Analyses on the Maximum Local Specific Absorption Rate of Multiple Antenna Devices in Different Measurement Planes

Dinh Thanh Le*, and Van Hai Chu*
*Faculty of Radio-Electronics Eng., Le Quy Don Technical University (LQDTU), 236 Hoang Quoc Viet, Hanoi, Vietnam
E-mails: le.dinhthanh.vn@ieee.org

***Abstract*—Among the technical issues of electromagnetic compatibility for multiple antenna devices, determining the maximum specific absorption rate (SAR) is a challenging work because it is complicated and time-consuming. The SAR should be reported in term of the peak spatial-average SAR, which is determined by a plane measurement (area scan) and a volume measurement (zoom scan). For multiple antenna devices, the maximum local SAR in different measurement planes may correspond to different sets of relative phases of the sources, thus resulting in different volume measurements. This paper presents analyses on the maximum local SAR for a such device in different measurement planes, and suggest a simple and reasonable procedure to determine the spatial-average SAR.**

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

I. Introduction

Multiple-antenna communication systems, including Multi-Input Multi-Output (MIMO) techniques and phased array antennas, have been received a number of attentions in research and developments in recent years. Yet, to put them into services in the reality, not only technologies to enhance the data rate, but also electromagnetic compatibility issues, which ensure safe and reliable services of the systems, are needed to be thoroughly investigated. Among the electromagnetic compatibility issues, determination the maximum specific absorption rate (SAR) is an important task. The SAR is defined as the amount of power absorbed per unit mass of a biological body when it is exposed to the electromagnetic field. The SAR is specified as a limit restriction in international RF safety standards, and it should be reported in term of peak spatial-average value. The spatial-average SAR is determined by averaging local SARs in a cube volume of liquid tissues, which have electrical properties similar to a biological body. The local SAR is proportional to the power of internal electric field, and can be determined by [1]–[3]

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

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

For multiple antenna devices utilizing two or more antennas working at a same frequency, the total E-field, thus the SAR, depends not only the magnitude but also the relative phases of the signals radiated from the multiple antennas. The reason is quite straightforward because the total E-field is the vector summation of individual E-fields. Regarding to the change of the relative phases of signals, a basic solution to measure SAR of such devices is to measure for every relative phase combination of the antennas, each relative phase sweeping from 0 deg. to 360 deg. with a phase step [1]–[3]. This method remains the advantage of using scalar electric field probes but very time-consuming or even unpractical when the phase step is small, or the number of antennas is large. An alternative method is to measure SAR for individual activated antennas (turned ON) while the others being inactivated (turned OFF). Each individual SAR is measured accordingly to the respective activated antennas. The total SAR will be then obtained by combining the individual measured SARs [1], [4]. This method, however, can only provide an upper bound of the SAR, thus potentially overestimating the actual SAR.

To address this problem, our research group has proposed estimation techniques to reduce number of measurements [5]–[7]. So far, we have carried out numerical and experimental validations for several cases with different configurations and frequencies [7] and confirmed good agreements between estimated and measured SARs. Thanks to the proposed methods, we are able to find the set of relative phase of the antennas corresponding to the maximum local SAR in each measurement plane. Each measurement plane can be chosen for area scan, which is clearly defined in international standards for measure the SAR of wireless devices [2], [3]. However, in different measurement planes, the set of relative phases yielding the maximum local SAR may be changed. Thus, we need to analyze such changes in order to define a reliable procedure to determine spatial-average SAR in a volume. This paper will focus on analyzing the maximum local SAR of multiple antenna devices in different measurement planes, and suggesting a procedure to determine the spatial-average SAR of such devices.

II. Estimation principles

Suppose that we have a wireless communication devices which consists of two transmitting antennas working at a same frequencies. The phase difference between the two antennas at a measurement point is called the relative phase (β) between them. At each measurement point, the total electric field radiated by the two antennas is equal to the vector summation

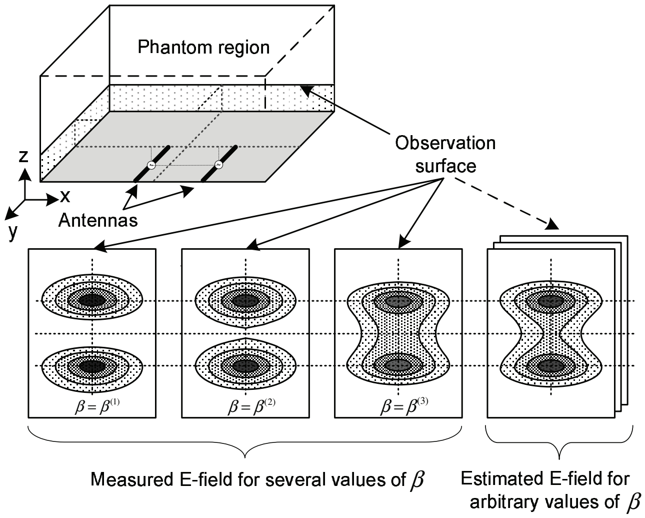

Fig. 1. Fundamental concepts of SAR estimation

TABLE I
PARAMETERS OF THE PHANTOM

Parameters	Values
Frequency	2140 MHz
Phantom size	180 × 180 × 150 mm^3
Shell thickness	2 mm
Distance between phantom liquid and DUT	2 mm
Liquid's permittivity	39.2
Liquid's conductivity	1.8 S/m
Liquid's mass density	1000 Kg/m^3

of the two, and can be given as

$$\mathbf{E}_{tot} = \mathbf{E}_1 + \mathbf{E}_2 e^{i\beta} \quad (2)$$

where β is the relative phase of the two elements, $\mathbf{E}_1$ and $\mathbf{E}_2$ are the E-field radiated from antennas 1 and 2 (complex values), respectively.

By calculating the square of magnitude of the total E-field from the above equation, and incorporating with σ and ρ according to the Eq. (1), we obtained the formula of the SAR for two transmitting antenna devices as [6], [7]

$$\text{SAR} = a_1 + a_2 \cos\beta + a_3 \sin\beta \quad (3)$$

where a_1, a_2, and a_3 are real factors those can be expressed in terms of the real and imaginary parts of E_1 and E_2.

The estimation factors, a_1, a_2, and a_3, are independent from β. They can be determined from SAR measurements for three different relative phases, for example β of 0, 90, and 180 deg. After they are determined, the SAR for an arbitrary β_{est} can be estimated by substituting estimation factors a_1, a_2, and a_3 into Eq. (3). Figure 1 presents a basic configuration of SAR measurements, which consists of two dipole antennas, a phantom, and liquid inside the phantom, and the principles of the proposed estimation technique. Thanks to limited number of necessary measurements, the time and efforts (thus the cost) in SAR evaluation for multiple antenna devices can be significantly saved.

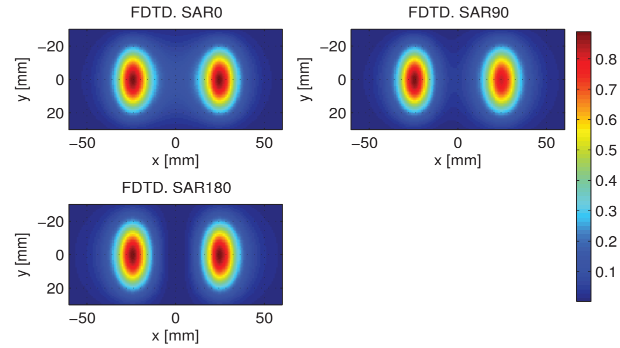

Fig. 2. Normalized SAR distributions for the relative phases of 0, 90, and 180 deg.

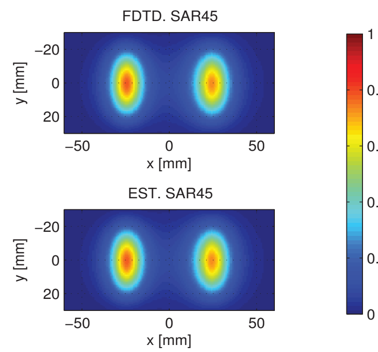

Fig. 3. Comparison of calculated and estimated SARs for the relative phase of 45 deg.

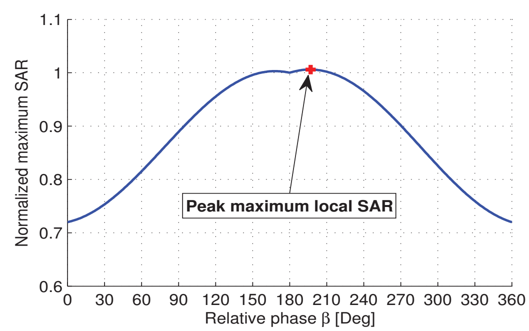

Fig. 4. Normalized maximum local SAR at the plane

So far, we have conducted various validations for different antenna configurations, frequencies, and confirmed that estimated and measured SARs in different observation scanning areas are in very good agreements [6], [7]. Let take an example to two dipole antennas at 2.14 GHz. They are separated by a distance of a half of wavelength at the frequency. The phantom size and liquid's electrical properties are listed in the table I. Calculated SARs are normalized to the maximum value of the SAR for the relative phase of 180 deg. Fig. 2 shows the normalized SAR distributions of two dipole antennas for the relative phases of 0, 90 and 180 deg in a measurement plane. By utilizing this data, we can estimate the SAR for

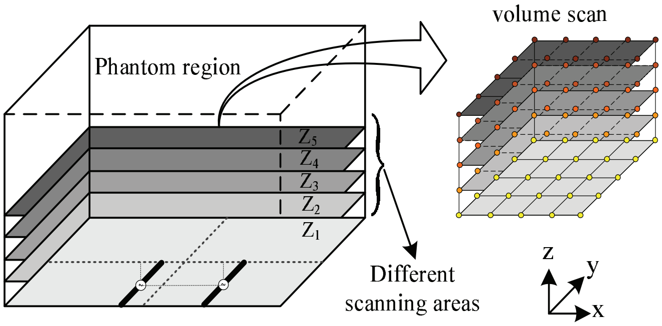

Fig. 5. Different area scans, and a volume scan in determining the spatial-average SAR

any other values of relative phase in the same plane. Fig. 3 shows a comparison of calculated SAR and estimated SAR when the relative phase equals to 45 deg. Good agreement between calculation and estimation can be seen from this figure. Furthermore, we can estimate SAR for other value of the relative phase, and finally can identify the relative phase that yields the maximum SAR in the measurement plane. Fig. 4 shows the normalized maximum local SAR at the plane for different values of the relative phase. As can be seen from this figure, the peak maximum local SAR in this plane corresponds to the relative phase of 197 deg.

III. SAR IN AREA SCANS

In order to evaluate the SAR of the devices, one needs to measure electric fields in a given plane (called ”area scan”), and in a given volume (called ”zoom scan”) which consists of the point yielding the maximum local SAR in the measured plane. The measurement in the plane is called as *area scan*, while the measurement in the volume is referred to as *zoom scan* [2], [3]. Basically, the volume measurement can be considered as a set of measurements in different planes. Figure 5 illustrates an example of SAR evaluation for multiple antenna cases which include area scan and zoom scan in a phantom. In determination the maximum spatial-average SAR of a wireless device, an area scan in the *XY* plane will be carried at first. A maximum local SAR will be then identified, which allows to define a volume covering the location of the maximum local SAR. A zoom scan will be conducted in this volume with a number of measurement points to determine SARs. Finally, spatial-average SAR can be calculated by averaging the measured local SAR in the defined volume.

By using the estimation method in the above section, we can find the value of the maximum local SAR, and the relative phase of the antennas yielding that value in an area scan. The area scan is important in SAR measurement because it allows to find the maximum local SAR and define the volume for zoom scan. Besides, the volume measurement, i.e zoom scan, is also important in compliance test because we need to report the peak spatial-average SAR, which is determined from zoom scan. For multiple antenna devices, in different measurement planes, i.e area scan, the relative phase yielding the maximum local SAR may change. Thus, it is necessary to investigate

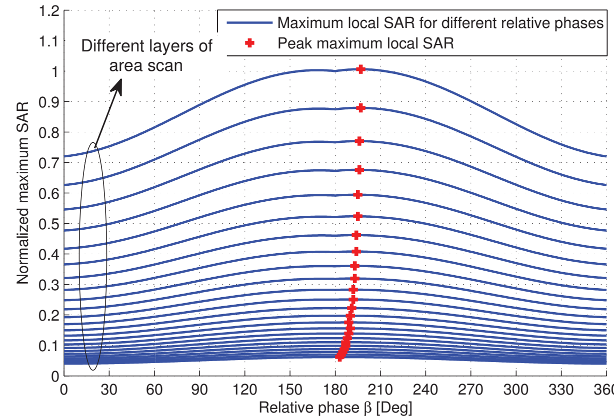

Fig. 6. Normalized maximum local SAR and its peak in different layers of area scans: dipole antennas

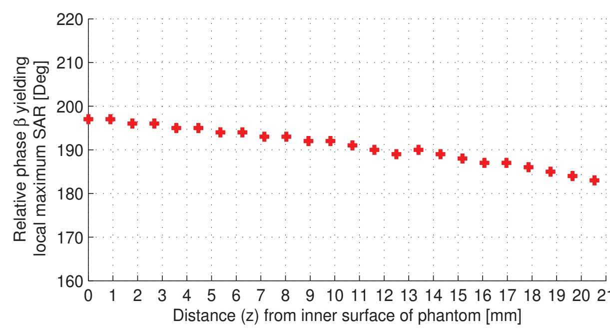

Fig. 7. Relative phase yielding the peak maximum local SAR vs different planes: dipole antennas

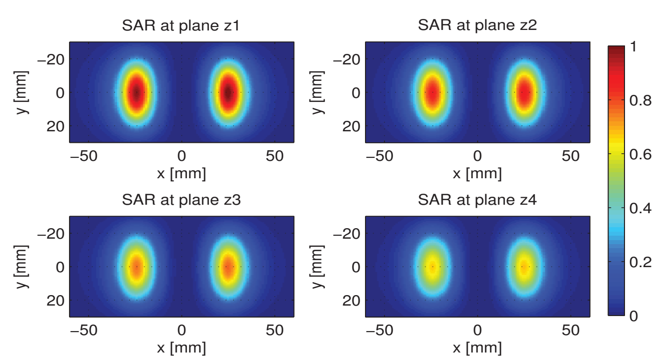

Fig. 8. SAR distributions in different layers of area scans (z1=0, z2=0.9, z3=1.8, z4=2.7 [mm], from the inner surface of the phantom to the observation planes): dipole antennas

such change of the relative phase. In this paper, we will take two examples of antenna configurations with typical types of antennas, named the dipole antennas and the F-Inverted antennas (IFA).

A. *Model 1: dipole antennas*

Two half-wavelength dipole antennas separated by a distance of a half wavelength at the frequency of 2.14 GHz, placed under a flat phantom as shown in Fig. 1, will be taken as the first model. The SAR distributions for the relative phase of 0, 45, 90, and 180 deg. in a *XY* plane is presented in Figs. 2 and 3 in the previous section.

Now, we will analyze how the relative phase, which yields the maximum local SAR, changes in different measurement planes. Fig. 6 presents the plots of maximum local SARs at different measurement planes (different area scans). The highest curve corresponds to the closest plane to the phantom inner surface (where z1=0), while the lowest one corresponds to the plane which is most far from phantom inner surface. It is noted that the liquid inside the phantom is lossy environment where electromagnetic field is absorbed. The maximum local SAR, therefore, should be at the planes which are close to the phantom inner surface. Fig. 8 shows the SAR distributions in different area scans, and Fig. 7 presents change of the relative phase yielding the peak maximum local SAR in different planes (represented by the distance z of the plane to the inner surface of the phantom in the horizontal axis). From these figures, we can see that, in several planes close to the inner surface of the phantom (which have most effects to the peak spatial-average SAR), the relative phase yielding the maximum local SAR changes in a few degrees. In the inner surface of the phantom (the highest curve), the relative phase yielding the maximum local SAR is 197 deg. while this relative phase slightly changes to 196 deg. at the plane far from inner phantom surface a distance of 2.6 mm. In planes far from the inner surface of the phantom, the change of the relative phase can be up to 183 deg. However, the SAR in such planes are relatively small (Fig. 8), thus, they may not effect to the peak spatial-average SAR.

At the planes, which are far from inner surface of the phantom, the relative phase changes to several degrees. However, the SARs in these planes are relatively weak compared to the SARs in planes which are closer to the inner surface of the phantom. So, we can find that, the area scan in plane, which is closest to the inner surface of the phantom, should be carried to identify the relative phase yielding the maximum local SAR (β_{SARmax}) and the position of the maximum local SAR. Then, by setting the relative phase of the sources to the β_{SARmax}, the volume scan, which covers the position of the maximum local SAR, should be carried to determine the peak spatial-average SAR. The β_{SARmax}, as the above analyses, will also, or mostly, yield the maximum local SAR of other planes in the volume scan. This procedure is simple and reasonable to avoid measurement duplications in the volume scan for different values of the relative phase which yield the maximum local SAR in different planes.

B. Model 2: F-Inverted antennas

The second model is with two Inverted-F Antennas (IFA) designed in a mobile-phone-size case. These antennas working at the frequency of 2.14 GHz. Antenna configurations and dimension parameters are shown in Fig. 9. A flat phantom, and liquid tissues are similar to the first model.

Fig. 12 shows the SAR distributions in different area scans. Here, we can clearly see that the SAR distributions, including the position of maximum local SAR, are quite similar except

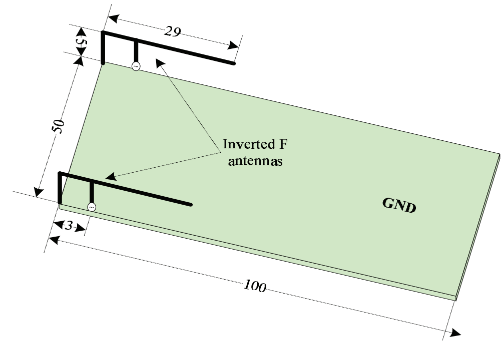

Fig. 9. Inverted-F antenna device with two elements. All dimension in [mm]

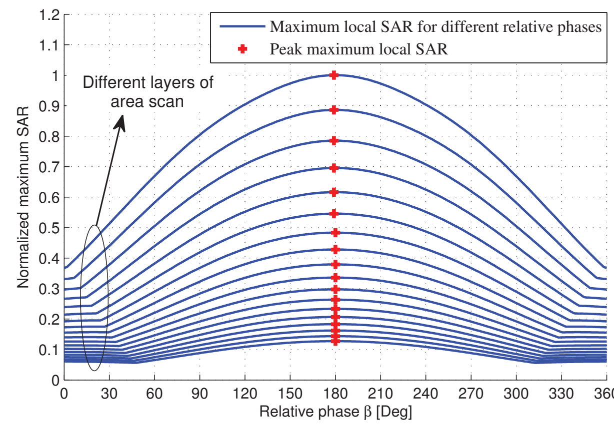

Fig. 10. Normalized maximum local SAR and its peak in different layers of area scans: Inverted-F antennas

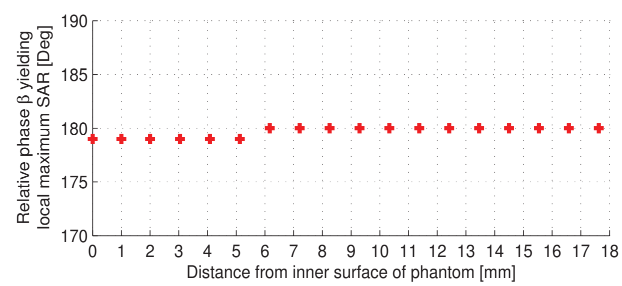

Fig. 11. Relative phase yielding the peak maximum local SAR vs different planes: Inverted-F antennas

the values of SAR in these planes. Figs. 10 and 11 present the maximum local SARs at different planes, and the change of the relative phase yielding the peak maximum local SAR in different planes. As can be seen from this figures, there is a slight change of the relative phase yielding the maximum local SAR in different plane. This change does not cause any difference in SAR distribution and the position of the maximum local SAR. Thus, by measuring SAR in a plane, which should be close to the inner surface of the phantom, we can identify the value of β_{SARmax}, the position of maximum local SAR. This information will be use to determine the volume for zoom scan, and determine the peak spatial-average SAR.

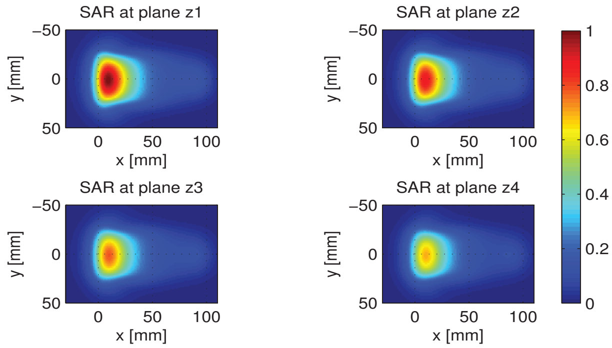

Fig. 12. SAR distributions in different layers of area scans (z1=0, z2=1, z3=2, z4=3 [mm], from the inner surface of the phantom to the observation planes): Inverted-F antennas

IV. Conclusion

This paper presented analyses on the maximum local SAR of multiple antenna devices in different measurement planes, and suggested a procedure to determine the spatial-average SAR of such devices. As a result, we found that in different area planes, the relative phase of the sources yielding the maximum local SAR slightly changes within several degrees. In the planes close to the inner surface of the phantom (where the electric fields are relatively strong, and affect most to the peak spatial-average SAR), the change is within few degrees. Such little changes do not cause any difference of SAR distribution, or the position of maximum local SAR. Therefore, the procedure to determine the peak spatial-average SAR of multiple antenna devices can be as similar as that of single antenna devices, except the requirement of finding the set of relative phases of the maximum local SAR (β_{SARmax}) in area scan. The zoom scan in a volume covering the position of the maximum local SAR should be then carried out for the set of relative phases. By doing this, one can avoid duplications of measurements in different area scans to determine different set of relative phases of the sources.

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