Control of Power Distribution for Multiple Receivers in SIMO Wireless Power Transfer System

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Abstract

A method to control the power distribution among receivers by the load values in a single-input, multiple-output (SIMO) wireless power transfer (WPT) system is investigated. We first derive the value of loads to maximize total efficiency. Next, a simple, but effective analytical formula of the load condition for the desired power distribution ratio is presented. The derived load solutions are simply given by system figure of merits and desired power ratios. The formula is validated with many numerical examples via electromagnetic simulations. We demonstrate that with the choice of loads from this simple formula, the power can be conveniently and accurately distributed among receivers for most practical requirements in SIMO WPT systems.

Key Words: Optimum Load, Power Distribution, Single-Input Multi-Output, Transfer Efficiency, Wireless Power Transfer.

I. INTRODUCTION

A magnetically coupled wireless power transfer (WPT) system consisting of one transmitter and one receiver was successfully demonstrated using coupled-mode theory (CMT) in [1]. The WPT technology has since been studied to enable various applications, such as charging mobile phones, tablets, notebooks, home appliances, motor vehicles, and biomedical devices. The ongoing goal of researchers in this field is to achieve a higher efficiency over a longer distance. The use of an optimum load to realize the upper limit of transfer efficiencies was highlighted from the beginning [1] and has been one important design guideline in practice. To enhance the WPT efficiency beyond the upper limit, some WPT systems using relay coils and meta-material slabs have been studied [2–4].

Recently, the research interest in WPT technology has been extended to accommodate multiple-input multiple-output (MIMO) systems. In particular, the MIMO WPT [5] system has been attracting attention as a way to enable the energy auto-

my of Internet of Things (IoT) sensors. For general MIMO WPT systems, the efficiencies are usually evaluated numerically using a Z-matrix circuit formulation [6]. The loads to achieve a specifically required power distribution to multiple receivers can be found numerically using a genetic algorithm. However, the exact analytic (or closed-form) solutions for them have not yet been found for a general MIMO system.

A single-input multiple-output (SIMO) system can be considered a subset of MIMO systems. The overall efficiency of a SIMO WPT system was initially examined using CMT [7]. A circuit-centric matrix analytical model that predicts the behavior of SIMO systems was also presented [8].

In addition to achieving high efficiency, power distribution among receivers has been of great interest in designing a SIMO WPT system. For example, [9] proposed a time-shared charging technique to distribute power to receivers. In an effort to reduce the coupling effects between receivers, [10] diversified the resonant frequencies among the receivers. In this method, the power division among receivers was still controlled by ad-

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justing the charging time. The methods proposed in [11, 12] were presented in a relatively complex and abstract form to be used in design practice.

Another method to control the power distribution among receivers is to adjust the loads at the receivers. In [13], a power division was achieved by utilizing impedance inverters at the receiver sides on a two-receiver example. In [14], an impedance matching method for the power distribution among receivers was proposed based on coupled-mode and circuit theories. The actual power distribution among receivers, however, differs greatly from the desired distribution, especially in a condition of highly asymmetric distribution. [15] developed a new power control scheme by combining maximum efficiency point tracking (MEPT) with time-division multiplexing (TDM). In [16], multiple-receiver WPT-based battery voltage equalization was investigated using analytical derivations and experiments.

In this paper, we derive and present a simple analytic solution to control the power distributions among multiple receivers. The necessary receiver load values for a desired power distribution can be easily computed using the presented solution with little loss of accuracy. The proposed method of realizing arbitrarily desired power distributions is verified using numerical examples in circuit and electromagnetic (EM) simulations.

II. MODELING OF A SIMO WPT SYSTEM

1. Formulation of a SIMO WPT System

Fig. 1(a) and (b) show a typical SIMO WPT system and its equivalent circuit. The system is assumed to have a single transmitter and multiple receivers. All the loops (or coils) have some inductances (L_i) and resistances (R_i). Each coil is loaded with a capacitor (C_i) for resonance at a specific design frequency. The transmitter is excited by a voltage source (V_0), and the N receivers have load resistances (R_{Li}) to receive transferred powers. Once the sizes and positions of the transmitter and receivers are specified, the coupling coefficients between any two loops can be determined using the ratio of magnetic flux lines from one loop to the other [17]. The WPT system can then be analyzed in terms of the efficiencies for each receiver and for the total system. For $(N+1)$ loops of the SIMO WPT system in Fig. 1, we can write $(N+1)$ equations using KVL. They can be rearranged using a Z -matrix formulation. The Z -matrix as a function frequency is given by:

$$\begin{bmatrix} V_0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} Z_{00} & Z_{01} & Z_{02} & \cdots & Z_{0N} \\ Z_{10} & Z_{11} & Z_{12} & \cdots & Z_{1N} \\ Z_{20} & Z_{21} & Z_{22} & \cdots & Z_{2N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ Z_{N0} & Z_{N1} & Z_{N2} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix}. \quad (1)$$

Fig. 1. A general configuration of a SIMO WPT system with one transmitter and N receivers. (a) Geometry and (b) equivalent circuit.

In (1), V_0 in the column matrix $[V]$ is the supplied voltage of the transmitter. The principal diagonal elements of $[Z]$ at the resonant design frequency are given by:

$$Z_{00} = R_0 \quad (2)$$

and

$$Z_{ii} = R_i + R_{Li} \quad (\text{for } i = 1, 2, \dots, N), \quad (3)$$

where R_s are the loop resistances and R_{Li} 's are the load resistances for the receivers. The other elements of $[Z]$ are given by:

$$Z_{ij} = Z_{ji} = -j\omega_0 k_{ij} \sqrt{L_i L_j} \quad (i \neq j \text{ for } i, j = 0, 1, 2, \dots, N), \quad (4)$$

where k_{ij} s are the coupling coefficients between two loops. When all the elements of the Z -matrix are given, the current on each loop is determined by $[I] = [Z]^{-1}[V]$, in which all couplings between any two loops including the mutual are all considered. The input power and the received power at each receiver can then be evaluated using:

$$\begin{aligned} P_{in} &= \frac{1}{2} \text{Re}[V_0 I_0^*] \\ &= \frac{1}{2} |I_0|^2 R_0 + \frac{1}{2} \sum_{i=1}^N |I_i|^2 (R_i + R_{Li}) \quad (\text{for } i = 1, 2, \dots, N) \end{aligned} \quad (5)$$

and

$$P_{Li} = \frac{1}{2} |I_i|^2 R_{Li} \quad (\text{for } i = 1, 2, \dots, N). \quad (6)$$

2. Derivation of the Optimum Load and Efficiency in SIMO

The efficiency for the i^{th} receiver at the resonant frequency is defined and expressed as:

$$\eta_i = \frac{P_{Li}}{P_{in}} = \frac{\frac{1}{2}|I_i|^2 R_{Li}}{\frac{1}{2}|I_0|^2 R_0 + \frac{1}{2} \sum_{i=1}^N |I_i|^2 (R_i + R_{Li})}$$

$$= \frac{\left| \frac{I_i}{I_0} \right|^2 \frac{R_{Li}}{R_0}}{1 + \sum_{i=1}^N \left| \frac{I_i}{I_0} \right|^2 \left(\frac{R_i + R_{Li}}{R_0} \right)} \quad (7)$$

The efficiency can be evaluated using (7) or by $|S_{i0}|^2/(1-|S_{00}|^2)$ using EM simulations. The efficiencies using the two methods always agree well. If the coupling coefficients between any two receivers shown in Fig. 1 are negligible ($k_{ij} \rightarrow 0$, $i \neq j$ for $i, j=1, 2, \dots, N$), the ratio of the currents on the i^{th} receiver and the transmitter is expressed in an analytic form, as in [18]:

$$\frac{I_i}{I_0} = \frac{j\omega k_i \sqrt{L_i L_0}}{R_i + R_{Li}}, \quad (8)$$

and (7) can be simplified to:

$$\eta_i(\beta_1, \beta_2, \dots, \beta_N) = \frac{\frac{F_i^2 \beta_i}{(1+\beta_i)^2}}{1 + \sum_{i=1}^N \frac{F_i^2}{(1+\beta_i)}} \quad (9)$$

where F_i and β_i are defined as the *figure of merit* and the *normalized load resistance* defined by:

$$F_i = k_i \sqrt{Q_i Q_0} = k_i \omega_0 \sqrt{\frac{L_i L_0}{R_i R_0}} \quad (10)$$

and

$$\beta_i = \frac{R_{Li}}{R_i}, \quad (11)$$

where k_i is the coupling coefficient between the transmitter and i^{th} receiver [17], and Q_i is the quality factor of the i^{th} receiver.

The figure of merit (10) is entirely determined by the specification of the Tx and Rx loops and the arrangement between them and is not dependent on the load R_{Li} . The *system efficiency* (or *total efficiency*) is defined and given by:

$$\eta_t(\beta_1, \beta_2, \dots, \beta_N) = \frac{\sum_{i=1}^N P_{Li}}{P_{in}} = \sum_{i=1}^N \eta_i = \frac{\sum_{i=1}^N \frac{F_i^2 \beta_i}{(1+\beta_i)^2}}{1 + \sum_{i=1}^N \frac{F_i^2}{(1+\beta_i)}} \quad (12)$$

as a function of N normalized loads.

To derive β_i ($i=1, 2, \dots, N$), which maximize η_t in (12), we require:

$$\frac{\partial \eta_t}{\partial \beta_i} = 0 \text{ for } i = 1, 2, \dots, N. \quad (13)$$

The N partial differential equations must be solved simultaneously. The normalized load resistance β_i for $i=1, 2, \dots, N$ satisfying (13) turned out to be identical as a constant β_{opt} for all receivers [11], although the figures of merit (F_i s) given by (10) are different. They are:

$$\beta_1 = \beta_2 = \dots = \beta_N = \sqrt{1 + \sum_{i=1}^N F_i^2} = \beta_{opt}. \quad (14)$$

It is convenient if we define the *overall figure of merit* of a SIMO system (F) as:

$$F = \sqrt{\sum_{i=1}^N F_i^2}. \quad (15)$$

The normalized optimum load β_{opt} in (14) can then be simply expressed as:

$$\beta_{opt} = \sqrt{1 + F^2}. \quad (16)$$

With (16), the maximum of η_t in (12) can be expressed as:

$$\eta_t(\beta_{opt}) = \sum_{i=1}^N \eta_i(\beta_{opt})$$

$$= \frac{\sum_{i=1}^N F_i^2}{\left(1 + \sqrt{1 + F^2}\right)^2} = \frac{F^2}{\left(1 + \sqrt{1 + F^2}\right)^2} \quad (17)$$

after some algebraic arrangements. Notice that (16) and (17) have exactly the same forms as those for SISO systems [16]. Note that as F (15) becomes very large, the efficiency in (17) goes to 1. As F becomes very small, the efficiency goes to zero.

3. Numerical Examples with One Transmitter and Two Receivers ($N=2$)

As an example, assume that we have one Tx and two Rx loops, where the figures of merit between the Tx and Rx loops are $F_1=16.2$ and $F_2=10.7$. The efficiency of individual Rx η_i and the total system efficiency η_t can be controlled by the (normalized) load β_i . From Fig. 2, we can analyze how selectively power can be distributed to each Rx in the following scenarios.

In the first scenario, let us suppose we want to deliver the most power to Rx1 instead of Rx2. Intuitively, one can achieve this by opening the load of Rx2 ($\beta_2 \rightarrow \infty$) to suppress any power flow into Rx2 and re-direct that power to Rx1. Simultaneously,

the load value of Rx1 should be optimized to receive the maximum power. This conjecture is consistent with the result in Fig. 2. Explicitly, when β_1 is about 16.2 and $\beta_2 \rightarrow \infty$, η_1 is maximized to 88.4% and η_2 decreases to zero in Fig. 2(a) and (b).

The opposite is true in the second scenario in which we want to deliver the most power to Rx2 instead of Rx1. Fig. 2 shows that when $\beta_1 \rightarrow \infty$ (Rx1 is open) and β_2 is about 10.7, η_1 and η_2 reach zero and 82.9%, respectively. Obviously, the maximum η_1 (88.4%) is greater than the maximum η_2 (82.9%) because Rx1 is inherently more strongly coupled to Tx than Rx2; F_1 (=16.2) is greater than F_2 (=10.7).

Next, one may choose to maximize the total system efficiency η_t . The maximum total efficiency in Fig. 2(c) is about 90.2% when $\beta_1 = \beta_2 = \beta_{opt} = \sqrt{1 + F^2} = \sqrt{1 + 16.2^2 + 10.7^2} = 19.4$.

Fig. 2. Efficiencies as a function of the normalized load resistances β_1 and β_2 in the SIMO system ($N=2$, $F_1=16.2$, and $F_2=10.7$). (a) Efficiency for the 1st receiver (η_1), (b) efficiency for the 2nd receiver (η_2), and (c) total efficiency of the SIMO system (η_t).

When the total efficiency is maximized, the power is distributed to Rx1 and Rx2, with efficiency of $\eta_1=63.1\%$ and $\eta_2=27.1\%$.

Another important observation from Fig. 2(c) is that over a wide region of β_1 and β_2 , the total efficiency η_t is nearly invariant from the maximum of 90.2%. This implies the power can be distributed among multiple receivers in almost any ratio users desire, with minimum loss in total efficiency.

III. CONTROL OF POWER DISTRIBUTION RATIO

The choice of power delivery distribution is not limited to the three scenarios mentioned above in Section II-C. The continuous distribution of efficiencies in Fig. 2 suggests that users are allowed an infinite number of choices of power distribution to each Rx, with total efficiency nearly unchanged. In this section, we propose a simple method to determine the load resistances of receivers to control the power distribution ratio. We also demonstrate the method using numerical examples.

1. Load Resistance for Desired Power Distribution

To demonstrate the method, we first define the power distribution ratio ($\alpha_1, \alpha_2, \dots, \alpha_N$) for the receivers as follows:

$$\alpha_i = \frac{\eta_i}{\eta_t} = \frac{\frac{F_i^2 \beta_i}{(1 + \beta_i)^2}}{\sum_{i=1}^N \frac{F_i^2 \beta_i}{(1 + \beta_i)^2}} \text{ for } i = 1, 2, \dots, N. \quad (18)$$

Clearly, $\sum_{i=1}^N \alpha_i = 1$. When F_i s (for $i=1, 2, \dots, N$) are all known, α_i is determined by the choices of β_i s (for $i=1, 2, \dots, N$). In particular, when $\beta_i = \beta_{opt}$ (for $i=1, 2, \dots, N$) (14), α_i in (18) becomes:

$$\alpha_{i,opt} = \frac{\eta_i(\beta_{opt})}{\eta_t(\beta_{opt})} = \frac{\frac{F_i^2 \beta_{opt}}{(1 + \beta_{opt})^2}}{\sum_{i=1}^N \frac{F_i^2 \beta_{opt}}{(1 + \beta_{opt})^2}} = \frac{F_i^2}{\sum_{i=1}^N F_i^2} = \frac{F_i^2}{F^2}, \quad (19)$$

where $\alpha_{i,opt}$'s (for $i=1, 2, \dots, N$) are the optimum power distribution ratio to maximize the total efficiency (12). If the desired power distribution ratio (α_i 's for $i=1, 2, \dots, N$) is different from the optimum power distribution ratio ($\alpha_{i,opt}$'s for $i=1, 2, \dots, N$), the total efficiency may become somewhat lower than the maximum depending on the degree of the difference of the optimum (12).

In case a desired power distribution ratio (α_i 's) is specified first in (18), the load values, β_i s, of the receivers can be obtained numerically. However, the exact analytic solution in a simple form has not been found yet.

Fig. 3. Normalized load $(R_{Li}/R_i)/\sqrt{1+F^2}$ ($=\beta_i/\beta_{opt}$) as a function of desired α_i and F_i^2/F^2 ($=\alpha_{i,opt}$) ($0.05 \leq \alpha_i$ and F_i^2/F^2 ($=\alpha_{i,opt}$) ≤ 0.95).

Instead, we propose a simple, approximate solution to control the power distribution ratio. We first note that the total efficiency is insensitive to the choice of load resistances from Fig. 2(c) unless they deviate significantly from their optimum (16). Based on this observation, the ratio of (18) and (19) can be approximated as:

$$\frac{\alpha_i}{\alpha_{i,opt}} \approx \frac{\frac{F_i^2 \beta_i}{(1+\beta_i)^2}}{\frac{F_i^2 \beta_{opt}}{(1+\beta_{opt})^2}} = \frac{\beta_i}{\beta_{opt}}. \quad (20)$$

We further assume $1+\beta \approx \beta$ (or $\beta \gg 1$), which is indeed the case for most practical WPT problems. This leads to the conclusion that to achieve the desired α_i , β_i is:

$$\beta_i = \frac{R_{Li}}{R_i} = \beta_{opt} \frac{\alpha_{i,opt}}{\alpha_i} = \sqrt{1+F^2} \frac{F_i^2/F^2}{\alpha_i} \quad (21)$$

for i from 1 to N . The receiver load solution (21) can be used as a formula determined by only F (15), F_i (10), and the desired α_i . In Sections III-B and III-C, we will show that the accuracy of (21) is high enough for most practical problems unless the desired power distribution ratio ($\alpha_1, \alpha_2, \dots, \alpha_N$) deviates too much from its optimum ($F_1^2/F^2, F_2^2/F^2, \dots, F_N^2/F^2$) (19).

In Fig. 3, based on (21), we plot $(R_{Li}/R_i)/\sqrt{1+F^2}$ (or β_i/β_{opt}) as a function of the desired α_i and F_i^2/F^2 ($=\alpha_{i,opt}$). With this universal curve, we can determine the normalized load resistance β_i (or R_{Li}/R_i) to realize the desired α_i (for $i=1, 2, \dots, N$) once the figures of merit (F s) for any specific SIMO WPT system are known.

For example, when $F_1=16.2$ and $F_2=F_3=11.4$, $F=22.9$ using (15), $\alpha_{1,opt}=F_1^2/F^2=0.5$, $\alpha_{2,opt}=\alpha_{3,opt}=0.25$ from (19), $\beta_{opt}=22.9$ from (14) or (16), and $\eta_t(\beta_{opt})=91.6\%$ from (17). If the desired α_1, α_2 , and α_3 are 0.7, 0.2, and 0.1, we can obtain $\beta_1=$

16.4, $\beta_2=28.6$, and $\beta_3=57.3$ using (21) and $\eta_t=91\%$ using (12).

2. Numerical Validation by Circuit Simulations ($N=2$)

The proposed power distribution method was validated using circuit simulations. We physically have one Tx loop and two Rx loops, and the resonant frequencies of all of them are set to 6.78 MHz. The circuit element values (R , L , and C) are 0.034 Ω , 0.533 μH , and 1.034 nF for the Tx loop and 0.017 Ω , 0.223 μH , and 2.472 nF for the Rx loop. The quality factors of the Tx and Rx loops are 668 and 559, respectively.

The coupling coefficients between the Tx and each Rx (k_1 and k_2) are assumed to be identical at 0.0265; therefore, $F_1=F_2=16.2$ using (10). Fig. 4(a) shows the realized (or achieved) power distribution ratios and the total efficiencies as a function of the desired α_1 . Note that $\alpha_2=1-\alpha_1$.

The optimum power distribution ratio is $\alpha_{1,opt}=\alpha_{2,opt}=0.5$ ($=16.2^2/(16.2^2+16.2^2)$) from (19). When $\beta_1=\beta_2=\beta_{opt}=22.9$ (16), the total efficiency is maximized to $\eta_t(\beta_{opt})$ of 91.64%. One can find that the power is distributed to Rx1 with an accurate ratio as we target. Fig. 4(a) also demonstrates that the closed-form formula (21) is more accurate than the formula presented in

Fig. 4. Realized α_1 and η_t as a function of desired α_1 ($f_0=6.78$ MHz and $N=2$). (a) $\alpha_{1,opt}=F_1^2/F^2=0.5=\alpha_{2,opt}$ ($F_1=F_2=16.2$) and (b) $\alpha_{1,opt}=F_1^2/F^2=0.7$ and $\alpha_{2,opt}=0.3$ ($F_1=16.2$ and $F_2=10.7$).

[14]. Furthermore, we can see that even when the mutual coupling between two receivers is considered with $F_{21}/F_1=0.5$, the results do not show much difference.

As an asymmetric example, the coupling coefficients between the Tx and each Rx (k_1 and k_2) are assumed to be 0.0265 and 0.0175. Therefore, F_1 and F_2 are 16.2 and 10.7. The realized power distribution ratios and the total efficiencies are shown in Fig. 4(b) as a function of the desired α_1 . The optimum power distribution ratio at Rx1 ($\alpha_{1,opt}$) is 0.7 using (19). When $\beta_1=\beta_2=\beta_{opt}=19.4$, the total efficiency is maximized to 90.21%. Unlike the first example, the realized power distribution ratio slightly deviates from the target ratio, especially when the target power distribution ratio is low. For example, when the target ratios α_1 and α_2 are 0.3 and 0.7, the realized ratios are about 0.34 and 0.66.

In Fig. 5, the realized power distribution ratios and total efficiencies are shown as a function of desired α_1 for various maximum total efficiencies of 0.99, 0.9, 0.8, and 0.7 (17) obtained when the overall figures (F) of merit are 199, 19, 8.9, and 5.6, respectively. It is assumed that $N=2$ and $F_1^2/F^2=\alpha_{1,opt}=0.7$ for

Fig. 5. Realized α_1 and η_t as a function of desired α_1 for different maximum total efficiencies $\eta_t(\beta_{opt})$ s (17) ($N=2$ and $\alpha_{1,opt}=F_1^2/F^2=0.7$ assumed).

Side view

Top view

Fig. 7. A configuration of SIMO WPT system with one transmitter and three receivers for validation by full wave EM simulation (unit: cm).

Fig. 6. Realized α_1 and η_t as a function of F for different desired α_1 s ($N=2$ and $\alpha_{1,opt}=F_1^2/F^2=0.7$ assumed).

all cases. Although the accuracy of the realized power distribution ratio slightly decreases as the desired α_1 deviates from its optimum, the proposed simple solution (21) is good enough for all practical applications. If a higher accuracy is required, the numerical method can be used to obtain the exact solution.

Fig. 6 shows the realized power distribution ratios and total efficiencies as a function of F (15) for different desired α_1 s of 0.3 and 0.5. The optimum power distribution ratio $\alpha_{1,opt}$ is fixed at 0.7. The accuracy of power distribution ratio increases as F increases. This figure also demonstrates that the proposed method is good enough unless F in (15) is extremely small. Notice also that the realized total efficiency η_t (12) is only slightly lower than its maximum of $\eta_t(\beta_{opt})$ (17) obtained when the desired α_1 is identical to $\alpha_{1,opt}$ of 0.7 (21).

3. Validation by Full Wave Electromagnetic Simulation with Three Receivers ($N=3$)

Fig. 7 shows a configuration of the SIMO WPT system with one transmitter and three receivers for the validation of the proposed solution (21) using full wave EM simulation. The resonant frequencies (f_0 's) of Tx and Rx loops are 6.78 MHz. The

Table 1. Element values of Tx and Rx loops ($f_0 = 6.78$ MHz)

	Tx loop		Rx loop	
	Theory	Simul.	Theory	Simul.
r (cm)	10		5	
r_{ring} (cm)	0.2		0.2	
R (Ω)	0.034	0.035	0.017	0.017
L (μ H)	0.533	0.502	0.223	0.207
C (nF)	1.034	1.097	2.472	2.657
Q-factor	668	614	559	506

radii of Tx and Rx loops are 10 cm and 5 cm, respectively. The radii of the loop ring are 0.2 cm. Theoretical and EM-simulated circuit element values of Tx and Rx loops are summarized in Table 1. The quality factors of the Tx and Rx loops based on EM simulations are 614 and 506 at 6.78 MHz, respectively.

The center positions of one Tx and three Rx loops in Fig. 7 are (0 cm, 0 cm, 0 cm), (9 cm, 0 cm, 10 cm), (-5.5 cm, -9.4 cm, 10 cm), and (-5.5 cm, 9.4 cm, 10 cm), respectively. The centers of the Rx loops are 9 cm, 10.9 cm, and 10.9 cm away from the z-axis. The coupling coefficients between two loops can be theoretically evaluated using [17] and can also be extracted using the S-parameter obtained from EM simulations [19]. Figures of merit can be obtained using (10). Coupling coefficients and figures of merit between two loops are summarized in Table 2. The EM-simulated k s agree well with the theoretical ones. F_1 , F_2 , and F_3 are 14.8, 10.4, and 10.4, respectively, using (10). For this example, $\alpha_{1,opt} = F_1^2/F^2 = 0.5$ and $\alpha_{2,opt} = \alpha_{3,opt} = 0.25$ from (19).

Fig. 8(a) and (b) show the necessary load resistances (R_{Li} s) using (21) based on Tables 1 and 2 to realize a desired power distribution ratio (α_i s) based on the assumptions of $\alpha_2 = \alpha_3$ and $\alpha_2 = 2\alpha_3$, respectively. Note that for each case, $\alpha_1 + \alpha_2 + \alpha_3 = 1$. As we can see in (21), R_{Li} decreases as the desired α_i increases.

When the desired α_1 , α_2 , and α_3 are 0.5, 0.25, and 0.25 in Fig. 8(a), the load resistances (R_{L1} , R_{L2} , and R_{L3}) are the optimum values ($R_{L,opt}$ s) (16), which are about 0.39 Ω .

Table 2. Coupling coefficients and figure of merits between two loops

	k_i or k_{ij}		F_i or F_{ij} using (10)	
	Theory [17]	Simul.	Theory	Simul.
Tx-Rx1 (k_1 , F_1)	0.0265		16.2	14.8
Tx-Rx2 (k_2 , F_2)	0.0186		11.4	10.4
Tx-Rx3 (k_3 , F_3)	0.0186		11.4	10.4
Rx1-Rx2 (k_{12} , F_{12})	-0.0071		-3.95	-3.96
Rx1-Rx3 (k_{13} , F_{13})	-0.0071		-3.95	-3.96
Rx2-Rx3 (k_{23} , F_{23})	-0.0053		-2.95	-2.95

Fig. 8. Necessary load resistances ($R_{Li} = R\beta_i$ for $i = 1, 2, 3$) using (21) based on Tables 1 and 2 as a function of desired α_1 ($f_0 = 6.78$ MHz, $N = 3$, $r_0 = 10$ cm, $r_1 = r_2 = r_3 = 5$ cm, $r_{ring} = 0.2$ cm, $\alpha_{1,opt} = 0.5$, and $\alpha_{2,opt} = \alpha_{3,opt} = 0.25$). (a) $\alpha_2 = \alpha_3$ assumed, (b) $\alpha_2 = 2\alpha_3$ assumed.

Fig. 9 shows the realized power distribution ratios and the total system efficiencies of the same SIMO system used in Fig. 8 using theory based on (12) and (18), EM-simulation with R_{Li} , and EM simulation with and additional feeding loop (50 Ω) [20].

In Fig. 9(a), they have been plotted as a function of the desired α_1 , with $\alpha_2 = \alpha_3$. For this case, the maximum efficiency is 91.6%, and realized power distribution ratios are shown to be almost the same as the desired ones. Again, we can see that the realized α s agree well with the desired ones for all cases.

Similarly, the realized α s and total efficiency are plotted as a function of the desired α_1 , with $\alpha_2 = 2\alpha_3$ in Fig. 9(b). We can also see that the α s are well realized, as we desire. For example, when the desired α_1 , α_2 , and α_3 are 0.7, 0.2, and 0.1, respectively, they are realized as 0.69, 0.2, and 0.11. The results of EM simulations without and with a feeding loop [20] are also shown to be in good agreement with the results of circuit simulations.

(a)

(b)

Fig. 9. Realized α_i and η_t as a function of desired α_i ($f_0=6.78$ MHz, $N=3$, $r_0=10$ cm, $r_1=r_2=r_3=5$ cm, $r_{ring}=0.2$ cm, $\alpha_{1,opt}=0.5$, and $\alpha_{2,opt}=\alpha_{3,opt}=0.25$). (a) $\alpha_2=\alpha_3$ assumed, (b) $\alpha_2=2\alpha_3$ assumed.

Finally in Fig. 10, we show the EM-simulated $|H_z|$ distributions for the cases of desired $\alpha_1=0.5$ and $\alpha_2=\alpha_3=0.25$ and desired $\alpha_1=0.7$, $\alpha_2=0.2$, and $\alpha_3=0.1$. For these field distributions, a power source of 1 W was used in HFSS EM simulations. The $|H_z|$ field distributions in Fig. 10(a) and (b) well reflect the desired power distributions or efficiencies. The total efficiencies and power distribution ratios based on theory and EM simulations are in good agreement.

In summary, the realized α_i s using the simple closed-form solution (21) show good agreement with the desired ones for a wide range of applications.

IV. CONCLUSION

In this paper, we analyzed the efficiencies and power distribution ratio among receivers of the SIMO system consisting of multiple receivers. The optimum load for maximum total efficiency was derived using the equivalent circuit. In addition, we obtained the simple formula of the load condition for the desired power distribution ratio. We employed various nu-

(a)

(b)

Fig. 10. EM-simulated $|H_z|$ distribution ($f_0=6.78$ MHz, $N=3$, $r_0=10$ cm, $r_1=r_2=r_3=5$ cm, $r_{ring}=0.2$ cm, $\alpha_{1,opt}=0.5$, $\alpha_{2,opt}=\alpha_{3,opt}=0.25$, $\beta_{opt}=22.9$, and $\eta_t(\beta_{opt})=0.916$). (a) Desired $\alpha_1=0.5$, $\alpha_2=\alpha_3=0.25$, and $\eta_t=0.916$, (b) desired $\alpha_1=0.7$, $\alpha_2=0.2$, $\alpha_3=0.1$, and $\eta_t=0.91$.

merical examples and validated the derived formula by comparing the target distribution ratio with the realized one from circuit and EM simulations. The proposed simple formula can also be applied to arbitrary N receivers. There have also been some analytical or closed-form solutions, but their accuracy is far lower than the proposed solution. The proposed formula is expected to be implemented in future SIMO industrial applications due to its simple but relatively accurate property.

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