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On the measurement procedures for the assessment of the specific absorption rate (SAR) from MIMO cellular-equipment of fast varying relative phases

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Abstract. This article introduces a measurement methodology for the evaluation of the specific absorption rate (SAR) of MIMO systems (multiple-input and multiple-output) in which the relative phases between the antennas are rapidly changing and in very short durations.

This measurement methodology is enabled by SAR systems that uses vector field measurements combined with a vector spectral analysis of the measured radiofrequency signals for SAR assessment. By exploiting the equivalence principle and the uniqueness of the solution of Maxwell's equation, the proposed approach allows for an accurate SAR assessment of complex MIMO systems in a very short duration (few seconds).

Keywords. SAR, MIMO, Near field measurements, Vector field measurements, Time averaged SAR.

1. Introduction

In recent years, communication systems witnessed a fast evolution and an exponential increase of their complexity, especially with the advent of the LTE-advanced and the 5G. These technologies are based, among others, on the introduction of complex communication techniques such as the multiplication of transmitting and receiving antennas also known as MIMO (Multiple-Input Multiple-output) [1]. The introduction of MIMO technology in communication devices raises new challenges in the experimental evaluation of the specific absorption rate (SAR) and the human exposure to radiofrequency radiation [2]. In the case of a MIMO system, the exposure

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level must be evaluated for all the possible phase configurations of the system [3, 4]. By considering, for instance, a 10° step, this will lead to 36 measurements in the case of a two antennas system. Different methods have been proposed in the literature in order to evaluate the SAR of MIMO system with a small number of measurements [5, 6]. However, these methods assume a direct access to the excitations of the antennas of the systems, thus allowing a unique phase reference for the emitting antennas and the measurement. This is generally not possible in realistic practical scenarios.

In [7], time averaged local SAR is used in order to evaluate RF exposure level in the case of MIMO systems with a quick time domain variation. The proposed measurement method is faster than the classical measurement method. However, it requires a relatively large integration time of measurements in order to obtain the time averaged local SAR. It was also demonstrated in [7] that the sampling frequency used in the measurement of the electric field (E-field) is a key factor for the determination of the measurement time of this new MIMO technology. For measurement technologies using diode probes, the typical sampling frequency is of a few kHz. This requires the integration time of the measured signal ever more than one second at each point of the scan volume in order to achieve 2% precision on SAR. On the other hand, radiofrequency vector measurement technology such as the one introduced in [8] has a sampling frequency of 250 MHz that satisfy Shannon sampling theorem. The use of such high sampling frequency will drastically reduce the required integration time.

In this paper, a method for the evaluation of the time averaged SAR is presented. The proposed method is the extension of the work presented in [9, 10] to the case of MIMO systems with fast time domain variations. The proposed method is based on the use of vector measurement systems with a finite measurement probes grid and using E-field reconstruction in the measurement volume.

2. MIMO SAR measurement systems

2.1. *Signal classification*

Changes in the relative phases of signals transmitted by MIMO systems have a significant impact on the total electric field variation and thus on its time averaged value. Thus, it might be convenient to classify MIMO signals depending on the variation rate of their relative phases. In the context of SAR measurement, MIMO signals are divided into two main classes.

The first class consists of signals with relative phases that stay unchanged during a relatively long duration. The MIMO system configuration and the corresponding SAR value is then stable throughout this duration. This is for instance the case for antenna array systems where the phase shift is used to control the radiation pattern and the radiation direction. For these systems, the methods presented in [9,10] allow for a rigorous SAR assessment of all the possible configurations of the MIMO system using only $N+1$ measurements (where N is the number of antennas of the MIMO system). These fast and rigorous methods, requiring such minimal number of measurements, are made possible through the simultaneous measurement of the amplitude and the phase of the electric field phasor, combined with a vector spectral analysis of the radiofrequency signals for SAR assessment.

The second class includes signals with fast relative-phase variation rate. This is for instance the case when space–time coding is used such as STBC (space–time block code). In this type of configuration and due to its fast variation, the measurement of the SAR value is very difficult. However, it has been shown in [7] that the time averaged electric field converges when the integration time is sufficiently long. This integration time is significantly reduced if the SAR measurement system exploits a time domain acquisition of the demodulated RF signals with a sampling rate that satisfies the Shannon theorem.

In this paper, a SAR measurement method for MIMO systems with a fast relative phase variation rate is presented. This method is based on the work presented in [9, 10] and on the convergence of the time averaged electric field. The proposed method is intended for SAR measurement systems with vector probes measuring the electric field phasor, with a frequential selectivity and a time-domain acquisition of the demodulated radiofrequency signals.

2.2. *Time averaged SAR convergence*

The SAR value at a point (x, y, z) from space is defined as:

$$\mathrm{SAR}(x,y,z)=\frac{\sigma|\mathbf{E}(x,y,z)|^2}{2\rho} \tag{1}$$

where σ is the electric conductivity (S/m) and ρ is the mass density (kg/m^3) of the medium simulating the human tissues.

$\mathbf{E}(x, y, z)$ is the complex phasor of the harmonic electric-field.

Let's consider a MIMO system composed of two transmitting antennas that generates the electric fields $\mathbf{E}_1$ and $\mathbf{E}_2$ respectively. By injecting the signals $s_1(t)$ and $s_2(t)$ in these two antennas, the total field $\mathbf{E}_t$ is obtained as:

$$\mathbf{E}_t(x,y,z,t)=s_1(t)\mathbf{E}_1(x,y,z)+s_2(t)\mathbf{E}_2(x,y,z). \tag{2}$$

Squaring Equation (2) and calculating its module leads to:

$$\begin{aligned}|\mathbf{E}_t(x,y,z,t)|^2 &= |s_1(t)\mathbf{E}_1(x,y,z)|^2+|s_2(t)\mathbf{E}_2(x,y,z)|^2\\ &\quad +2|s_1(t)||s_2(t)||\mathbf{E}_1(x,y,z)||\mathbf{E}_2(x,y,z)|\cos(\phi(t))\end{aligned} \tag{3}$$

with $\phi(t)=\arg(s_1(t)s_2(t)\mathbf{E}_1(x,y,z)\mathbf{E}_2(x,y,z))$.

The time averaging of (3) gives:

$$\begin{aligned}\langle|\mathbf{E}_t(x,y,z,t)|^2\rangle &= \langle|s_1(t)|^2\rangle|\mathbf{E}_1(x,y,z)|^2+\langle|s_2(t)|^2\rangle|\mathbf{E}_2(x,y,z)|^2\\ &\quad +2\langle|s_1(t)||s_2(t)|\cos(\phi(t))\rangle|\mathbf{E}_1(x,y,z)||\mathbf{E}_2(x,y,z)|\end{aligned} \tag{4}$$

where $\langle\cdot\rangle=(1/T)\int_0^T\cdot\,\mathrm{d}t$ and T is the integration time.

In the case of space time coding, the relative phase shift between the signals $s_1(t)$ and $s_2(t)$ changes very quickly, and the term $\langle|s_1(t)||s_2(t)|\cos(\phi(t))\rangle$ tends to zero for a sufficiently long integration time T. From (4), the time average of the instantaneous SAR, $\mathrm{SAR}(x, y, z, t)$ becomes:

$$\langle\mathrm{SAR}(x,y,z,t)\rangle=\langle|s_1(t)|^2\rangle\mathrm{SAR}_1(x,y,z)+\langle|s_2(t)|^2\rangle\mathrm{SAR}_2(x,y,z) \tag{5}$$

where $\mathrm{SAR}_1(x, y, z)$ and $\mathrm{SAR}_2(x, y, z)$ are the local SAR values resulting respectively from the two antennas of the MIMO system when they are excited separately.

The result obtained in (5) can then be extended to the general case of an N antenna MIMO system.

2.3. *Measurement method*

In this section, a measurement method is proposed for SAR assessment in the case of MIMO signals with fast relative phase variation. Equation (5) shows that the assessment of the time averaged SAR of such systems comes down to the determination of the individual SAR ($\mathrm{SAR}_i(x, y, z)$) resulting from each antenna of the system, together with the time averaged value $\langle|s_i(t)|^2\rangle$ of the squared amplitude of the signals that are injected in these antennas.

Considering these observations, a two steps method is proposed for the assessment of the time averaged SAR of MIMO systems composed of N antennas. The proposed method is presented as follows:

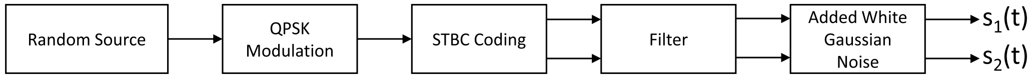

Figure 1. Block diagram of a MIMO system transmitting two signals with an STBC coding.

1. *Step 1—Configuration with slow relative phase variations:*
   a. Force the DUT to operate in a configuration with a stable relative phase distribution.
   b. Using $N+1$ measurements, follow the method presented in [9, 10] in order to obtain, at each point (x, y, z) of the measurement domain, the individual local SAR distributions $\mathrm{SAR}_i(x, y, z)$ corresponding to an independent excitation of each antenna of the MIMO system.
2. *Step 2—Configuration with fast relative phase variations:*
   a. Put the DUT in the configuration with quick relative phase variations where the SAR measurement needs to be performed.
   b. Measure the local instantaneous SAR $(\mathrm{SAR}(x_k, y_k, z_k, t))$ at K points (x_k, y_k, z_k) $(K \geq N)$ of the sensor grid, for a duration T that is sufficiently large in order to obtain the convergence of the time averaged local SAR $\langle \mathrm{SAR}(x_k, y_k, z_k, t)\rangle$.
   c. Using these time averaged SAR values $\langle \mathrm{SAR}(x_k, y_k, z_k, t)\rangle$ and the individual SAR of the MIMO antennas $\mathrm{SAR}_i(x, y, z)$ obtained in step 1, calculate the time averaged value $\langle |s_i(t)|^2\rangle = \alpha_i$ of the squared amplitude of the excitation signals, and this by minimizing the following expression:
$$\min_{\alpha_i} \sum_{k=1}^{K} \left| \langle \mathrm{SAR}(x_k, y_k, z_k, t)\rangle - \sum_{i=1}^{N} \alpha_i \mathrm{SAR}_i(x_k, y_k, z_k) \right|. \tag{6}$$
   d. From the values of α_i, calculate the time averaged SAR value $\langle \mathrm{SAR}(x, y, z, t)\rangle$ at every point (x, y, z) of the measurement domain using the following equation:
$$\langle \mathrm{SAR}(x, y, z, t)\rangle = \sum_{i=1}^{N} \alpha_i \mathrm{SAR}_i(x, y, z). \tag{7}$$

It should be noted that the step 1 of the proposed method does not need to be repeated if additional MIMO configurations with fast relative phase variations are considered.

3. Numerical validation

In order to validate the proposed measurement method, a MIMO configuration composed of two transmitting dipole antennas with a working frequency of 750 MHz. The electric field E generated by a horizontal dipole placed over a phantom of dielectric parameters $(\varepsilon_r; \sigma) = (42.8; 0.85\ \mathrm{S/m})$ was simulated using the FDTD (Finite Difference in Time Domain) software EMPIRE XPU [11]. The result was then used in order to obtain the filed generated by the two dipole MIMO system for different configurations.

In order to obtain a high temporal variation of the relative phase, STBC coded time domain signals were generated by following the block diagram described in Figure 1. The obtained signals were then combined with the simulated electric fields in order to simulate a MIMO system with a high variation rate of the relative phase of the transmitted signals.

3.1. *Convergence of the time averaged SAR*

A first important step is the validation of the convergence of the time averaged SAR value and the validity of (5). This will allow us to determine the integration time T that is necessary in order to

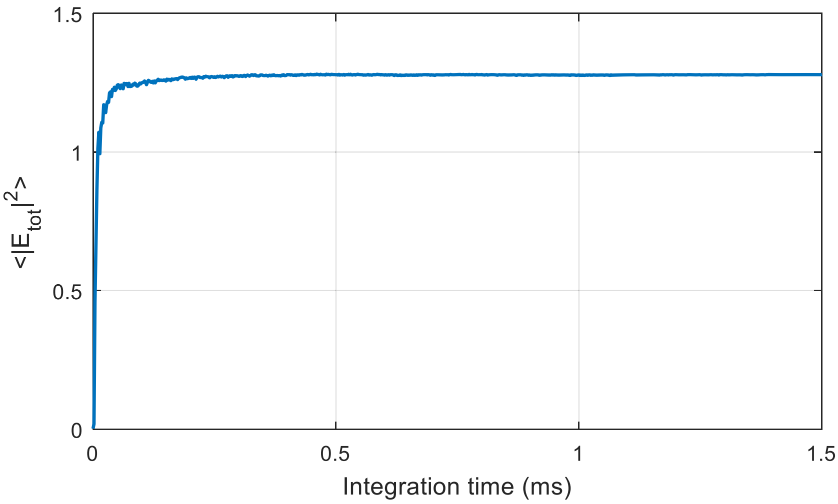

Figure 2. Variation of the time averaged squared amplitude of the electric field as a function of the integration time in (ms).

perform the measurement. In order to do that, random QPSK signals are generated by following the block diagram described in Figure 1. The generated signals have the following parameters:

Symbol rate: 10^6 symbol/s (corresponding to a symbol duration of 1 µs)
Modulation: QPSK
Coding: STBC
Filter: Raised cosine filter with a Rolloff factor of 0.25
Signal to Noise Ratio (SNR): 30 dB

The sampling frequency of the demodulated signals used by the SAR measurement system is set to 50 MHz, thus 5 times the higher frequency of the signal. It should be noted that acquiring analog-to-digital converters with a sampling frequency of several hundreds of MHz is very affordable.

The signals $s_1(t)$ and $s_2(t)$ that are generated at the end of this step are combined in order to obtain the total field (c_1 and c_2 are two complex numbers representing the electric fields generated by the two antennas of the system). The squared amplitude of the resulting total field is then averaged by varying the integration time T. The obtained results are represented in the Figure 2. It can be seen from the figure that the time averaged squared amplitude of the total electric field converges after a short integration time of a few fractions of milliseconds.

The calculation process is repeated many times (1000 times) for different sampling frequencies Fe in order to obtain the variation of the standard deviation with respect to the integration time. The obtained results are represented in the Figure 3. It can be seen from the figure that the sampling frequency has a significant effect on the convergence speed of the time averaged SAR. This is even more the case when the choice of the sampling frequency does not satisfy Shannon's theorem, such as for Fe = [10, 20, 50] MHz. This leads to a significant increase of the integration time ensuring less than 1% error. At the considered sampling frequency (50 MHz), the standard deviation is smaller than 1% for an integration time larger than 80 µs. It is this integration time that will be used for the rest of this article.

The generated STBC signals are combined with the electric fields of two horizontal dipoles simulated at a planar surface inside a flat phantom. This is performed in order to simulate SAR measurement system exploiting a vector measurement of the electric field over a finite

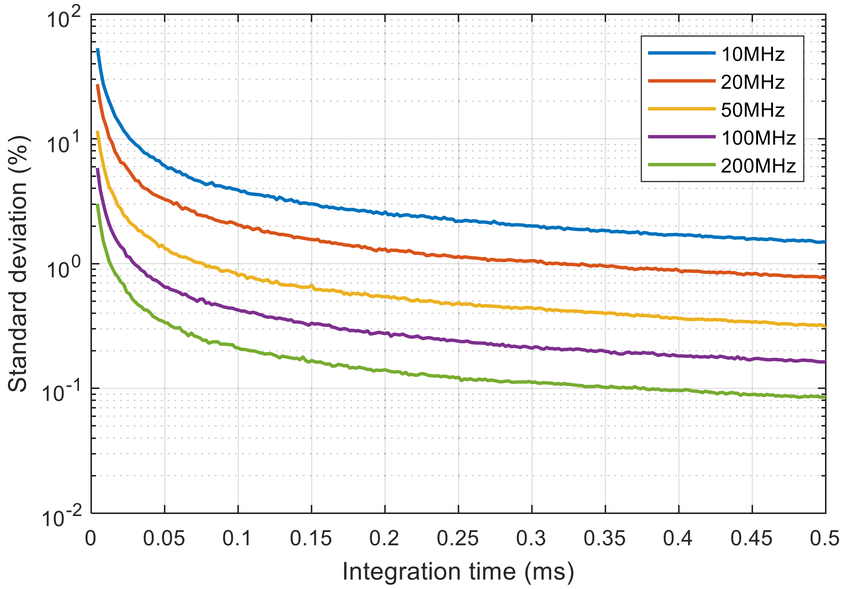

Figure 3. Variation of the local SAR standard deviation in % as a function of the integration time for different sampling frequencies. The results were obtained by repeating the calculation process 1000 times.

grid of sensors and using reconstruction algorithms of the electric field inside the measurement volume.

In the considered example, the two dipoles are centered at the positions à $(x, y) = (0, 30)$ mm and $(x, y) = (0, -30)$ mm and are rotated with respect to the z axis by +45° et −45° respectively. The considered transmitted signals have a unitary amplitude in order to obtain: $\langle|s_1(t)|^2\rangle = \langle|s_2(t)|^2\rangle = 1$. The corresponding variations of the time averaged squared amplitude of the fields over the measurement domain are represented in the Figure 4. It can be seen from the Figures 4(c) and (d) that the variations of $\langle|\mathbf{E}_t|^2\rangle$ and the sum $|\mathbf{E}_1|^2 + |\mathbf{E}_2|^2$ are very similar, with a quadratic error of less than 3%. This confirms that the term $\langle|s_1(t)||s_2(t)|\cos(\phi(t))\rangle$ to zero for a sufficiently large integration time and thus validating (5) on which the proposed measurement is based.

3.2. *Numerical validation of the proposed SAR measurement method for fast varying MIMO systems*

In order to validate the proposed measurement method, the steps described in Section 2.3 are applied on electric field distributions similar to those used in the previous subsection. The two considered dipoles are rotated by the angles −15° and 45° respectively. The amplitudes of the generated excitation signals are defined in order to have $\langle|s_1(t)|^2\rangle = 0.5$ et $\langle|s_2(t)|^2\rangle = 0.75$.

As the first step of the measurement method was previously validated in [9, 10], the local SAR values $\mathrm{SAR}_1(x, y, z)$ and $\mathrm{SAR}_2(x, y, z)$ corresponding to the two antennas can be assumed to be known in every point of the measurement domain. The corresponding local SAR variations are represented in Figure 5.

By combining the signals $s_1(t)$ and $s_2(t)$ with the simulated electric fields E, the time averaged SAR values $\langle\mathrm{SAR}(x_k, y_k, z_k, t)\rangle$ is evaluated at two measurement points (x_1, y_1, z_1) and (x_2, y_2, z_2) of space (for example at the maximums of the individual local SAR of the two antennas).

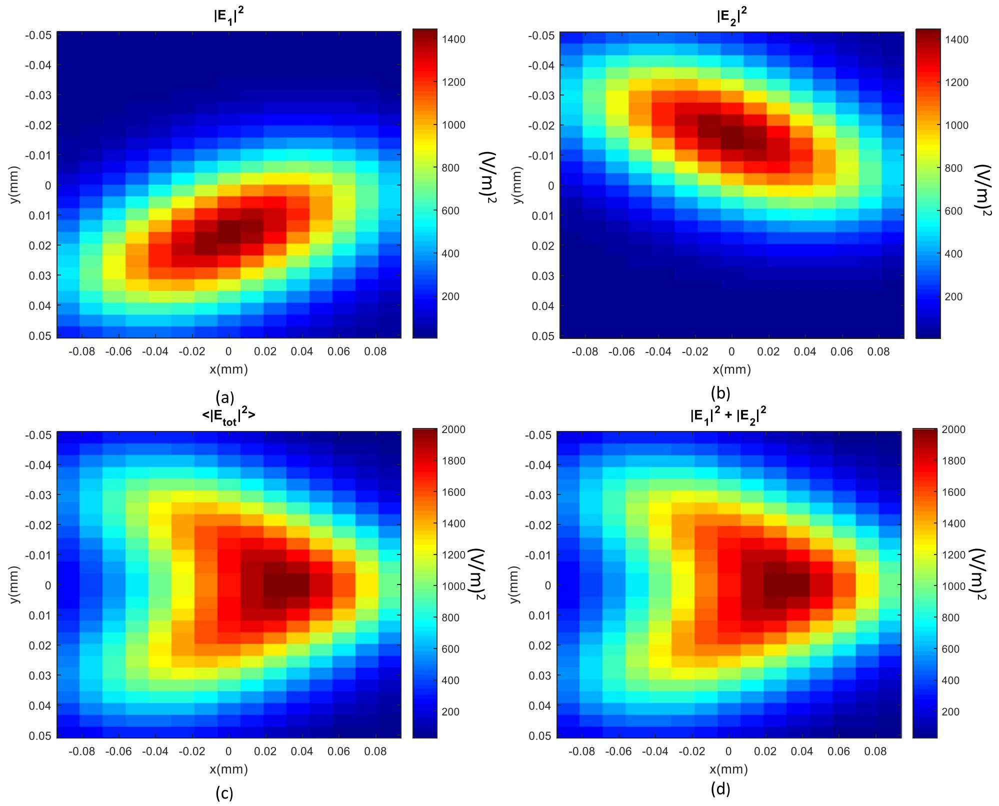

Figure 4. Variations of the time averaged squared field amplitudes in $(\mathrm{V/m})^2$: (a) $|E_1|^2$. (b) $|E_2|^2$. (c) $\langle |E_{\mathrm{tot}}|^2 \rangle$. (d) $|E_1|^2 + |E_2|^2$.

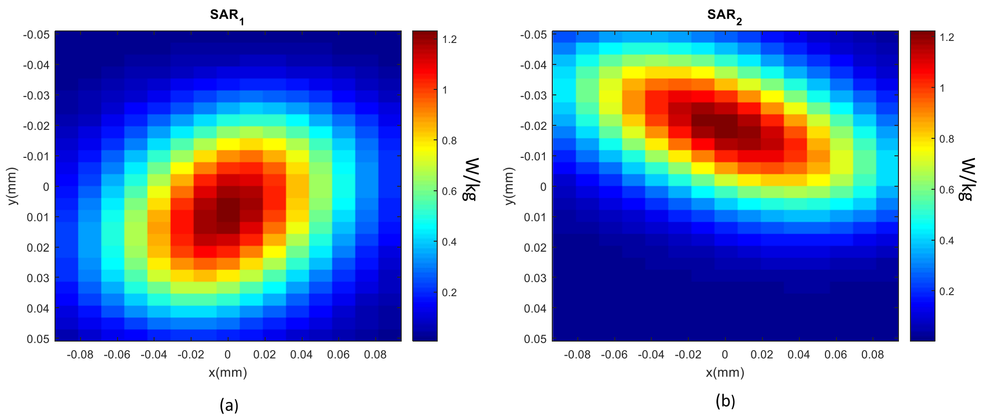

Figure 5. Variations of the simulated local SAR. (a) Antenna 1 alone. (b) Antenna 2 alone.

A cost function $f(\alpha_1, \alpha_2)$ is then defined as follows:

$$f(\alpha_1, \alpha_2) = \sum_{k=1}^{2} |\langle \mathrm{SAR}(x_k, y_k, z_k, t) \rangle - (\alpha_1 \mathrm{SAR}_1(x_k, y_k, z_k) + \alpha_2 \mathrm{SAR}_2(x_k, y_k, z_k))|. \tag{8}$$

The variations of the cost function defined in (8) are obtained by varying the values of the

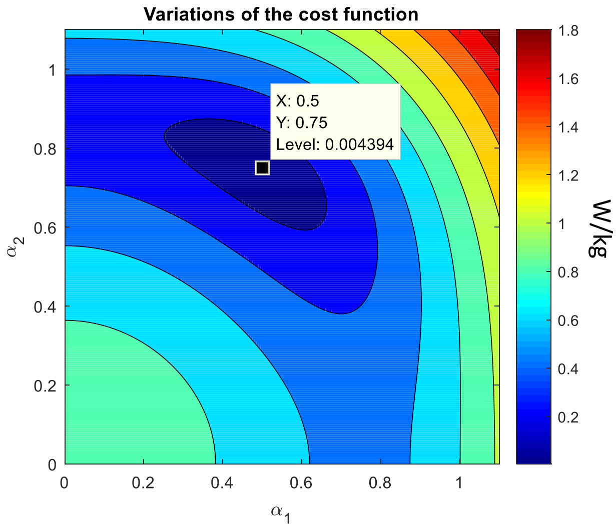

Figure 6. Variations of the cost function defined in (8).

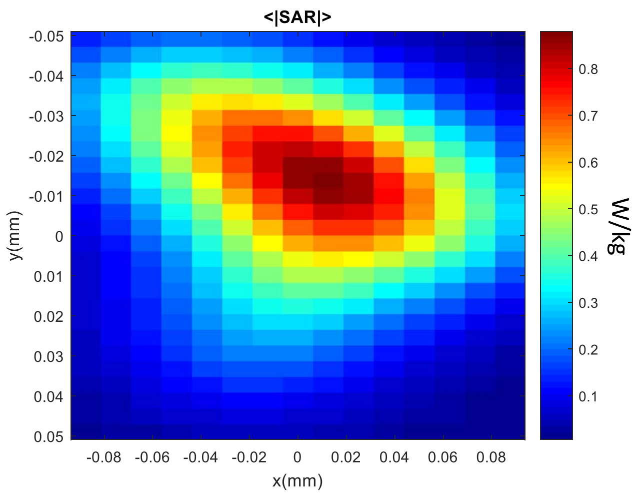

Figure 7. Time averaged local SAR distribution. The results were obtained by following the measurement method proposed in this article.

variables α_i. The corresponding results are represented in Figure 6. It can be seen from the figure that the minimum of the cost functions is obtained for $(\alpha_1, \alpha_2) = (0.5, 0.75)$. This corresponds to the time averaged values $\langle|s_1(t)|^2\rangle \langle|s_2(t)|^2\rangle$ that were imposed when generating the MIMO signals. From the retrieved values of (α_1, α_2), the time averaged SAR $\langle \mathrm{SAR}(x, y, z, t)\rangle$ is obtained at each point of the measurement domain by using (7). The obtained results are given in Figure 7.

In summary, the determination of the time averaged SAR (at every point of the measurement domain) in the case of a fast varying, 2 antenna MIMO system required a total of 3 classical vector measurements (with a typical duration of 15 s each) and two time averaged SAR measurements at two points of space (with a 80 μs duration each).

4. Conclusion

This article presents a practical, rigorous and innovative method for the experimental evaluation of electromagnetic exposure resulting from wireless communication devices exploiting MIMO technologies with a fast variation of the relative phases between its antennas. In the case of a N antenna system, the proposed method uses $N+1$ vector measurements of the E-field with distinct known interference states, coupled with additional measurements of time averaged SAR. These additional measurements have a typical duration a few milliseconds and are performed on a very limited number of points of the E-field sensor grid allowing the user to avoid the time integration of the instantaneous SAR at all the points of the measurement space.

In addition to its fastness and practicality, the proposed method is compatible with the case of a non-random relative phase distribution of the excitation signals as well as with the case of MIMO configurations of slow time domain variation. All the possible configurations of a MIMO can then be addressed with the same set of initial measurements.

Finally, it has been shown in this article that the use of the new generation of vector SAR-measurement systems, that integrates a time domain acquisition of the radiofrequency signal with a sufficiently high sampling frequency (a few hundreds of MHz), allow for the reduction of the SAR measurement time of fast varying MIMO systems to a few tens of seconds, whereas the typical measurement time is of a few tens of minutes with classical diode probe systems that suffer from a limitation of low sampling frequency of few kHz only.

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