An Analysis of Vector Estimation for Uncertainty Reduction in Evaluating the Specific Absorption Rate of Multiple Transmitting Antenna Devices

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***Abstract*—Advanced communication systems utilizing multiple transmitting antennas working in a same frequency, such as phased array antennas or MIMO (Multi-Input Multi-Output) antennas, recently receive more and more research attentions. One of technical issues, which certainly need to take into account, is the electromagnetic compatibility. In particular, the evaluation of Specific Absorption Rate (SAR), in the aspect of RF safety specification, is an essential requirement. This paper presents a technique of using vector electric field probes to evaluate the maximum SAR of multiple transmitting antenna devices. Thanks to the information of the phase and magnitude of the measured electric field from the vector probes, the electric fields, or SARs, corresponding to different sets of relative phases of antennas can be estimated from measured E-fields when antennas are turned ON/OFF alternatively. Fundamental concepts are presented, and the errors caused by estimation are analyzed.**

***Index Terms*—SAR, estimation, multiple-antenna transmitters, MIMO, vector probes.**

I. INTRODUCTION

Advanced communication systems utilizing multiple transmitting antennas working in a same frequency, such as phased array antennas or MIMO (Multi-Input Multi-Output) antennas, recently receive more and more research attentions. Among technical issues of such systems, the electromagnetic compatibility is a key point, which certainly need to take into account. In particular, the evaluation of Specific Absorption Rate (SAR), in the aspect of RF safety specification, is an essential requirement. The specific absorption rate (SAR), which indicates the amount of power absorbed per unit mass of a biological body when it is exposed to the electromagnetic field, is the basic restriction specified by international RF safety standards. It is proportional to the power of internal electric field, and can be expressed as

$$\text{SAR} = \sigma \left|E\right|^2/\rho \qquad \text{[W/Kg]} \tag{1}$$

where σ and ρ represent the electric conductivity (S/m) and the mass density (kg/m^3) of the medium, respectively.

In SAR measurement for conventional communication systems, the E-field at a measured point only depends on the signal radiated from a single antenna. The SAR, therefore, can be measured by using a scalar electric field probe, of which the probe output is proportional to power of internal electric field. However, for advanced communication systems utilizing multiple antennas, the E-field at each measured point, will depend strongly on the relative phases of the E-field radiated from individual antennas. Several measurement methods, which utilize conventional scalar probes, have been introduced to measure SAR of a device employing multiple transmitting antennas [1]- [3]. However, they remain one critical drawback. The total evaluation time could be very long, particularly when number of antennas is large. Furthermore, these techniques may overestimate actual SAR, or require additional switches, making measurement system more expensive and complex [2].

Recently, some new advanced measurement systems, however, allow measuring E-field with vector probes, which provide information of both amplitude and phase of measured E-field [4]. Thanks to this advantage, the vector probe may be used to efficiently evaluate SAR of multiple antenna transmitting systems. This paper will present a fast and accurate estimation method to evaluate SAR of such systems using measured data acquired from a vector probe. The main idea is to measure SAR for individual activated antennas while turning OFF the other ones. The SAR corresponding to any set of relative phases of the sources can be then estimated based on the measured data.

II. ESTIMATION CONCEPTS

The total field of an antenna array is determined by the vector summation of the fields radiated by individual elements, and depends on the relative phase and amplitude of them. To make it simple, we assume that only relative phases of the sources are considered whereas the amplitudes are kept unchanged at their maximum values. This assumption is quite suitable for evaluating maximum SAR since it normally corresponds to maximum amplitude of feeding sources.

For N-antenna array, let us assume that each individual antenna is excited with a excitation phase $\beta_i (i = 1..N)$. Without loss of generality, we can take $\beta_1 = 0$ (i.e. the first antenna is considered as a reference), the other β_i is considered as the relative excitation phase between the i^{th} antenna and the first antenna. The total electric field radiated by the N antennas is equal to the vector summation of all the individuals. To avoid duplication in E-field notations, the total E-field at an evaluation point can be expressed as

$$E_{tot} = a_1 + a_2 e^{i\beta_2} + \cdots + a_N e^{i\beta_N} \tag{2}$$

where a_i denotes the electric field (complex value) radiated from the i^{th} antenna.

It should be noted that the factors $\{a_1, a_2 \ldots a_N\}$ are independent of $\{\beta_1, \beta_2 \ldots \beta_N\}$. Therefore, if we can calculate these estimation factors, we will be able to estimate E-field, thus the SAR, for arbitrary sets of β_i. In [6], we suggested that these estimation factors can be determined by measuring E-field for several sets of pre-known relative phases, then building up N equations to calculate $\{a_1, a_2 \ldots a_N\}$. Each equation corresponds to one measurement with a particular set of relative phases. This proposal is quite simple but very effective, and it only requires N measurements for the case of N antennas. However, in the reality, fixing the relative phases of the antennas during measurements would require precise devices and special attentions. The change of relative phases during measurements will easily cause large errors in estimations. Thus, in this paper, we propose a simpler way to determine the estimation factors, which will reduce the uncertainty caused by incorrect relative phases of the antennas during measurements.

In order the determine the estimation factors $\{a_1, a_2 \ldots a_N\}$, we only need to alternatively turn each antenna ON (the activated antenna) and turn OFF the other ones, and measure the E-field accordingly to the activated one (the ON antenna). For example, to determine the estimation factor a_1, only antenna 1 will be activated (turning ON), the others will be deactivated (turning OFF). By doing so, the estimation factor a_1 is equal to the measured E-field at the respective measurement. In general, we also need only N measurements to determine all N estimation factors $\{a_1, a_2 \ldots a_N\}$ as

$$\begin{cases} a_1 &= E_{tot} \text{ when the ant. 1 ON - the others OFF} \\ a_2 &= E_{tot} \text{ when the ant. 2 ON - the others OFF} \\ \vdots & \\ a_N &= E_{tot} \text{ when the ant. } N \text{ ON - the others OFF} \end{cases} \tag{3}$$

As soon as the factors $\{a_1, a_2 \ldots a_N\}$ were determined, the E-field for any set of β_{est} can be easily estimated by substituting these factors into Eq. (2).

Let take an example for the case of two antennas. The total electric field at an evaluation point can be expressed as

$$E_{tot} = a_1 + a_2 e^{i\beta}. \tag{4}$$

Now, in order to determine a_1 and a_2, we proposed in [6] the solution, which requires two electric field measurements (using vector electric field probes) for two pre-known values of β, i.e. $\beta^{(1)} = 0$ and $\beta^{(2)} = 180$ deg. Then, the estimation factors a_1 and a_2 can be calculated as

$$\begin{aligned} a_1 &= (E^{(1)} + E^{(2)})/2 \\ a_2 &= (E^{(1)} - E^{(2)})/2 \end{aligned} \tag{5}$$

where $E^{(1)}$ and $E^{(2)}$ are the measured E-field (complex values) corresponding to $\beta^{(1)} = 0$ and $\beta^{(2)} = 180$ deg., respectively.

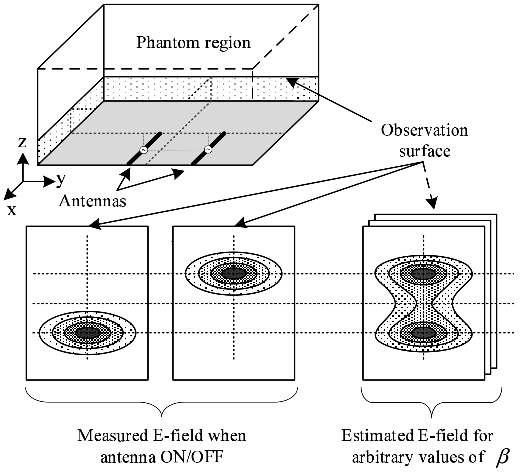


Fig. 1. Two-element co-polarization antenna array configuration

The electric fields (thus the SAR) corresponding to other values of β can be estimated accordingly to the Eq. (4). This solution is quite simple, but as mentioned above, it remains one practical challenge when measuring the electric field. That is, to keep the relative phase between two antennas, β, unchanged during measurements, we need special attention, calibration as well as precise devices. In fact, the relative phase β can be changed several degrees among its averaged value. This change will raise the uncertainty of measured results.

In order to avoid this challenge and thus reduce the uncertainty of measured electric field, the ON/OFF method we propose here would be very useful. Now, to determine the estimation factors a_1 and a_2, we need to turn antennas 1 and 2 ON and OFF alternatively and measure the respective electric fields. The value of a_1 is equal to the measured electric field when the antenna 1 is turned ON and the antenna 2 is OFF. Similarly, the value of a_2 is equal to the measured electric field when the antenna 2 is turned ON and the antenna 1 is OFF. It should be noted that this method is only applicable for the measurement systems utilizing vector electric field probes, which provide the information of both phase and magnitude of measured field. For the measurements utilizing scalar electric field probes, we proposed another estimation method introduced in [7].

III. NUMERICAL VALIDATIONS

A. Models

In order to validate the proposed estimation, we modeled a simple multiple antenna array which consists of two dipoles. The two antennas are placed below a flat phantom. Simulations are conducted by using the Finite-Difference Time-Domain (FDTD) based SEMCAD X software [5]. Simulated data will be used as measurement references. Figure 1 shows the model in simulation program. The operating frequency of the antenna array is 2.45 GHz as an example. It should be noted that because the estimation method does not depend on the frequency and antenna type, one may choose other

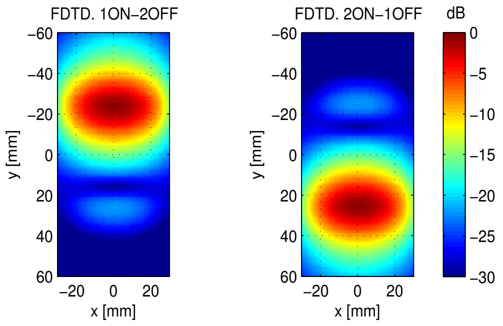
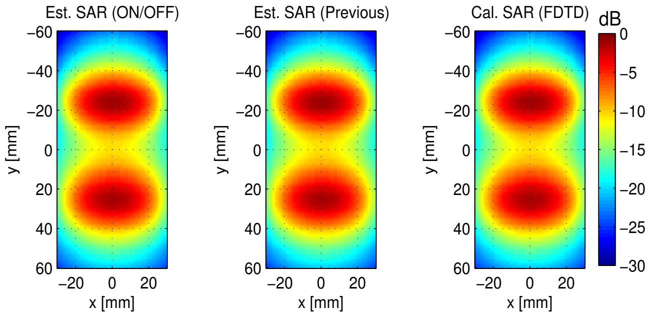


Fig. 2. SAR distributions when antennas are turned ON/OFF



(a) (b) (c)

Fig. 3. A comparison for vector estimation methods and calculation for β of 45 deg.: (a) estimated by ON/OFF method, (b) estimated by the technique in [6], and (c) FDTD calculation.

frequencies as well as other antenna configurations for their own validations.

Simulated E-fields (complex values including phase and magnitude information) for the case of antenna 1 ON - antenna 2 OFF, and antenna 2 ON - antenna 1 OFF are collected to compute the estimation factors a_1 and a_2 as mentioned in Eq. (4). In order to compare the vector estimation technique in [6], we also collected simulated E-fields corresponding to β of 0 deg., and 180 deg. All estimated and simulated (measured) data were normalized to the maximum SAR value of the SAR for β of 180 deg.

B. Results

Figure 2 shows the normalized 2-D SAR distributions in the xy-plane when antennas are turned ON/OFF alternatively. From this measured data, we can estimate to the SAR corresponding to any values of the relative phase β. Figure 3 shows a comparison of the SAR corresponding to β of 45 deg. for different estimation methods and the FDTD calculation. As we can see from this figure, the estimated and calculated SARs are in very good agreements. The SAR estimated accordingly to the method requiring ON/OFF antennas alternatively agrees well with the SAR estimated accordingly to the method in [6]. Other validations for some different antenna configurations such as PIFA (Planar Inverted-F Antennas), IFA (Inverted-F Antenna) antennas as well as other frequencies are also investigated. In all examined cases, the estimated SAR agrees well with simulated SAR. To keep this paper concise, those verified cases will not be presented here.

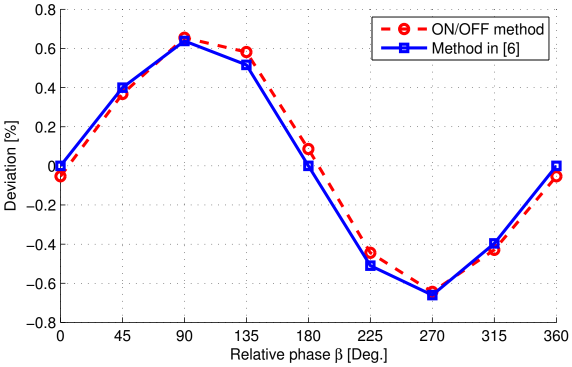


Fig. 4. Deviation between estimated and calculated SARs for two estimation techniques

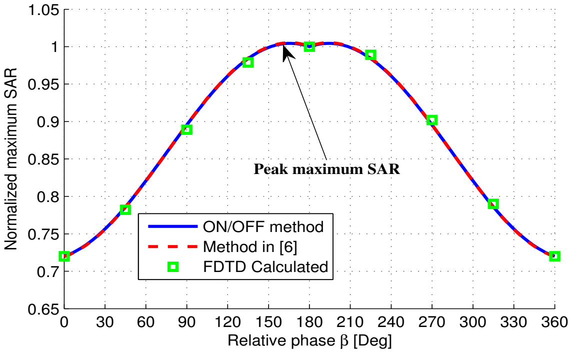


Fig. 5. Normalized maximum SAR, computed accordingly to the ON/OFF method (red, dashed), the technique in [6] (blue, solid), and the FDTD calculation (green, squared).

To evaluate the different between estimation and calculation, let $\overline{\text{SAR}}_{sim}$ and $\overline{\text{SAR}}_{est}$ be the normalized SAR obtained by FDTD simulation and the normalized SAR obtained by applying the proposed estimation methods, respectively. The deviation between estimation and calculation can be defined as

$$Deviation = 100 \cdot (\overline{\text{SAR}}_{est} - \overline{\text{SAR}}_{sim}) \quad [\%] \qquad (6)$$

Because the maximum SAR value is more important in compliance tests, the deviation evaluation for the maximum SAR values of different relative phases will be considered. Figure 4 shows the estimation error of the maximum SAR for the two-element antenna configuration illustrated in Fig. 1. As can be seen from the figure, the deviation for the maximum SAR point between estimation and calculation are kept under 0.8% for both estimation methods. It confirms that the proposed estimation methods are quite reliable. The main reason causing high deviation is due to ignoring the reflections from phantom surfaces in Eq. (2). In fact, reflections are negligible because the electric field is absorbed exponentially inside the phantom liquid.

In the aspect of finding the peak SAR corresponding to a particular set of the relative phase, we can computationally estimate the SAR for every relative phase, sweeping from 0 deg. to 360 deg. with an phase step. For each value of the relative phase, we can find the maximum SAR. Among them, the peak maximum SAR can be indicated. Figure 5 shows the peak maximum SAR for different values of the relative phase β in the examined two-antenna array. We utilized both estimation methods to plot this figure. Here, a good correlation between two methods can be seen from this figure.

IV. CONCLUSION

This paper presents a new estimation method to evaluate specific absorption rate of multi-antenna transmitting systems. The proposed method bases on estimating E-field for different relative phases of array antennas using vector E-field probes, and allows to reduce the uncertainty of estimating the SAR in practical cases. To evaluate SAR of an N-antenna transmitting device, only N measurements are necessary. The correctness of proposed method has been verified by numerical simulations for various antenna configurations. The validations confirm that estimation works well in most examined cases, and the errors caused by proposed estimation method are very small, mainly kept under few percents of the maximum measured SAR.

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