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令和２年度学内公募研究（実用化型）
〔研究紹介〕

MIMO システムにおける最大電力伝送効率計算手法

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Approach to Calculate Maximum Power Transfer Efficiency of MIMO system

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Abstract

In this report, firstly, the elegant and universal approach to obtain the maximum transfer efficiency (MTE) of multipole input multipole output (MIMO) system is briefly introduced, then the useful software which combines the simulation results obtained either from electromagnetic simulation software or from the measurement and the MTE will be demonstrated. Finally, the beamforming of array antenna based on the MTE of MIMO system will be given to show one of potential applications of E-MIMO (MTE of MIMO).

1 Introduction

In [1], the efficiency of MIMO-WPT system was expressed by using multi-port impedance Z matrix or scattering S matrix. Consequently, a very concise and universal approach to calculate the power transfer efficiency and also its maximum one for arbitrary MIMO system was presented successfully. Here MIMO-WPT means Multiple Input Multiple Output Wireless Power Transfer. MIMO system not only includes MIMO WPT system but also MIMO communication system. The effectiveness and flexibility of the proposed approach were demonstrated by applying to calculate the MTEs of various MIMO-WPT systems including four SISOs, one 2×2 MIMO, one 2×3 MIMO and two 3×1 MISO WPT systems.

In this research report, the elegant and universal approach (E-MIMO) will be introduced in section 2. Then in section 3, an application programmed by C++ for calculating the MTE of MIMO system will be demonstrated. This application combines the simulation results either from electromagnetic simulation software or from the measurement via a network analyze and the MTE. In section 4, finally, E-MIMO will be applied to a 16×1 MISO system and a 16×4 MIMO system to confirm how to control the 16-elements array antenna's beam to desired directions.

１）工学部情報通信工学科
Department of Information and Communication Engineering Introduction

2 E-MIMO

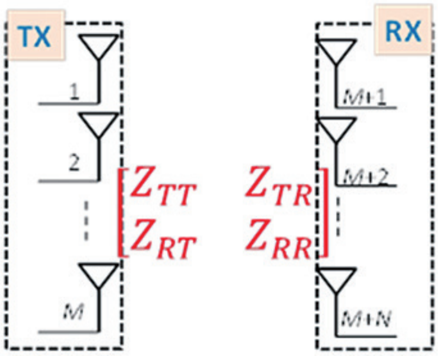


Fig.1 MIMO system with M transmitters and N receivers

To a general MIMO system as shown in Fig.1, the voltages and currents at M transmitting ports and N receiving ptorts have the relationship as expressed by Z matrix or S matrix. For the simplicity, here only Z matrix is expressed, that is

$$V = ZI \tag{1}$$

where, V and I are the $M + N$ voltage vector and current vector for all transmitting and receiving ports, that is

$$V = \begin{bmatrix} V_T \\ V_R \end{bmatrix},\ I = \begin{bmatrix} I_T \\ I_R \end{bmatrix}, \tag{2}$$

Z is the $(M + N) \times (M + N)$ impedance matrix which is

$$Z = \begin{bmatrix} Z_{TT} & Z_{TR} \\ Z_{RT} & Z_{RR} \end{bmatrix} = \begin{bmatrix} R_{TT} + jX_{TT} & R_{TR} + jX_{TR} \\ R_{RT} + jX_{RT} & R_{RR} + jX_{RR} \end{bmatrix}. \tag{3}$$

V_T, V_R are the M transmitting ports' voltage vector and the N receiving ports' voltage vector, respectively. While I_T, I_R are the M transmitting ports' current vector and the N receiving ports' current vector, respectively. Z_{TT}, Z_{TR}, Z_{RT}, Z_{RR} are the $M \times M$ self-impedance matrix among the M transmitters, $M \times N$ mutual-impedance matrix, $N \times M$ mutual-impedance matrix between the receivers and the transmitters, and $N \times N$ self-impedance matrix among the N receivers, respectively.

The power transfer efficiency η is the ratio of the output power P_{out} over the input power P_{in}, that is

$$\eta = \frac{P_{out}}{P_{in}}, \tag{4}$$

where, P_{out} and P_{in} represents the total power consumed at all receiving ports and the total transmitting power at all transmitting ports, respectively. P_{out} and P_{in} can be obtained from the port voltage vector and the port current vector which are

$$P_{in} = \frac{1}{2} Re(I_T^H V_T), \tag{5}$$

$$P_{out} = -\frac{1}{2} Re(I_R^H V_R). \tag{6}$$

In all equations and formulations in this paper, the superscript ^{T} means matrix-transpose, while superscripts * and ^{H} express complex conjugate and matrix complex conjugate-transpose, respectively.

According to equation (4), the transfer efficiency η is a scalar function of current vectors I_T and I_R, and can be obtained if the load impedance and Z impedance matrix are known. The efficiency expressed in equation (4) is the generalized Rayleigh quotient and has the maximum value $\eta_{\max}$. Because $\eta_{\max}$ is equivalent to the maximum eigenvalue of equation (4), the corresponding eigenvector of the maximum eigenvalue is the optimal current vector to be required at each port for achieving the $\eta_{\max}$. If the corresponding eigenvectors of the maximum eigenvalue are denoted by $I_T{}^E$ and $I_R{}^E$, then the optimum source impedance $(Z_s{}^{opt})_i$ of i^{th} transmitter port and the load impedance $(Z_l{}^{opt})_j$ of j^{th} receiver port can be obtained. Simultaneously, the optimized excitations for transmitters can be obtained.

3 E-MIMO Software

Nowadays, to an arbitrary MIMO system shown as in Fig.1, it's available to obtain the S parameters either by using the electromagnetic simulation software such as FEKO, HFSS and so on, or by measuring via a network analyzer. However, the MTE of this MIMO system, the optimal excitation conditions for the transmitters and optimal loads for the receivers cannot be obtained directly by the electromagnetic software or by measurement. Therefore, the software application based on Visual Studio for MTE of MIMO shown in Fig. 2 was developed in my laboratory. The

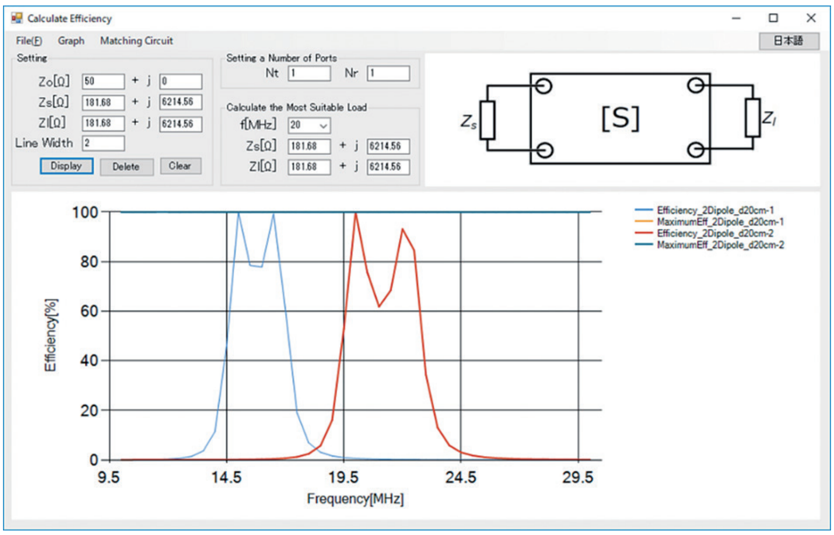


Fig. 2 E-MIMO Software

main functions are the following.

(1) Calculate the MTE of MIMO system
(2) Visualize the MTE versus frequency
(3) Show the optimal the optimal excitation conditions for the transmitters and optimal loads
(4) Matching circuit design
(5) Comparing MTEs between different MIMO systems
(6) The language is switchable.

With the above functions, E-MIMO becomes a very powerful tool for the design of MIMO-WPT systems and also MIMO communication systems.

4 Beamforming with using E-MIMO

Antenna pattern synthesis is a vast subject in the antenna literature. The number of publications is extensive. Several of the classical methods used for linear arrays are both elegant and analytical. For instance, there are the Woodward–Lawson synthesis, Dolph–Chebyshev synthesis, Fourier synthesis, and methods derived from the Taylor line-source synthesis [2-4]. Since 1970, numerical synthesis methods have become increasingly popular. In [5-6], several examples were demonstrated to control the radiation patterns by using E-MIMO. In this section, two examples will be explained. One example is using 16 elements- array antenna to direct the maximum beam to the central direction of the array antenna as shown in Fig.3, the other example is using the same array antenna to radiate power forward mostly to the four desired directions as shown in Fig.5.

Both in Fig.3 and Fig. 5, 16 dipole elements are used as the transmitting array antenna. In Fig. 3, one dipole located as the desired direction is used as the receiver, and while in Fig.5, four dipoles located in four desired directions are used as the receivers, respectively. Meanwhile, the directions of receiving antennas are the desired directions. The elements of the transmitting array antenna consisting of 16 dipoles are set in xy-plane and separated from the neighbor element by 0.65λ either in x-direction or y-direction where λ represents the wavelength. The length of each dipole is 0.5λ, and the length of receiving dipole is 0.1λ. In Fig. 5, four receiving dipole antennas are noted by RX1, RX2, RX3, and RX4, respectively. RX1, RX2, RX3, and RX4 are located at the places of $(0.65\lambda, 0.65\lambda, d)$, $(-0.65\lambda, 0.65\lambda, d)$, $(-0.65\lambda, -0.65\lambda, d)$, $(0.65\lambda, -0.65\lambda, d)$, respectively, which means the distances between all receivers and xy-plane are the same and are separated by d.

The radiation patterns using the optimized excitations when the receivers are located on the plane of $z=10\lambda$ are shown in Fig. 4 and Fig. 6. In Fig. 4 and Fig.6, (a), (b) are the 3D directivity patterns of total field and 2D directivity patterns of total field at the cut plane of $\phi=0.25\pi$, 0.75π, respectively. ϕ is the annular angle in the spherical coordination. From Fig.4 and Fig. 6, it can be found that the maximum beams are directed to the receivers' directions, that means the optimal voltages of the transmitting elements when the receivers are located in the far region of the transmitting array antenna and achieve the maximum power can be applied to array antenna's beamforming. This method can be extended to an arbitrary array structure whatever each element structure is and can take the element mutual coupling affection completely and correctly.

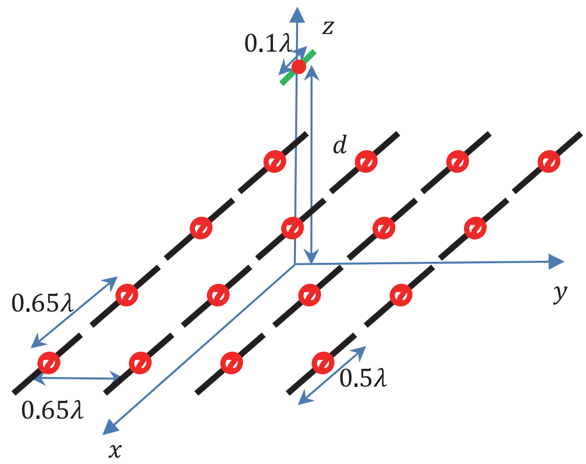
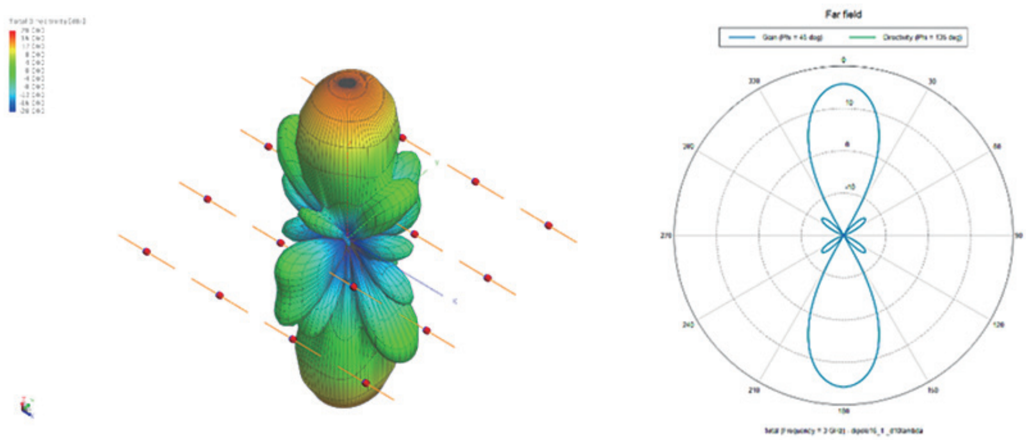


Fig. 3　16 dipole transmitting array antenna and one receiving antenna (16×1 MISO)



(a)　3D pattern of total field　　(b)　2D pattern at the plane of ϕ=0.25π, 0.75π

Fig. 4　Radiation patterns of 16 dipole array antenna

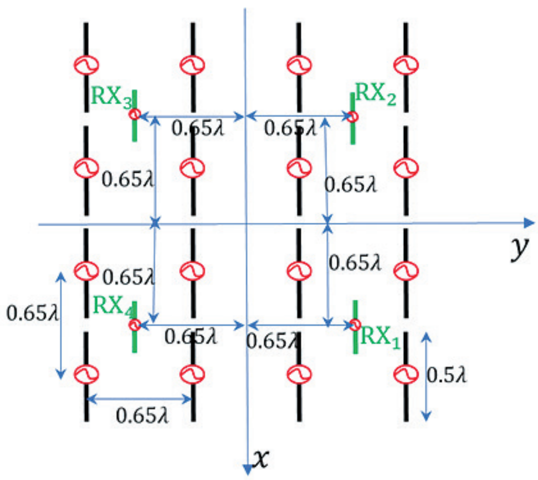
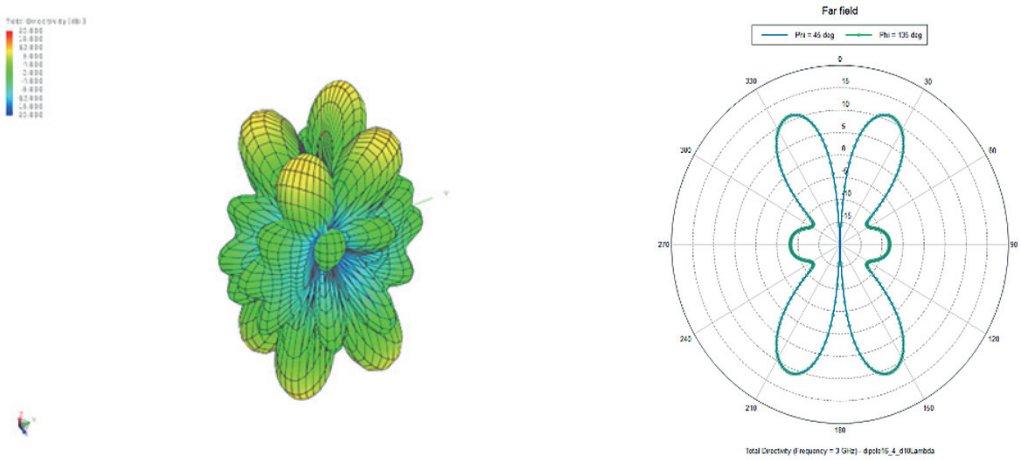


Fig. 3　16 dipole transmitting array antenna and 4 receiving antennas (16×4 MIMO)



(a) 3D pattern of total field (b) 2D pattern at the plane of ϕ=0.25π, 0.75π

Fig. 5 Radiation patterns of 16 dipole array antenna

5 Conclusions

The elegant and universal approach to obtain the maximum transfer efficiency (MTE) of MIMO system and its useful software have been introduced in this report. E-MIMO is an exact method and can be applied to an arbitrary MIMO system scenario, no matter whatever the transmitting/receiving elements' structure and operating frequency are. Moreover, E-MIMO also take into the effect from surrounding scatters if the simulation model includes those surrounding scatters. One of the potential applications of E-MIMO to successful control the array antenna's beams to desired directions has also been shown.

6 Acknowledgement

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