Antenna Characterization for Wireless Power Transfer Using Near-Field Coupling of Multi-antenna

Qiang Chen, Mingda Wu
Tohoku University
Sendai, Japan

Qiaowei Yuan
Sendai National College of Technology
Sendai, Japan

Abstract— **Numerical analysis of the near-field power transfer using multi-antennas is performed based on the scattering parameters for an equivalent circuit model of multi-port networks. The transfer power efficiency is derived by using the multi-port scattering parameters. Since the multi-port scattering parameters are easily measured by a vector network analyzer and calculated by a full-wave numerical analysis, it is convenient to investigate the relation between the power transfer efficiency and the geometry of the power transfer system such as relative positions between transmitting antennas and receiving antennas, antenna geometry, impedance matching of the antennas, and ohmic loss in antennas, which are important parameters to develop a near-field power transfer system with high power transfer efficiency.**

Keywords—Wireless Power Transfer, Impedance Matching, Power Transfer Efficiency, Multi-Antennas, Near-Field

I. INTRODUCTION

Wireless power transfer (WPT) attracts great attention because of its potential application to charge laptop computers, mobile phones, household robots, potable music players and other portable electronic devices without cords. It was experimentally demonstrated that very efficient power transmission can be achieved by using the so-called evanescent resonant-coupling method, showing its potential for practical application [1]. It was shown that the evanescent resonant coupling method can transmit energy for a longer distance than the previously used near-field induction method [2].The evanescent resonant-coupling method was shown to be more efficient than the far-field radiation method, wherein the vast majority of the energy was wasted, due to the transmission loss [3]-[5].

The power transfer efficiency (PTE) is one of the most important parameters to evaluate the performance of a WPT system. In order to develop a WPT system with a high PTE, it is required to have an efficient method to calculate the PTE by analyzing electromagnetically the WPT system. If the transmitting antenna and receiving antenna are described as a two-port network circuit, the power transfer between the transmitting antenna and receiving antenna in the WPT system can be indicated by using the scattering parameters of the network circuit and further the PTE can be calculated by using the scattering parameters [6]. Because the scattering parameters of a WPT system can be either measured by a vector network analyzer or calculated by a full-wave numerical analysis, the scattering parameters are a very efficient tool in analyzing and designing the antennas and RF modules for a WPT system.

A fundamental study focused on the PTE of a WPT system composed of dipole and loop antennas as the transmitting and receiving antennas was carried out by the present authors, where a two-port scattering parameters calculated by the method of moments (MoM) were used to analyze the system and it was found the largest PTE was obtained when the near-field coupled antennas of both transmitting and receiving sides were conjugate-matched with the impedance of the transmitting and receiving circuits, respectively [6]. The optimum load for maximum transfer efficiency of a practical WPT system was derived when the WPT system was equivalent to a 2-port lossy network [7] also by the present authors.

This report shows the result of the continued study published in [8], where multi-port scattering parameters are applied to the analysis of multi-antennas in a WPT system. The expression of PTE is defined in term of the multi-port scattering parameters. Some numerical simulations are shown to demonstrate it is easy to evaluate the PTE for various models of the antenna geometries, locations of transmitting and receiving antennas in a multi-user WPT system by using the multi-port scattering parameters.

II. ANALYSIS OF MULTI-PORT NETWORL FOR MULTI-ANTENNA WPT SYSTEM

A generalized 4-port network is shown in Fig. 1, which represent a 4-antenna WPT system with one transmitting antenna and three receiving antennas. 4 ports are named A, B, C and D, respectively. 4×4 scattering parameters of this 4-port network are assumed to be obtained by either measurement using the vector network analyzer or a numerical full-wave EM analysis. The reflection coefficients at every port are labeled in the Fig. 1, and the reference impedance is Z_0 =50 Ω. P_A is the power available from the source, P_B, P_C and P_D is the power delivered to each load. The a_1, a_2, a_3 and a_4 in the Fig. 1 are the incident waves of port A, B, C and D, respectively. Besides, b_1, b_2, b_3 and b_4 are the reflected waves of each load. Therefore, if these 4 ports are impedance matched simultaneously, four equations can be obtained:

$$\Gamma_A = \Gamma_1^*,\ \Gamma_B = \Gamma_2^*,\ \Gamma_C = \Gamma_3^*,\ \Gamma_D = \Gamma_4^* \quad (1)$$

Fig. 2 is the signal flow graph of this 4-port network. From the Mason's gain formula and the definition of reflection coefficient, follow equations can be obtained

$$\Gamma_1 = \frac{b_1}{a_1} = f_1(\Gamma_A, \Gamma_B, \Gamma_C, \Gamma_D) = \Gamma_A^*$$

$$\Gamma_2 = \frac{b_2}{a_2} = f_2(\Gamma_A, \Gamma_B, \Gamma_C, \Gamma_D) = \Gamma_B^* \quad (2)$$

$$\Gamma_3 = \frac{b_3}{a_3} = f_3(\Gamma_A, \Gamma_B, \Gamma_C, \Gamma_D) = \Gamma_C^*$$

$$\Gamma_4 = \frac{b_4}{a_4} = f_4(\Gamma_A, \Gamma_B, \Gamma_C, \Gamma_D) = \Gamma_D^*$$

In equation (2), Γ_1, Γ_2, Γ_3 and Γ_4 are expressed by functions of Γ_A, Γ_B, Γ_C and Γ_D. Solving equation (2), Γ_A, Γ_B, Γ_C and Γ_D can be figured out. From the relationship between the reflection coefficient and the load impedance below,

$$Z_L = \frac{1+\Gamma_L}{1-\Gamma_L} \quad (3)$$

the optimal load impedance Z_{oA}, Z_{oB}, Z_{oC} and Z_{oD} that make the 4-port network impedance matched can be figured out.

Power flow at each port is expressed as:

$$P_A = (1-|\Gamma_A|^2)\frac{|a_s|^2}{|1-\Gamma_A\Gamma_A^*|^2} = \frac{|a_s|^2}{1-|\Gamma_A|^2}$$

$$P_B = |b_2|^2 - |a_2|^2 = (1-|\Gamma_B|^2)|b_2|^2 \quad (4)$$

$$P_C = |b_3|^2 - |a_3|^2 = (1-|\Gamma_C|^2)|b_3|^2$$

$$P_D = |b_4|^2 - |a_4|^2 = (1-|\Gamma_D|^2)|b_4|^2$$

The individual PTE to each load can be expressed as:

$$\eta_B = \frac{P_B}{P_A} = \frac{(1-|\Gamma_B|^2)|b_2|^2}{\frac{|a_s|^2}{1-|\Gamma_A|^2}} = (1-|\Gamma_A|^2)(1-|\Gamma_B|^2)\left|\frac{b_2}{a_s}\right|^2$$

$$\eta_C = \frac{P_C}{P_A} = \frac{(1-|\Gamma_C|^2)|b_3|^2}{\frac{|a_s|^2}{1-|\Gamma_A|^2}} = (1-|\Gamma_A|^2)(1-|\Gamma_C|^2)\left|\frac{b_3}{a_s}\right|^2 \quad (5)$$

$$\eta_D = \frac{P_D}{P_A} = \frac{(1-|\Gamma_D|^2)|b_4|^2}{\frac{|a_s|^2}{1-|\Gamma_A|^2}} = (1-|\Gamma_A|^2)(1-|\Gamma_D|^2)\left|\frac{b_4}{a_s}\right|^2$$

$$\eta_t = \eta_B + \eta_C + \eta_D$$

In the equation (5), η_B, η_C, η_D are the individual PTE to the load Z_B, Z_C, Z_D, respectively. η_t is the total PTE of this 4-port system. Using Mason's gain formula again, the ratios at the right part of the equation (5) can be expressed by functions of Γ_A, Γ_B, Γ_C and Γ_D:

$$\frac{b_2}{a_s} = f_5(\Gamma_A, \Gamma_B, \Gamma_C, \Gamma_D)$$

$$\frac{b_3}{a_s} = f_6(\Gamma_A, \Gamma_B, \Gamma_C, \Gamma_D) \quad (6)$$

$$\frac{b_4}{a_s} = f_7(\Gamma_A, \Gamma_B, \Gamma_C, \Gamma_D)$$

where, Γ_A, Γ_B, Γ_C, Γ_D can be calculated from equation (2). That is the whole process in calculating the PTE and optimal loads of an arbitrary 4-port network when knowing its scattering parameters.

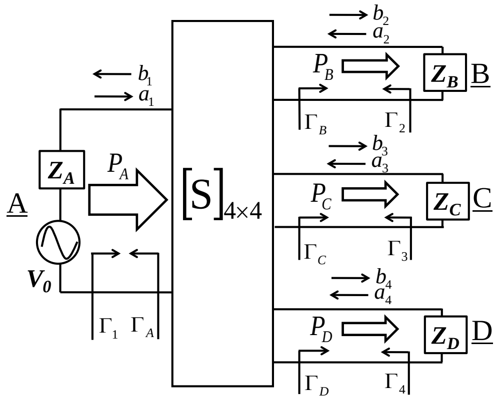

Fig. 1. 4-port network with 1 Tx port and 3 Rx ports.

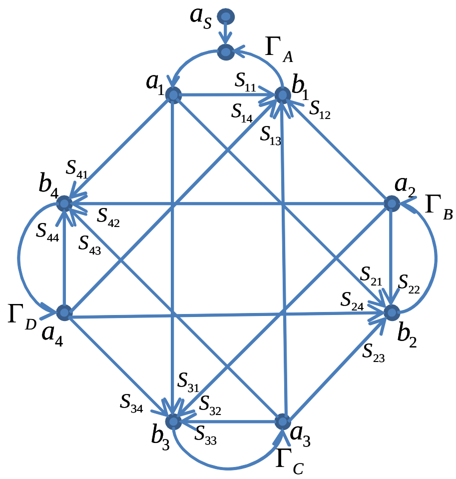

Fig. 2. Signal flow graph of 4-port network.

III. NUMERICAL RESULTS FOR PTE OF MULTI-ANTENNAS

A WPT system model shown in Fig. 3 with 1 dipole antenna as transmitting antenna and 3 dipole antennas as receiving antennas is assumed for numerical simulation. 4 dipole antennas are placed parallel with each other along the *z*-axis. 4 dipole antennas have same antenna length *l*, same antenna radius *a* and antenna material with conductivity *σ*. Transmitting antenna A is placed in the center, three receiving antennas B, C and D are placed around the antenna A with distance d_B, d_C and d_D.

Fig. 4 shows the relationship between the PTE and antenna conductivity. It is found that the total PTE η_t of the analysis model increases with increase of conductivity *σ*. This result demonstrates the importance of including conducting loss into the analysis model because in the wireless power transfer using near-field coupling, the transmitting and receiving antennas should be electrically small to reduce radiation loss and the conducing loss becomes the major loss of the WPT system when the antennas are conjugate-matched with the port impedance [6].

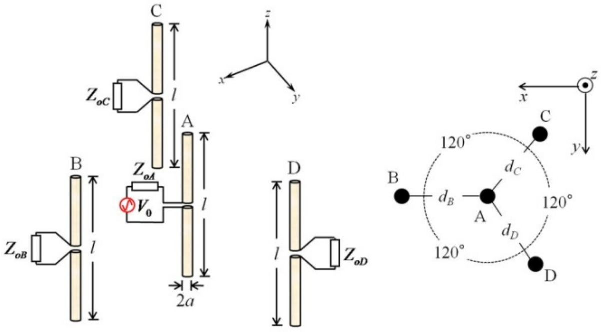

Fig. 3. Analysis model with 4 dipole antennas.

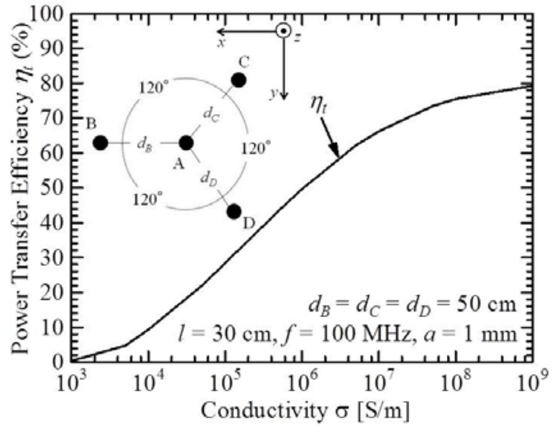

Fig. 4. PTE versus antenna conductivity.

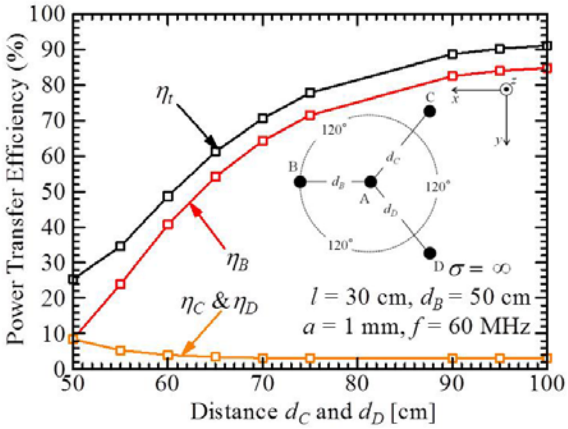

Fig. 5. PTE versus relative antenna positions in 60 MHz.

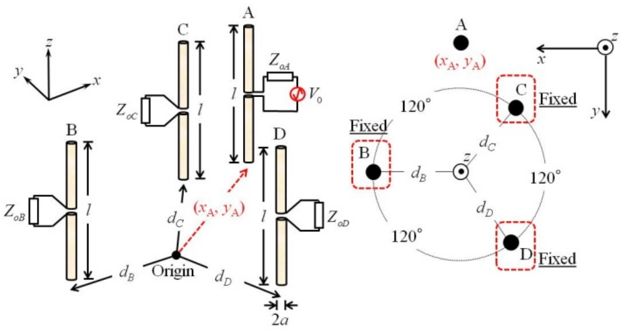

Fig. 6. Analysis model.

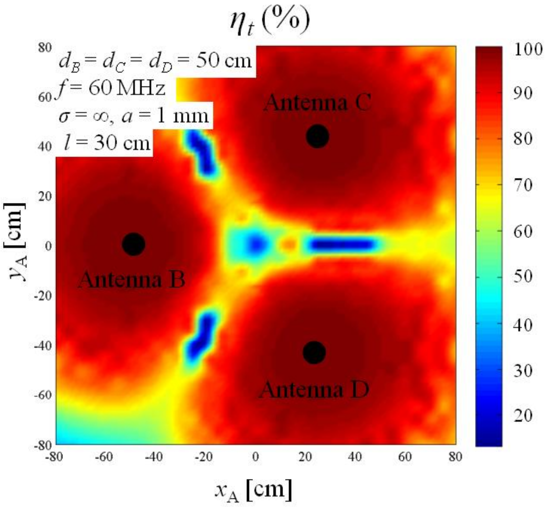

Fig. 7. The total PTE η_t when moving Tx antenna A

Consider the case where the distance d_C and d_D in the model shown in Fig. 3 are changed from 50 cm to 100 cm to investigate the relationship between PTE and relative antenna positions. The simulation results are shown in Fig. 5. It is found that the individual PTE η_B gets larger with the increasing of d_C and d_D, however, the individual η_C and η_D get decreased with increase of d_C and d_D. That means in a multi-antennas WPT system, the power transfer to each receiving antennas is extremely unbalanced and majority of the transferred power is absorbed by the nearest receiving antenna.

In order to further investigate the relationship between PTE and antenna relative positions, another simulation was conducted. The simulation model is shown in Fig. 6. In this case, the positions of 3 receiving antennas B, C and D are fixed. The position of only transmitting antenna (x_A, y_A) is changed.

It is found that there exist several weak areas in Fig. 7, which means that the total PTE η_t is low when the transmitting antenna A is placed in these areas. It is observed that the transmitting antenna in these areas has an equal distance to several receiving antennas, demonstrating a symmetric placement tends to have a weak mutual coupling between transmitting and receiving antennas and a high total PTE is obtained when the transmitting antenna is located near to one of the receiving antennas. Therefore, it is necessary to determine a good antenna arrangement in designing multi-antennas WPT system to obtain high power transfer efficiency

IV. SUMMERY

Multi-port scattering parameters were applied to the analysis of antennas in a WPT system corresponding to multi-antennas situations. The expression of PTE was defined in term of the multi-port scattering parameters. Some numerical simulations were shown to demonstrate it is easy to evaluate the PTE for various models of the antenna geometries, antenna materials and locations of antennas by using the multi-port scattering parameters.

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