance to achieve the enhanced PTE. With optimization in both transmitter and receiver of the M to 1 WPT system, the maximum PTE can be reached under any circumstances, and it is verified by circuit simulation. In section V, we conclude our paper.

II. BASIC ANALYSIS OF WPT SYSTEM

2.1> Circuit Analysis

2.1.1> Single Transmitter to Single Receiver

As explained above, the WPT system using the magnetic field to transfer the electrical power wirelessly is common in these days. The basic principle of the WPT system is as follows. The AC current flowing the transmitter circuit induces the magnetic field at the transmitter coil. Then, the induced magnetic field passes through the receiver coil, which makes a current that transfers the electrical power to the device. It is important that the performance of the WPT system depends on the intensity of the magnetic field penetrating through the receiver coil. The WPT system can be modeled and analyzed by the circuit analysis with Kirchhoff Voltage Law (KVL) [21]. This section introduces the basic circuit analysis of the WPT system for further understanding in the following sections.

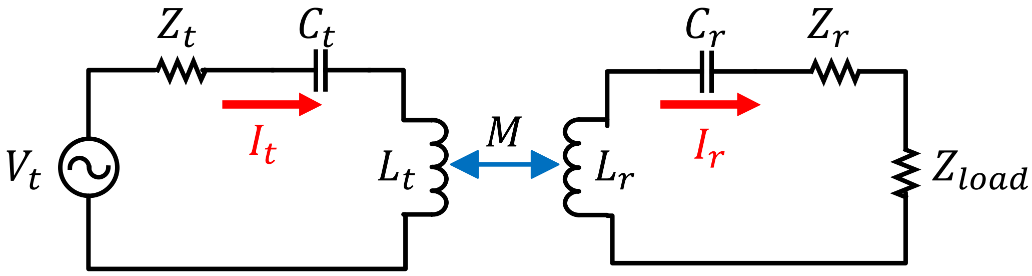
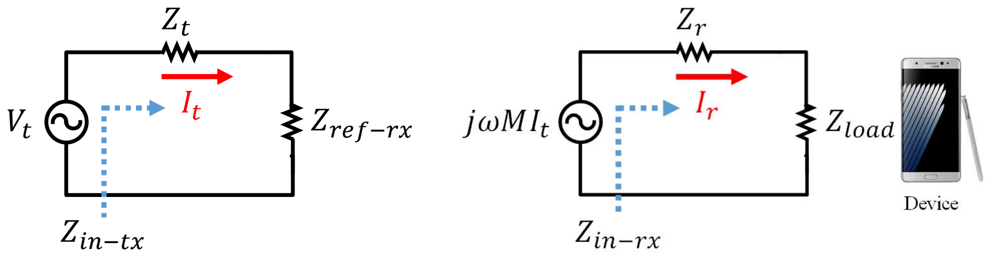


Fig. 5. Illustration of single to single WPT system

Fig. 5 represents the single to single magnetic resonance WPT system (i.e., 1 to 1 WPT system) by circuit modeling. Both transmitter and receiver circuits are magnetically coupled with a mutual inductance M that indicates the strength of the magnetic coupling. The mutual inductance M is determined by the factor of a magnetic coupling coefficient k and the self-inductance of two coil L_t and L_r [3]. The relationship is represented as follows.

$$M = k\sqrt{L_t L_r} \tag{1}$$

Z_t and Z_r indicates the impedance caused by the copper wire of the coil L_t and L_r. Z_{load} indicates the resistance that implies the device to be charged wirelessly. The value of Z_{load} is also an important factor for the PTE, it will be covered in the following section. To enhance the PTE, the capacitance C_t and C_r are added to transmitter and receiver circuit, which makes both circuits are resonated at the same frequency. This scheme is called ‘two-coil magnetic resonance WPT’ or simply ‘magnetic resonance WPT’ [4]. In magnetic resonance state, most of the input power from the voltage source V_t is able to be transmitted to the receiver. The two-coil magnetic resonance scheme as shown in Fig. 5 is adapted as basis concept in this paper.



(a) Equivalent transmitter circuit (b) Equivalent receiver circuit

Fig. 6. Equivalent circuit of 1 to 1 WPT system during charging procedure

As explained above, the WPT system in Fig. 5 is analyzed by two circuit equations by KVL [2, 21]. Fig. 6 represents the equivalent transmitter and receiver circuit of the 1 to 1 WPT system during charging procedure. As shown in Fig. 6 (b), the receiver current I_r is induced from the transmitter current I_t via the mutual inductance M. It seems that the transmitter current I_t generates a voltage source $j\omega MI_t$ at the receiver through the mutual inductance M, i.e.:

$$j\omega MI_t = I_r(Z_r + Z_{load} + j\omega L_r + \frac{1}{j\omega C_r}) \tag{2}$$

where ω is an angular frequency and the receiver voltage generated by the transmitter current I_t is multiplied by the complex term j. Since both circuits are magnetically coupled, the receiver current I_r also affects the transmitter circuit by generating the voltage:

$$V_t = I_t\left(j\omega L_t + \frac{1}{j\omega C_t} + Z_t\right) - j\omega MI_r \tag{3}$$

Both equations above play a significant role for the analysis of the WPT system. As both circuits are in the magnetic resonance state, both imaginary terms $j\omega L_t$ and $\frac{1}{j\omega C_t}$ are eliminated. Thus, Eq. (2), (3) are changed:

$$j\omega MI_t = I_r(Z_r + Z_{load}) \tag{4}$$

$$V_t = I_t Z_t - j\omega MI_r \tag{5}$$

By substituting I_r with I_t, the voltage source V_t consists of a function I_t.

$$V_t = \left(Z_t + \frac{\omega^2 M^2}{Z_r + Z_{load}}\right) I_t \tag{6}$$

Then, the input impedance of transmitter Z_{in-tx} as shown in Fig. 2 (a) is derived:

$$Z_{in-tx} = \frac{V_t}{I_t} = Z_t + Z_{ref-rx} = Z_t + \frac{\omega^2 M^2}{Z_r + Z_{load}} \tag{7}$$

The term $Z_{ref-rx} = \omega^2 M^2 / (Z_r + Z_{load})$ indicates the reflected impedance from the receiver circuit, which appears at the transmitter circuit. Fig. 6 (a) describes the equivalent transmitter circuit when both currents I_t and I_r flow. Both circuits are not directly connected but magnetically coupled similar as the transformer. So, they affects each other and it appears as a reflected impedance Z_{ref-rx}. Eq. (2), (3) above can describe the 1 to 1 WPT system well. In the following section, we expand both equations to the multiple transmitters to single receiver WPT system.

2.1.2> Multiple Transmitters to Single Receiver

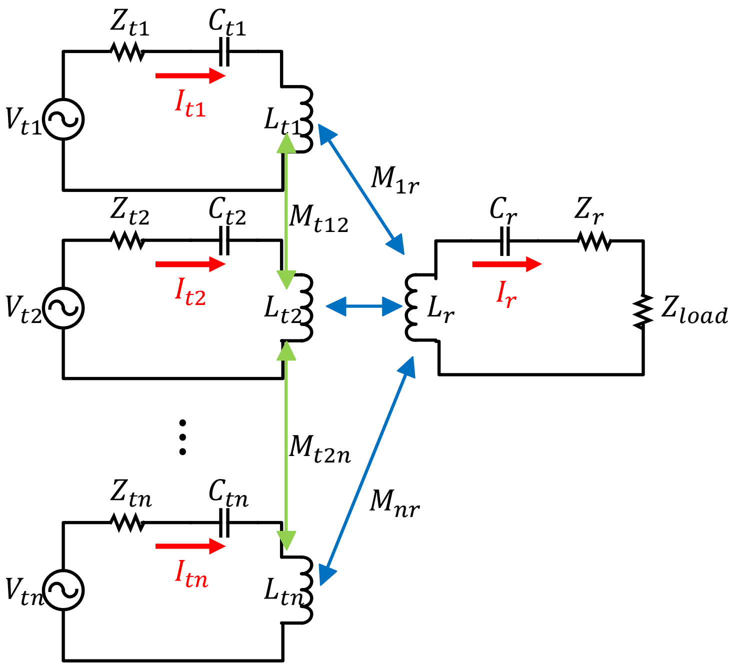


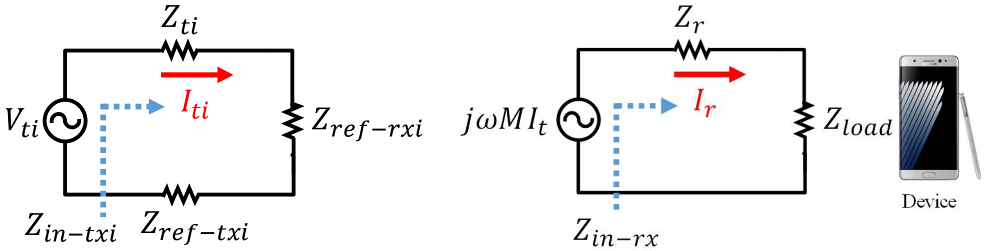
Fig. 7. Illustration of multiple transmitters to single receiver WPT system

To achieve a better performance of the WPT system, placing more transmitters seems reasonable. Fig. 7 illustrate the basic scheme of the M to 1 WPT system. The components of the i-th transmitter circuit are represented in the same way as the previous section, which are distinguished by subscripts. In this section, the analysis of the M to 1 WPT system is introduced. All of circuits are resonated at the same frequency in the same way as previous section. (i.e., magnetic resonance WPT) Since all of transmitter currents induce the receiver current, Eq. (4) is expanded to explain the affection of multiple transmitters as follows.

$$I_r(Z_r + Z_{load}) = \sum_{i=1}^{n} j\omega M_{ir} I_{ti} \tag{8}$$

where I_{ti} indicates the current flowing at the i-th transmitter circuit, and M_{ir} is the mutual inductance between the i-th transmitter and receiver. As explained previously, each transmitter is affected from other circuits via the magnetic coupling. The difference from the 1 to 1 WPT system is that each transmitter circuit is affected not only the receiver circuit, but also other transmitter circuits. In this case, the voltage in the i-th transmitter circuit should consider more magnetic couplings including other transmitter's effect [17]. Thus, Eq. (5) is expanded to comprise the additional magnetic couplings. i.e.:

$$V_{ti} = Z_{ti} I_{ti} + \sum_{\substack{k=1 \\ k \neq i}}^{n} j\omega M_{tik} I_{tk} + j\omega M_{ir} I_r \tag{9}$$



(a) Equivalent transmitter circuit (b) Equivalent receiver circuit

Fig. 8. Equivalent circuit of M to 1 WPT system during charging procedure

where V_{ti} indicates the voltage of i-th transmitter. Z_{ti} indicates the impedance of i-th transmitter caused by the coil L_{ti}, and n is the total number of transmitter circuits. After substituting I_r from Eq. (8) to Eq. (9), the relationship between the voltage and current of i-th transmitter circuit is derived as follows.

$$V_{ti} = Z_{ti}I_{ti} + \sum_{\substack{k=1 \\ k\neq i}}^{n} j\omega M_{tik}I_{tk} + \frac{\omega^2}{Z_r+Z_{load}}\left(\sum_{k=1}^{n} M_{ir}M_{kr}I_{tk}\right) \tag{10}$$

Then, the input impedance of i-th transmitter Z_{in-txi} is derived same as the previous section.

$$Z_{in-txi} = \frac{V_{ti}}{I_{ti}} = Z_{ti} + Z_{ref-txi} + Z_{ref-rxi} = Z_{ti+} \sum_{\substack{k=1 \\ k\neq n}}^{n} j\omega M_{tik}\frac{I_{tk}}{I_{ti}} + \frac{\omega^2}{Z_r+Z_{load}}\left(\sum_{k=1}^{n} M_{ir}M_{kr}\frac{I_{tk}}{I_{ti}}\right) \tag{11}$$

Compared with Eq. (7), Eq. (11) has an additional reflected impedances $\mathrm{Z}_{ref-txi}$ from other transmitters which is indicated by the middle term of Eq. (11). The last term of Eq. (11) indicates the reflected impedance $\mathrm{Z}_{ref-rxi}$ from the receiver. Fig. 8 represents the equivalent circuit of the i-th transmitter in M to 1 WPT system. Compared with Fig. 6 (a), there is an additional reflected impedance $\mathrm{Z}_{ref-txi}$ which is connected serially in Fig. 8 (a). Among the all impedances in Fig. 4, the power transmitted to the receiver is allocated at the $\mathrm{Z}_{ref-rxi}$. When the power allocated at the $\mathrm{Z}_{ref-rxi}$ increases under the fixed input power from the source, the performance of the WPT system improves. However, the reflected impedance $\mathrm{Z}_{ref-txi}$ from other transmitters interferes the transmission to the receiver. This causes performance attenuation and makes analysis complex [17-18].

In the following section, the conventional magnetic beamforming by [2, 12] is introduced to enhance the performance of the M to 1 WPT as shown in Fig. 3. The magnetic beamforming scheme makes and controls a magnetic beam according to the receiver spot, which improves the PTE of the WPT system [2]. Next section introduces the principle and simulation results of the magnetic beamforming. The simulation results regarding the transmitter current and power are described. Compared with the non-beamforming case, we can confirm the advantage of the magnetic beamforming scheme.

2.2> Introduction of Magnetic Beamforming Scheme

2.2.1> Principle of Magnetic Beamforming Scheme

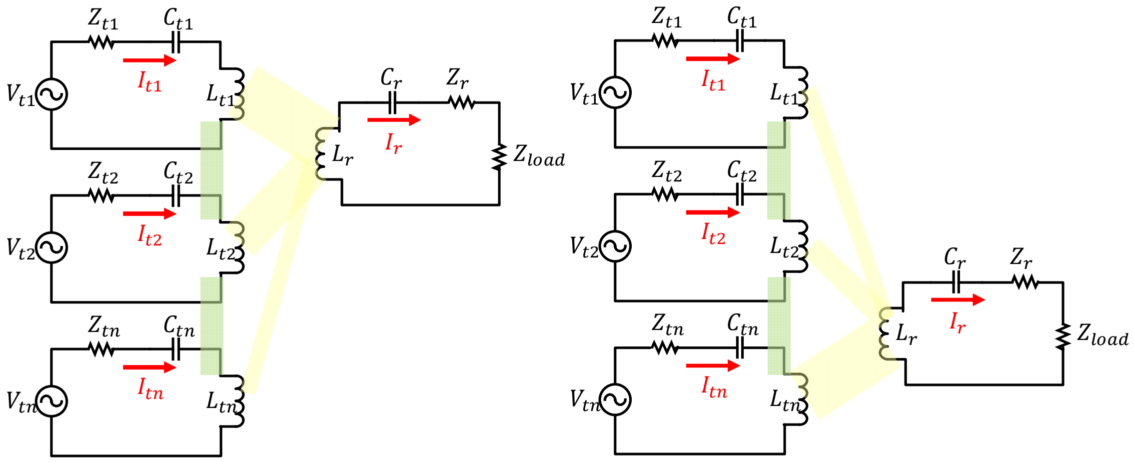


Fig. 9. Concept of magnetic beamforming scheme according to the receiver

As mentioned above, the magnetic beamforming scheme focuses the magnetic field from the multiple transmitter coils to the receiver coil, which can improve the performance of the WPT system. Fig. 9 illustrates the concept of the magnetic beamforming that can make and control the magnetic beam according to the receiver spot [2]. Since multiple transmitters are placed for the improved performance, magnetic couplings between transmitters appear inevitably. These couplings result in interference in transmitter sides, as shown in the green square in Fig. 9. On the other hand, the magnetic couplings which act as a path between transmitter and receiver are shown in the yellow square on the other hand.

In this section, how to achieve the magnetic beamforming scheme in the M to 1 WPT system is explained. The beamforming scheme has already been used in wireless communication. In wireless communication beamforming, the signal is adjusted according to the channel to maximize the SNR at the receiver [16]. To apply this beamforming scheme to the magnetic field, there must be parameters corresponding to the signals and channels in the wireless communication as shown in Table. 1.

Wireless communication	**Wireless power transfer**
Signal	Current
Channel	Mutual inductance

Table. 1. Corresponding parameters between wireless communication and wireless power transfer

The channel in wireless communication serves as a link between both signals in the transmitter and the receiver. In the M to 1 WPT system, Eq. (8) indicates the relationship between the current in the transmitter and the receiver. Looking closely at the Eq. (8), the mutual inductance term $j\omega M_{ir}$ serves as a magnetic channel that relates between the current in both sides. This term is defined as a magnetic channel $H_i = j\omega Z_{in-rx}^{-1} M_{ir}$ $(\mathrm{i} = 1,2,3 \cdots \mathrm{n})$. So, the next step is learning how to adjust the transmitter currents for magnetic beamforming. For derivation of the equations for the magnetic beamforming easily, some matrices for indicating the parameters are introduced as shown in Table. 2.

Term	Definition	Explanation
n	*Number of Tx coils*	
$\vec{V_t}$	$[V_{t1} \quad V_{t2} \quad V_{t3} \quad \cdots \quad V_{tn}]^T$	Transmitter voltage
$\vec{I_t}$	$[I_{t1} \quad I_{t2} \quad I_{t3} \quad \cdots \quad I_{tn}]^T$	Transmitter current
Z_{in-rx}	$Z_r + Z_{load}$	Total input impedance in the receiver circuit
$\vec{Z_t}$	$\begin{bmatrix} R_{t1} & \cdots & j\omega M_{t1n} \\ \vdots & \ddots & \vdots \\ j\omega M_{tn1} & \cdots & R_{tn} \end{bmatrix}$	Impedance and mutual inductances in the transmitter
$\vec{H}$	$[H_{1r} \quad H_{2r} \quad H_{3r} \quad \cdots \quad H_{nr}]$	Magnetic channel between transmitter and receiver

Table. 2. Matrix of parameters in M to 1 WPT system

By converting the scalar component in Eq. (8) to vector in Table. 2, Eq. (8) is changed by these matrices as follows.

$$I_r = \vec{H} \times \vec{I_t} \tag{12}$$

By the basis of circuit theory, the power is consumed only at the resistance among the passive elements such as resistance, capacitance and inductance [21]. The power transmitted to the receiver circuit P_r is:

$$P_r = I_r^2 Z_{in-rx} \tag{13}$$

where Z_{in-rx} indicates the total impedance in the receiver circuit. The transmitted power P_r indicates all power transmitted to the receiver circuit, not the device directly. Distributing the power in the receiver circuit is also important, which is covered in the section IV. In the transmitter circuit, there are resistances R_{ti} (i =

$1,2,\cdots$ n), which is the voltage source impedance of i-th transmitter, that consumes the power from the voltage source $\overrightarrow{V_t}$. The power consumed in the all transmitters is:

$$P_t = \overrightarrow{I_t}^* R_t \overrightarrow{I_t} \tag{14}$$

where the superscript$(*)$ indicates conjugate transpose, and R_t is a diagonal matrix of Z_t. So far, all of power consumed at the resistance in both sides are expressed. Therefore, the total input power P_{total} from the voltage source $\overrightarrow{V_t}$ is the sum of P_t and P_r as follows.

$$P_{total} = P_t + P_r = \overrightarrow{I_t}^* R_t \overrightarrow{I_t} + I_r^2 R_r \tag{15}$$

By substituting Eq. (12) to Eq. (15), the total input power P_{total} is expressed as a function of the transmitter current $\overrightarrow{I_t}$. i.e.:

$$P_{total} = P_t + P_r = \overrightarrow{I_t}^* R_t \overrightarrow{I_t} + \overrightarrow{I_t}^* H^* R_r H \overrightarrow{I_t} \tag{16}$$

Eq. (16) implies that the transmitter current $\overrightarrow{I_t}$ determines the power of both transmitter and receiver sides. The magnetic beamforming scheme is the method for finding and adjusting the optimal transmitter current to maximize the power P_r [2]. i.e.:

$$\overrightarrow{I_t^{bf}} = argmax(P_r) = argmax(\overrightarrow{I_t}^* H^* R_r H \overrightarrow{I_t}) \tag{17}$$

$$\text{The total input power constraint}: \; P_t + P_r = \overrightarrow{I_t}^* R_t \overrightarrow{I_t} + \overrightarrow{I_t}^* H^* R_r H \overrightarrow{I_t} = P_{total}$$

where $\overrightarrow{I_t^{bf}}$ is the transmitter currents for magnetic beamforming. With following the calculations in [2, 12], the solution of transmitter currents for the magnetic beamforming is:

$$\overrightarrow{I_t^{bf}} = c \cdot maxeig(H^* R_r H) \tag{18}$$

where $maxeig(H^* R_r H)$ denotes an eigenvector of $H^* R_r H$ that corresponds to the largest real eigenvalue λ, and c is a constant which is determined by the total input power constraint as expressed in Eq. (17).

In the M to 1 WPT system, Eq. (18) can be simplified by following the calculations as explained in [12]. In this case, the solution for optimal transmitter current $\overrightarrow{I_t^{bf}}$ is a proportional to the mutual inductance between each transmitter and receiver. That is, the optimal transmitter current $\overrightarrow{I_t^{bf}}$ is simply expressed:

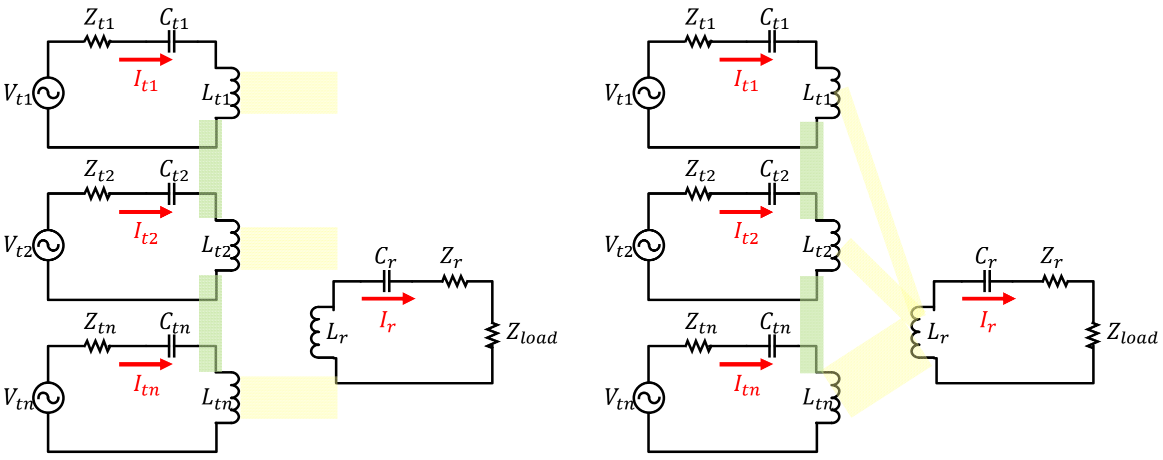
$$\overrightarrow{I_t^{bf}} = d[M_{1r} \quad M_{2r} \quad M_{3r} \quad \cdots \quad M_{nr}]^T \tag{19}$$

where the constant d is determined by the total input power constraint similar as the constant c in Eq. (17). Eq. (19) implies that when all of the transmitter currents are adjusted proportional to the mutual inductance between each transmitter and receiver, the M to 1 WPT system can achieve the magnetic beamforming. This is a special solution of magnetic beamforming only for the M to 1 WPT system. After adjusting the transmitter current $\overrightarrow{I_t}$ to the optimal transmitter current $\overrightarrow{I_t^{bf}}$, the WPT system can make the magnetic beam to the receiver as shown in Fig. 9, which increases the current I_r and power P_r in the receiver. However, using a current source as the input source of the circuit is not general. Many engineers usually use a voltage source instead of a current source for convenience. Therefore, the optimal transmitter voltage $\overrightarrow{V_t^{bf}}$, which can flow the optimal transmitter current $\overrightarrow{I_t^{bf}}$ should be derived. Since we already derived $\overrightarrow{I_t^{bf}}$, $\overrightarrow{V_t^{bf}}$ can be derived easily by Eq. (10) as follows.

$$\overrightarrow{V_t^{bf}} = (Z_t + \omega^2 M^T Z_{in-rx}^{-1} M)\overrightarrow{I_t^{bf}} \tag{20}$$

This result represents that when the input voltage of the M to 1 WPT system is adjusted to the optimal transmitter voltage $\overrightarrow{V_t^{bf}}$, it makes the optimal transmitter current $\overrightarrow{I_t^{bf}}$ and achieve the magnetic beamforming, which enhances the performance. We confirm the magnetic beamforming scheme by circuit simulation in the following section.

2.2.2> Verification of Improved Performance through Circuit Simulation



(a) Uniform input ($V_{t1} = V_{t2} = V_{t3}$) (b) Magnetic Beamforming

Fig. 10. Two cases of simulation scheme

So far, the magnetic beamforming introduced by [2, 12] was explained. This section, we use circuit simulation to verify the improved performance in terms of the PTE in magnetic beamforming compared to the 1 to 1 WPT system and M to 1 WPT system with uniform input. For the simulation, we assume one WPT system where the receiver is close to the third transmitter as shown in right scheme of Fig. 10.

Term	Definition	Explanation
$R_{t1}, R_{t2}, R_{t3}, Z_r$	1Ω	Resistance of all circuits
Z_{load}	4Ω	Resistance that implies the device to be charged
$C_{t1}, C_{t2}, C_{t3}, C_r$	2.53nF	Capacitance for magnetic resonance
$L_{t1}, L_{t2}, L_{t3}, L_r$	10μH	Coil for transmitting and receiving power
k_{1r}, k_{2r}, k_{3r}	0.06, 0.08, 0.1	Coupling coefficient between transmitter and receiver.
$k_{t-12}, k_{t-13}, k_{t-23}$	0.04	Coupling coefficient between multiple transmitters
$P_{total-in}$	10W	Total power from the voltage source

Table. 3. Specification of parameters for assuming specific situation

Table. 3 is values of components in Fig. 10 for circuit simulation. The magnetic coupling coefficients k_{ir} and k_{t-ik} $(\mathrm{i} = 1,2,\cdots \mathrm{n}, \mathrm{k} = 1,2,\cdots \mathrm{n}, \mathrm{i} \neq \mathrm{k})$ are determined by the distance and directionality between both coils, where the value is between 0 and 1 [3]. The relationship between magnetic coupling coefficient k and mutual inductance M is expressed as follows.

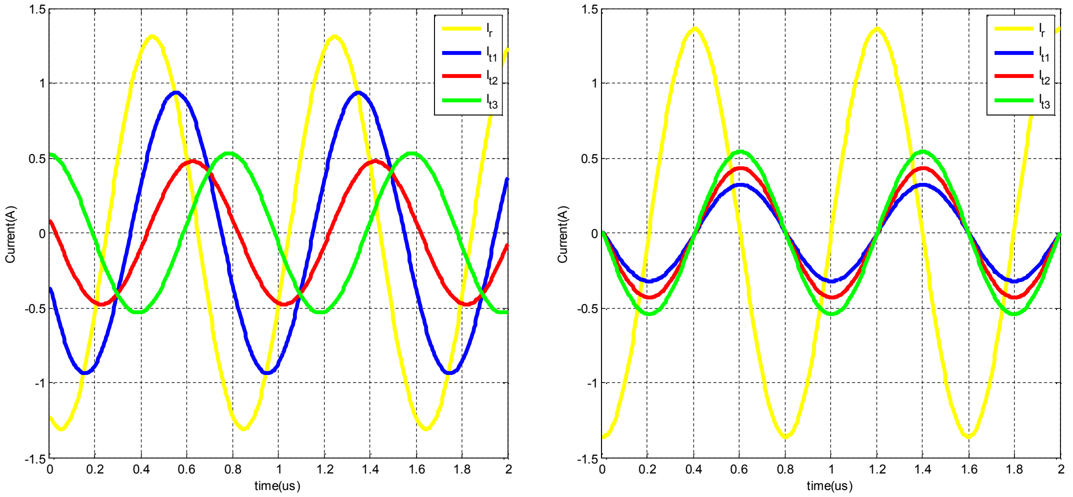
$$M_{ir} = k_{ir}\sqrt{L_i L_r} \quad (i = 1,2,3) \tag{21}$$

$$M_{t-ik} = k_{t-ik}\sqrt{L_i L_k} \quad (i = 1,2,3, k = 1,2,3, i \neq k)$$

All of the circuits are resonated at the same frequency by capacitance C_{ti} and C_r to enhance the PTE [1, 7]. For the simple simulation, it is assumed that the WPT system has a 1MHz resonance frequency. Additionally, physical parameter of coils and coupling coefficients among multiple transmitter coils are identical. This assumption implies that all transmitters are arranged in the form of an isosceles triangle where the distance is identical. (i.e., $k_{t-12} = k_{t-23} = k_{t-13}$)

The simulation procedure is as follows. First, we compare the transmitter current $\overrightarrow{I_t}$ and receiver current I_r between the uniform input and magnetic beamforming case. Next, we compare the PTE, which is defined by the power to the load P_{load} divided by the total input power $P_{total-in}$ (i.e. $\mathrm{PTE} = {}^{P_{load}}/_{P_{total-in}}$). The PTE result is compared including the 1 to 1 WPT simulation which is carried out by turning on only one among three transmitters step by step. To achieve the magnetic beamforming, the transmitter current $\overrightarrow{I_t}$ should be adjusted proportional to the mutual inductance between each transmitter and receiver by Eq. (19). That is: the optimal transmitter current $\overrightarrow{I_t^{bf}} = d[M_{1r} \quad M_{2r} \quad M_{3r}]^T = d[0.6 \quad 0.8 \quad 1]^T$. Eq. (20) which represents the general solution of optimal transmitter voltage $\overrightarrow{V_t^{bf}}$ is abbreviated as follows in this 3 to 1 WPT system simulation [17-18]:

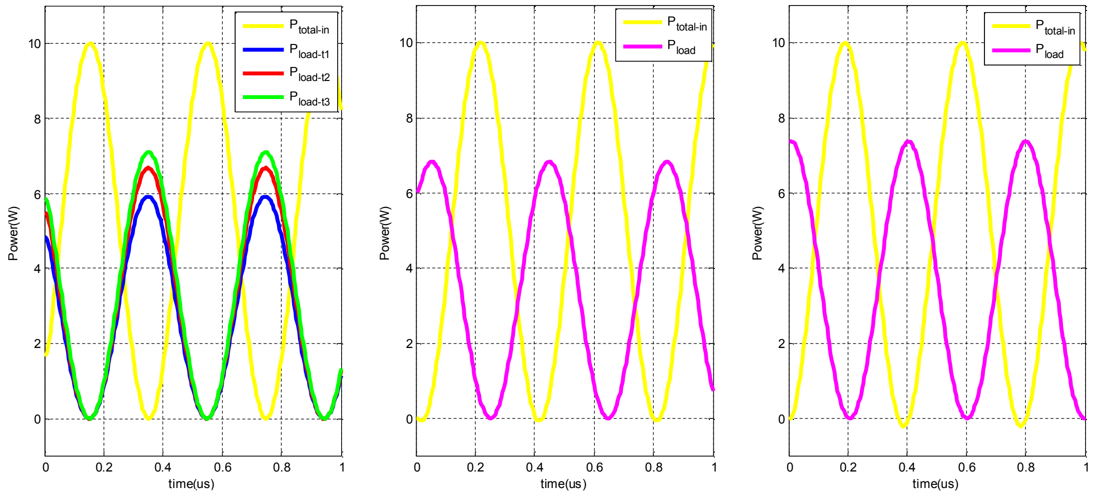
$$\overrightarrow{V_t^{bf}} = c\begin{bmatrix} M_{2r}\left(\frac{M_{1r}M_{2r}\omega^2}{Z_{in-rx}} + j\omega M_{t-12}\right) + M_{3r}\left(\frac{M_{1r}M_{3r}\omega^2}{Z_{in-rx}} + j\omega M_{t-13}\right) + M_{1r}\left(\frac{M_{1r}^2\omega^2}{Z_{in-rx}}\right) + Z_{t1}\Big) \\ M_{1r}\left(\frac{M_{1r}M_{2r}\omega^2}{Z_{in-rx}} + j\omega M_{t-21}\right) + M_{3r}\left(\frac{M_{2r}M_{3r}\omega^2}{Z_{in-rx}} + j\omega M_{t-23}\right) + M_{2r}\left(\frac{M_{2r}^2\omega^2}{Z_{in-rx}}\right) + Z_{t2}\Big) \\ M_{1r}\left(\frac{M_{1r}M_{3r}\omega^2}{Z_{in-rx}} + j\omega M_{t-31}\right) + M_{2r}\left(\frac{M_{2r}M_{3r}\omega^2}{Z_{in-rx}} + j\omega M_{t-32}\right) + M_{3r}\left(\frac{M_{3r}^2\omega^2}{Z_{in-rx}}\right) + Z_{t3}\Big) \end{bmatrix} \tag{22}$$



(a) Uniform input (Non-beamforming) case

(b) Magnetic beamforming case

Fig. 11. Transmitter and receiver current of all coils



(a) 1 to 1 case

(b) Uniform input (Non-beamforming) case

(c) Magnetic beamforming case

Fig. 12. Total input power $P_{total-in}$ and output power P_{load}

By Eq. (22), the optimal transmitter voltage is calculated: $\overrightarrow{V_t^{bf}} = [6.0\angle 24.2^\circ \quad 7.6\angle 16.7^\circ \quad 9.3\angle 11.8^\circ]V^T$. Fig. 11 shows the result graph of current between uniform input and magnetic beamforming case. Fig. 11 (a) is when the transmitter voltage is set identically (i.e. $V_{t1} = V_{t2} = V_{t3} = 7.04$V), while Fig. 11 (b) is the transmitter voltage is adjusted to the calculated optimal voltage $\overrightarrow{V_t^{bf}}$. In both graphs, the yellow line indicates the receiver current I_r, while blue, red, and green line indicate the transmitter current I_{t1}, I_{t2} and I_{t3}, respectively. In Fig. 10 (b), all of the transmitter current $\overrightarrow{I_t}$ are set to the optimal value $\overrightarrow{I_t^{bf}}$ with same phase, which contribute to induce the maximum receiver current I_r. This alignment of transmitter currents seems that makes a magnetic beam to receiver. That is the reason why it is called ‘magnetic beamforming’. However, in uniform input case, the phase of transmitter currents are out of phase, because of magnetic couplings between multiple transmitter coils. The effect of unaligned phase of transmitter currents becomes more apparent in terms of the electrical power. Fig. 12 represents the total input power $P_{total-in}$ and the output power P_{load}. Among three graphs, the yellow line indicates the output power P_{load}. Fig. 12 (a) is the input and output power graph of simulation which turns on only one transmitter while other transmitters are turned off. The blue, red and green line indicate the output power $P_{load-t1}$, $P_{load-t2}$ and $P_{load-t3}$. Fig. 12 (b), (c) shows the same input and output power when the transmitter current I_t is adjusted to Fig. 12 (a) and (b). The PTE calculated from the Fig. 12 is shown in the following Table. 4.

	Fig. 12 (a) – 1 to 1 WPT			3 to 1 WPT	
	First transmitter	Second transmitter	Third transmitter	Uniform Input Fig. 12 (b)	Magnetic Beamforming Fig. 12 (c)
PTE	59.18%	66.70%	71.0%	68.33%	**73.70%**

Table. 4. Power Transfer Efficiency calculated by Fig. 12.

Since the third transmitter is assumed to be closest to the receiver, the third transmitter achieves the maximum PTE 71.0% in 1 to 1 WPT case. It is expected that when the WPT system has multiple transmitters, the system can achieve better performance. However, in the 3 to 1 WPT system with the uniform input voltage, the performance is low compared to the maximum value in the 1 to 1 WPT system. This phenomenon is manifested by the magnetic couplings between multiple transmitters. Due to these couplings, each transmitter does not concentrate on transferring power to the receiver but disturbing another transmitter's operation, which decreases the performance of the overall WPT system [17, 18]. The advantage of multiple transmitters placement is shown by properly adjusting the transmitter voltage and current to achieve the magnetic beamforming. After adjusting the transmitter voltage $\overrightarrow{V_t}$ to the optimal voltage $\overrightarrow{V_t^{bf}}$, the M to 1 WPT system can achieve the improved PTE compared to 1 to 1 WPT system as shown in Table 4 and Fig. 12 (c). In this magnetic beamforming case, the PTE is improved to 73.7% from the maximum PTE 71.0% of 1 to 1 WPT system. The higher PTE also implies that the system can have a longer wireless charging distance [17, 18].

So far, the conventional magnetic beamforming is introduced briefly. Despite the improved performance of the magnetic beamforming explained above, it requires a complex calculation for the optimal transmitter voltage $\overrightarrow{V_t^{bf}}$ as shown in Eq. (22). Additionally, the transmitter needs not only a voltage amplifier, but also a phase shifter since the optimal voltage value is a complex number.. These disadvantages are caused by the magnetic couplings between multiple transmitters [17, 18]. Furthermore, these magnetic couplings not transfer power to the receiver, but trap power in the transmitters, which attenuates the performance of the WPT system. If these magnetic couplings are diminished or eliminated properly, it is expected that the WPT system can achieve a better performance than conventional magnetic beamforming. In the following sections, we propose optimization in the transmitter to enhance the performance of the WPT system. By proposed optimization scheme, the M to 1 WPT system can achieve a better performance with simple calculation.

III. OPTIMIZATION IN THE TRANSMITTER

3.1> Introduction of a Non-Coupling Coil Pattern

As mentioned above, the M to 1 WPT system with magnetic beamforming needs multiple transmitters to focus the magnetic field at the receiver. However, the magnetic couplings between multiple transmitters occur inevitably, which degrade the performance of the WPT system. In this section, how to optimize the multiple transmitters in the M to 1 WPT system to achieve an enhanced magnetic beamforming is introduced. Firstly, we consider the influence of magnetic couplings in terms of the PTE by simple simulation. Then, a magnetic coupling removal scheme – a non-coupling coil pattern – is introduced [20]. It is assumed that by replacing the non-coupling coil pattern as the transmitter in the M to 1 WPT system, the multiple transmitters are magnetically independent. This replacement of transmitter provides several advantages, which will be covered in this section. Identical simulations as the previous section about power, current, and the PTE are performed to verify the better performance. By optimization in the transmitter, the M to 1 WPT system can achieve an enhanced magnetic beamforming with a simple calculation.

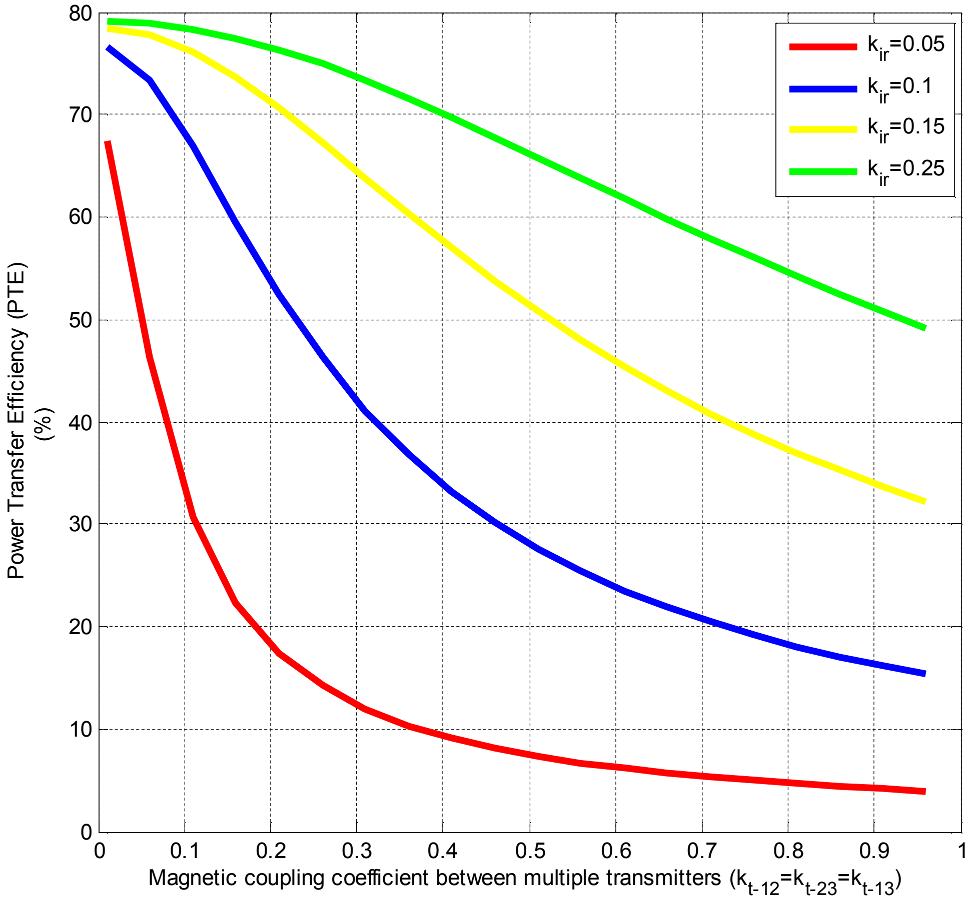


Fig. 13. Power Transfer Efficiency (PTE) versus magnetic couplings coefficient between multiple transmitters (k_{t-ir})

Fig. 13 represents the PTE versus the magnetic couplings between three transmitters. For the simple simulation, same assumptions as shown in Table. 3 are adapted except the distance between each transmitter and receiver is identical. (i.e. $M_{1r} = M_{2r} = M_{3r}$). As shown in Fig. 13, it is evidently shown the PTE and magnetic couplings k_{t-ir} are inversely relationship. By comparing the red line ($k_{ir} = 0.05$) and green line ($k_{ir} = 0.25$), this phenomenon clearly appears when the distance between transmitter and receiver is far [17]. It is confirmed that the performance of the WPT system is improved when the magnetic couplings between multiple transmitters are eliminated.

In order to make multiple transmitters magnetically independent, we proposed the non-coupling coil pattern that consists of heterogeneous multi-pole loops, as shown in Fig. 14. The coil B is a quadrupole loop which is composed of identical circular loops. These quadrupole loops can make cancellation plane which has '0' magnetic field strength via opposite magnetic fields from each loop of the quadrupole loop. When the center of coil A is placed on the cancellation plane of the coil B, both coils can eliminate magnetic coupling between them. The detailed explanation of this proposed coil pattern is introduced in [20]. The first step of optimization in the transmitter is eliminating the magnetic couplings between multiple transmitters by using magnetically decoupled condition above. After replacing the non-coupling coil pattern as the transmitter in the M to 1 WPT system, it is expected that all of the transmitters are magnetically independent. This replacement results in some advantages such as a better PTE and simple calculation for optimal transmitter voltage $\overrightarrow{V_t^{bf}}$. These advantages are verified by circuit analysis and simulation results following the previous section.

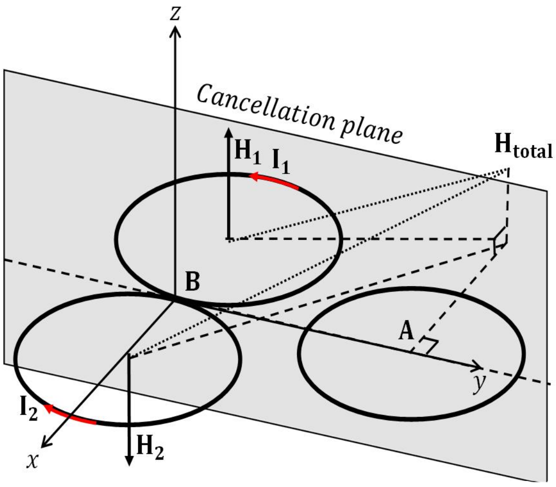


Fig. 14. Concept of non-coupling coil pattern with cancellation plane [20]

3.2> Derivation and Verification of Optimization in the Transmitter

After adapting the non-coupling coil pattern as the transmitter coil of WPT system, the input impedance of i-th transmitter Z_{in-txi} during charging procedure is altered. As explained previously, the input impedance Z_{in-txi} consists of three terms Z_{ti}, $Z_{ref-txi}$ and $Z_{ref-rxi}$ in M to 1 WPT system. By adjusting the transmitter current $\vec{I_t}$ to the optimal value $\overrightarrow{I_t^{bf}}$, the reflected impedance from the receiver $Z_{ref-rxi}$ has an only real term by Eq. (11). On the other hand, the reflected impedance from other transmitters $Z_{ref-txi}$ has an only imaginary term. That's why the transmitter voltage $\vec{V_t}$ should be adjusted both magnitude and phase terms by Eq. (22).

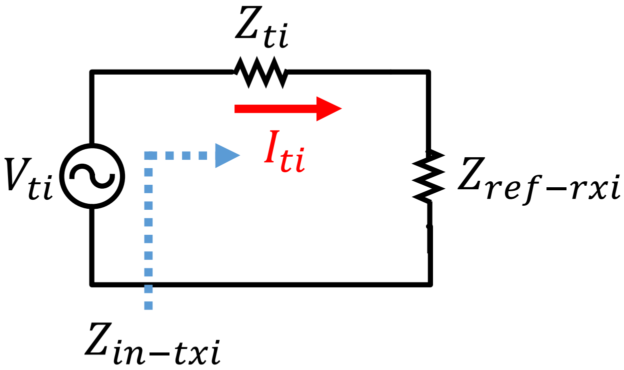
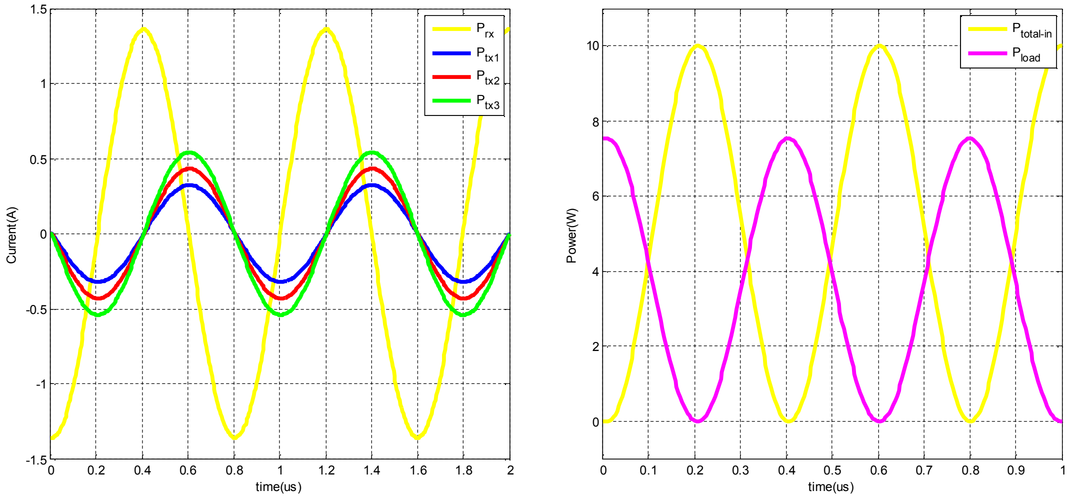


Fig. 15. Equivalent transmitter circuit in proposed WPT system during charging procedure

However, the magnetic couplings between multiple transmitters are eliminated in our proposal. This elimination makes all of the transmitters magnetically independent from other transmitters, which results in removing the reflected impedance $Z_{ref-txi}$ from other transmitters. That is, compared to the equivalent transmitter circuit in the conventional M to 1 WPT system, the input impedance Z_{in-txi} has only real number in our proposal. It is evidently shown by comparing between Fig. 8 (a) and Fig. 15. Additionally, the input impedance Z_{in-txi} of each transmitter circuit becomes identical (i.e., $Z_{in-tx1} = Z_{in-tx2} \cdots Z_{in-txn}$) when the intrinsic impedance Z_{ti} of all transmitters are identical. That is, the optimal transmitter current $\overrightarrow{I_t^{bf}}$ and the optimal voltage $\overrightarrow{V_t^{bf}}$ are same phase, which implies that the transmitter needs not adjusting the phase of the voltage in our proposal. Regardless of the presence of magnetic couplings between multiple transmitters, the optimal transmitter current $\overrightarrow{I_t^{bf}}$ are proportional to the mutual inductance between each transmitter and receiver by Eq. (19). The optimal transmitter voltage $\overrightarrow{V_t^{bf}}$ can be easily calculated with the optimal transmitter current $\overrightarrow{I_t^{bf}}$ and the Z_{in-txi} as follows.

$$\overrightarrow{V_t^{bf}} = c' \begin{bmatrix} M_{1r} \\ M_{2r} \\ M_{3r} \end{bmatrix} \tag{23}$$

where c' is a constant similar to the constant c in Eq. (22). Eq. (23) is valid when the intrinsic impedances Z_{ti} of each transmitter are identical. Contrary to the complex calculation for optimal transmitter voltage in the conventional magnetic beamforming, the calculation for the optimal transmitter voltage becomes greatly simple in our proposal. This simplification is evidently shown by comparing between Eq. (22) and Eq. (23). That is, our proposed M to 1 WPT system with the non-coupling coil pattern can achieve the magnetic beamforming easily by adjusting only the magnitude of transmitter voltage source. In addition, it is expected the performance such as the PTE is enhanced compared to the conventional magnetic beamforming. This expectation is comes from that the magnetic couplings between multiple transmitters trap the power in the transmitter, not transfer to the receiver as explained before. In this section, same simulations as the previous section is performed with assumption that eliminates the magnetic couplings between multiple transmitters.



(a) Transmitter and receiver current (b) Total input and output power

Fig. 16. Transmitter and receiver current and power after optimization in the transmitter

	3 to 1 WPT		
	Uniform Input Fig. 12 (b)	Magnetic Beamforming Fig. 12 (c)	Optimization in the transmitter Fig. 16
PTE	68.33%	73.70%	**75.24%**

Table. 5. Power Transfer Efficiency (PTE) after optimization in the transmitter

After elimination the magnetic couplings between multiple transmitters, the optimal transmitter voltage $\overrightarrow{V_t^{bf}}$ by Eq. (23) is $[5.50 \quad 7.33 \quad 9.17]^T$. Fig. 16 is the result of the current and power in the proposed magnetic beamforming when the transmitter voltage $\overrightarrow{V_t}$ is adjusted to the optimal value. As shown in Fig. 16 (a), it can be confirmed that the transmitter currents are aligned with same phase in a same manner as the conventional magnetic beamforming compa red to Fig. 11 (a). These aligned transmitter currents appear to generate a magnetic beam at the receiver, which results in the improved PTE [2]. As shown in Table. 5, the PTE improves from 73.70% in conventional magnetic beamforming case to 75.24% in our proposal. By circuit simulation, it is verified that the magnetic beamforming with non-coupling coil pattern is able to achieve the better performance with the simple calculation for the optimal voltage.

The additional circuit simulation is carried out assuming a different situation as shown in Fig. 17. In this simulation, the distance between each transmitter and receiver increases or decreases identically (i.e., $k_{1r} = k_{2r} = k_{3r}$). Then, the magnetic couplings between multiple transmitters are adjusted, thereby confirming variation of the PTE. Fig. 18 represents the PTE result of additional simulation. The green line indicates our proposal with a zero magnetic coupling coefficient k_{t-ir} between transmitters, while the yellow, blue and red lines show values of 0.05, 0.1 and 0.15 respectively. The lower value of magnetic coupling coefficient k_{ir} implies that the wireless charging distance between both transmitter and receiver is far, which indicates a near zero PTE in the graph. When the magnetic couplings between multiple transmitters is zero, as expressed a green line in the graph, the highest PTE is achieved regardless of the distance between both transmitter and receiver. In this case, the PTE does not drop dramatically compared to the other cases while the charging distance is increasing. This result represents that the proposed scheme with a non-coupling coil pattern is able to achieve the enhanced performance such as the PTE and the wirelessly charging distance by simple calculation [17].

So far, only the transmitter side of the M to 1 WPT system is controlled to achieve the better performance. That's why the proposed scheme is called 'optimization in the transmitter' in this paper. In the following section, we

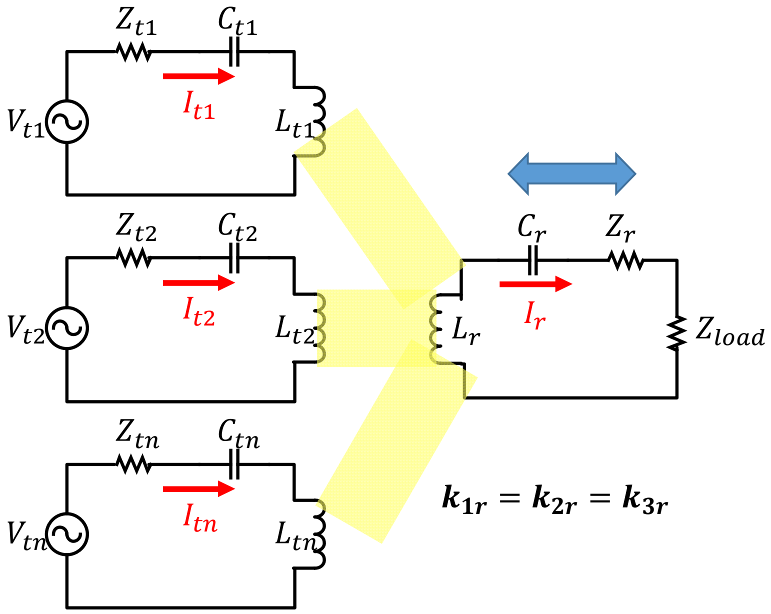


Fig. 17. Circuit scheme for additional simulation

discuss how to improve the performance of the M to 1 WPT system by further controlling the one parameter in the receiver after optimization in the transmitter.

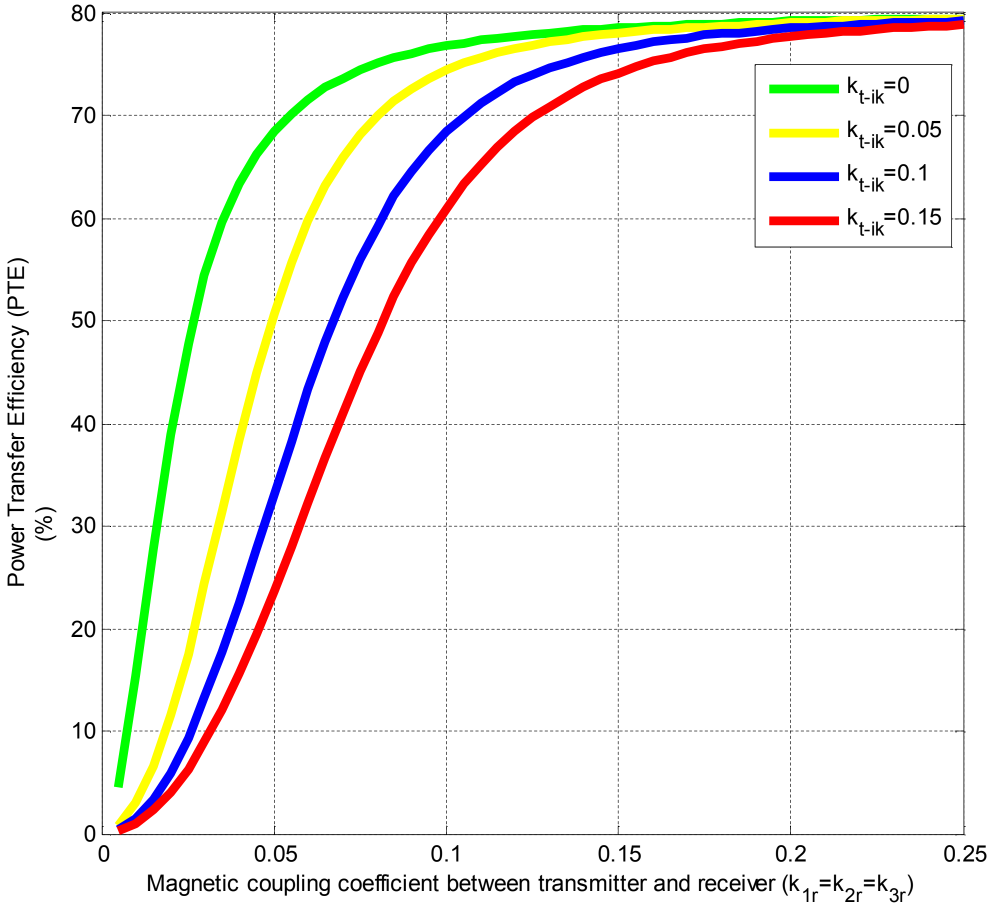


Fig. 18. Power Transfer Efficiency (PTE) versus magnetic couplings coefficient between transmitter and receiver (k_{ir})

IV. OPTIMIZATION IN THE RECEIVER

4.1> Introduction of Load Impedance Optimization

Optimization in the transmitter was introduced in the previous section. However, by the only optimization in the transmitter cannot achieve the maximum performance in the M to 1 WPT system. If the receiver is optimized after optimization in the transmitter, a meaningful performance improvement appears [18]. The parameter to be controlled in the receiver is the load impedance Z_{load}, which indicates the device to be charged wirelessly. The principle of finding the optimal load impedance Z_{load}^* is related to the maximum power transfer theorem using an impedance matching [11]. The impedance matching is the theory that if the load impedance is a complex conjugate of the source impedance, all the magnetic fields from the source are transmitted to the receiver, not reflected. In other words, when the impedance matching is performed in the circuit, the power source can transmit the maximum power to the load [13]. There have been lots of researches to find the optimal load impedance Z_{load}^* in the WPT system by adapting the maximum power transfer theorem. D.W. Seo derived the optimal load impedance in the 2-coil WPT system from the four-coil WPT system [11]. Q. T. Duong derived the solution in M to 1 WPT system [19]. However, his research does not explain in detail how to derive the value of optimal load impedance. M. Fu derived the solution in 1 to M WPT system [13]. These researches explain that the optimal load impedance is determined by the magnetic coupling k_{ir} and Q-factor $\omega L/_{R}$ between each transmitter and receiver. It implies that the optimal load impedance Z_{load}^* is related not only the components of each circuit, but also the distance between each transmitter and receiver. Fig. 8 (b) represents the equivalent receiver circuit when the power is transferred from the multiple transmitters. As expressed previously, the power is transferred via the magnetic coupling between the transmitter and receiver. That's why the receiver coil acts as a power source which is represented by $\sum_{i=1}^{n} j\omega M_{ir} I_{ti}$ (i=1,2,3,,,n). Since the variation of the load impedance Z_{load} affects the entire WPT system including the transmitter current and the reflected impedance, obtaining the optimal value is difficult. In this section, optimization in the receiver in M to 1 WPT system is introduced. It is achieved by adjusting the load impedance Z_{load} to the optimal load impedance Z_{load}^* which is derived through differentiation technique. The key point is that optimization in the receiver should be followed by optimization in the transmitter [18]. When optimization in the receiver is carried out, it implies the maximum power transfer theory is performed in the receiver, which is expected to enhance the performance of the WPT system. We verify that optimization in the receiver enhances the performance in terms of the power compared to results mentioned in the previous section.

The method for obtaining the optimal load impedance is explained as follows [13].

1) Derive an equation of the PTE as a function of the load impedance Z_{load}.
2) Find a maximum point of PTE by differentiation for the load impedance Z_{load}.

4.2> Derivation and Verification of Optimization in the Receiver

We designate the term η representing the PTE. η_{total} indicates the total PTE of the WPT system, η_{tx-i} indicates the PTE of i-th transmitter, and η_{rx} indicates the PTE of the receiver. To derive the total PTE η_{total}, analysis of each circuit should be performed. The PTE of i-th transmitter η_{tx-i} is derived easily by Fig. 8. In Fig. 8 (a), the power from the voltage source is assigned at the input impedance Z_{in-txi}. Among the total power, the power which is allocated at the reflected impedance $\mathrm{Z}_{ref-rxi}$ is the power to be transferred to the receiver. That is:

$$\eta_{tx-i} = \frac{Z_{ref-rxi}}{Z_{in-txi}} = \frac{Z_{ref-rxi}}{Z_t + Z_{ref-txi} + Z_{ref-rxi}} \tag{24}$$

The PTE in the receiver can be derived in the same way by Fig. 8 (b). The power to charge the device is the power allocated at the load impedance Z_{load}. i.e.:

$$\eta_{rx} = \frac{Z_{load}}{Z_{in-rx}} = \frac{Z_{load}}{Z_r + Z_{load}} \tag{25}$$

The PTE from the i-th transmitter to the load is the product of η_{tx-i} and η_{rx}. In the M to 1 WPT system with magnetic beamforming, the amount of power to be transferred from each transmitter is determined by the strength of the magnetic coupling between each transmitter and receiver [2, 12]. To derive the PTE of the total WPT system, the power contribution ratio of i-th transmitter D_i should be considered. The ratio D_i is calculated as follows.

$$D_i = \frac{P_{ti}}{P_{total-in}} = \frac{V_{ti} I_{ti}}{\sum_{k=1}^{n} V_{tk} I_{tk}} \tag{26}$$

where n is the number of transmitters, $P_{total-in}$ indicates the total power calculated by the sum of all transmitters input power. P_{ti} indicates the power from the i-th transmitter. Thus, the total PTE η_{total} can be calculated as follows.

$$\eta_{total} = \sum_{k=1}^{n} D_k \, \eta_{tx-i} \eta_{rx} \tag{27}$$

By Eq. (27), the total PTE η_{total} is a function of the load impedance Z_{load}. It is expected that if the solution of $\frac{\partial \eta_{total}}{\partial Z_{load}} = 0$ is obtained, the optimal load impedance Z_{load}^{*} is achieved. However, the solution is difficult obtain since the input impedance of all transmitters are not identical due to the magnetic couplings between multiple transmitters. That is, in the conventional magnetic beamforming as explained in section 2.2, the closed-form solution of the optimal load impedance Z_{load}^* is not able to be obtained. However, it is possible to obtain the closed-form solution of the optimal load impedance Z_{load}^* after our proposed optimization in the transmitter as expressed in section 3.1. When the transmitter is optimized, the input impedance of each transmitter is identical as explained previously. The optimal load impedance Z_{load}^*, which is calculated after optimization in the transmitter, is expressed as follows.

$$Z_{load}^* = Z_r\sqrt{1+\sum_{i=1}^{n}\frac{\omega^2 M_{ir}^2}{Z_{ti}Z_r}} \tag{28}$$

To achieve the closed-form solution of optimal load impedance Z_{load}^*, same assumptions are applied. All the intrinsic impedances in all of transmitters are identical (i.e., $Z_{t1} = Z_{t2} = \cdots = Z_{tn}$). This is a reasonable assumption if all circuits in transmitters are identically designed. Eq. (28) implies the optimal load impedance is related to the components of both transmitter and receiver, which is the same result as explained in [11, 19].

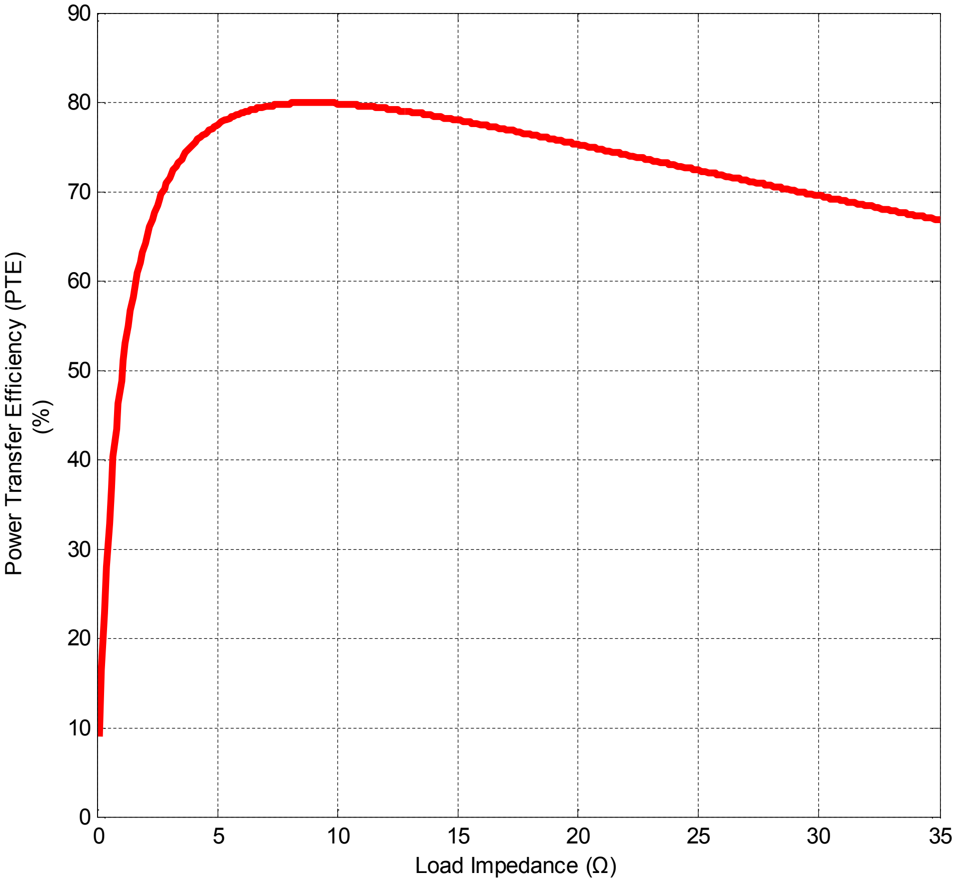


Fig. 19. Power Transfer Efficiency (PTE) versus Z_{load} after optimization in the transmitter

	3 to 1 WPT			
	Uniform Input Fig. 12 (b)	Magnetic Beamforming Fig. 12 (c)	Optimization in the transmitter Fig. 16	Transceiver Optimization Fig. 18
PTE	68.33%	73.70%	75.24%	**80.00%**

Table. 6. Power Transfer Efficiency(PTE) after optimization in the receiver

In circuit simulation of the previous section, the load impedance Z_{load} is fixed at 4Ω for convenience. In this section, the same circuit simulation is carried out while adjusting the load impedance to verify the enhanced performance of optimization in the receiver. After the simulation of optimization in the transmitter, the optimal load impedance Z_{load}^{*} by (28) is 8.8Ω. Fig. 19 shows the PTE in M to 1 WPT system versus the load impedance Z_{load}. As shown in Fig. 19, the maximum PTE is located when the load impedance Z_{load} is adjusted to the optimal value Z_{load}^{*}, around 8.8Ω. The PTE is improved to 80% when both transmitter and receiver are optimized as shown in Table. 6. This is the maximum value which can be achieved in M to 1 WPT system assumed by Table.

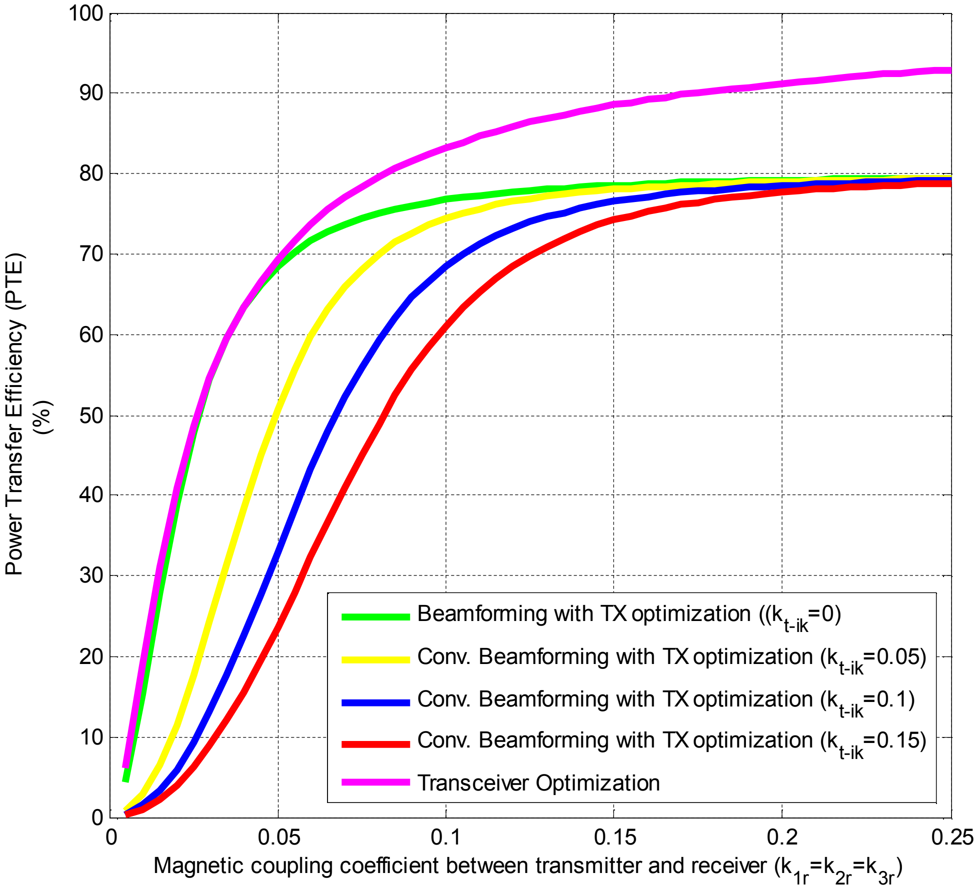


Fig. 20. Power Transfer Efficiency (PTE) of transceiver optimization compared to conventional scheme and optimization in the transmitter

3. That is, after optimization in both transmitter and receiver, the M to 1 WPT system can accomplish the maximum performance

Additional simulation based on Fig. 17 is carried out to verify the enhanced performance of transceiver optimization scheme. Fig. 20 shows the PTE of all schemes mentioned in this paper by changing the distance between the transmitter and receiver. The red, blue and yellow line indicate the PTE of conventional magnetic beamforming where the coupling coefficient k_{t-ik} is 0.05, 0.1 and 0.15, respectively. The green line indicates the PTE of optimization in the transmitter introduced in section 3.2. The magenta line indicates the PTE of transceiver optimization as explained in this section. For cases without optimization in the receiver, the load impedance Z_{load} is fixed at 4Ω. As expected, the PTE of transceiver optimization can achieve the maximum performance compared to other results. The enhancement of performance is evidently shown when the distance between transmitter and receiver is shorter. This result implies that the M to 1 WPT system with transceiver optimization can achieve the maximum performance such as the PTE and wireless charging distance under any circumstances.

V. CONCLUSION

This paper introduces how to achieve the maximum performance of the M to 1 WPT system by optimization of both transmitter and receiver. In the transmitter, optimization is carried out by eliminating the magnetic couplings among multiple transmitters and controlling the magnitude of the voltage source. This optimization scheme has some advantages over the conventional magnetic beamforming in terms of the PTE and ease of voltage control. The number of parameters to be controlled is reduced from two to one, which makes the circuit implementation and calculation much easier. Optimization in the receiver, which is performed after optimization in the transmitter, is an adjustment of the load impedance that indicates the device to be charged. The optimal load impedance is determined by the principle of maximum power transfer theorem and the impedance matching in the receiver. After optimization in both sides, the proposed M to 1 WPT system can achieve the maximum PTE under any circumstance, which implies it can charge device wirelessly at a longer distance compared to the charger on the market now. The proposed WPT system can act as a target performance to design the WPT system. Additionally, it is expected that the proposal is able to play a significant role in the following IoT world, which is composed of many electronic devices.

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요 약 문

다중 송신기와 단일 수신기 무선 전력 전송 시스템의 송/수신기 최적화

본 논문에서는 다중 송신기와 단일 송신기의 무선 전력 전송 시스템(M to 1 Wireless Power Transfer System) 에서 성능을 최대화 할 수 있는 송/수신기 최적화 기법을 제안한다. 스마트폰과 태블릿 등의 모바일 디바이스가 발전함에 따라 무선 충전 기술의 중요성이 대두되었다. 많은 제조사들이 2010년대 초반부터 무선 충전기를 출시했음에도 불구하고, 충전 거리가 짧고 효율이 떨어지는 탓에 소비자들이 기존에 희망했던 무선 충전을 제공할 수 없었다. 아쉽게도 오늘날에도 시장에 출시되어 있는 무선 충전 기술은 크게 발전되지 않았다. 이 단점을 극복하고, 소비자에게 편의성을 제공하기 위해 많은 연구가 진행되었다. 자기 빔포밍 기술은 충전기 내에 다수의 송신 코일을 배치한 뒤, 송신 코일에서 인가되는 자기장을 수신 코일에 집중시켜 수신 코일과 회로에 최대 전력을 유도하게 하는 기법이다. 이는 송신 코일에 인가되는 전류와 전압을 제어함으로써 달성할 수 있다. 그러나, 다수의 송신 코일의 배치로 인해 필연적으로 추가된 다수의 송신 코일 간의 자기 결합이 발생하게 된다. 이는 자기 빔포밍을 달성하기 위해 각각의 송신 회로에 인가 되어야 하는 최적 전압의 계산을 어렵게 하며, 위상 제어가 필요한 탓에 각 송신 회로에서 위상 천이기를 필요로 한다. 더욱이 이 자기 결합으로 인해 일부 전력이 송신 코일에 남아있게 되고, 이는 시스템의 성능 저하로 연결된다. 본 논문에서는, 송신기에서의 최적화는 앞서 언급한 다수의 송신 코일 간의 자기 결합을 제거함으로써 위상 제어 없는 간단한 제어로 높은 효율을 달성하는 법을 소개한다. 송신 코일 간의 자기 결합을 제거하는 방법으로는 무 결합 코일 패턴(non-coupling coil pattern)이 소개된다. 수신기에서의 최적화는 부하 저항 최적화(load optimization)를 다룬다. 부하 저항 최적화는 최대 전력 전송 이론(maximum power transfer theorem)에 기반하여 유도되며, 반드시 송신 최적화 후 유도가 가능하다. 양 쪽을 모두 최적화 함으로써, 다중 송신기와 단일 송신기의 무선 전력 전송 시스템은 주어진 상황에서 최대의 성능을 달성할 수 있다. 이를 회로 시뮬레이션을 통해, 입력 전압이 모두 동일할 때 (Uniform input) / 기존 빔포밍 적용 (Conventional Beamforming) / 송신기 최적화 (Optimization in the transmitter) / 송,수신기 최적화 (Optimization in both sides) 각각의 경우를 비교하고, 제안된 송/수신기 최적화 기법이 가장 뛰어난 효율을 달성함을 보인다.

핵심어: 자기 빔포밍, 무선 전력 전송, 최적화, 무 결합 코일, 임피던스 매칭, 최대 전력 전송