Personal Radio-Frequency Exposimeters in Indoor Diffuse Environments: Measurement and Simulation

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Abstract—The response of personal exposimeters (PEMs) is studied under diffuse field exposure in indoor environments. A numerical model and a setup for on-body calibration measurements in a reverberation chamber (RC) is proposed for 897-5500 MHz. The proposed numerical simulations are in good agreement with measurements. A difference around 2 dB between their 50% prediction intervals is observed.

Index Terms—diffuse fields, indoor environments, human exposure, personal exposimeters.

I. INTRODUCTION

Current technological advancement is accompanied by an increasing number of devices that use various radio-frequency (RF) electromagnetic (EM) sources. In recent years, many researchers have studied EM radiation from several RF sources in real environments [1]–[3]. Personal exposimeters (PEMs) are typically used in these studies to assess exposure to RF EM radiation using the relevant protocols (cf. [1], [4]).

Previous studies (for example [5]) show that PEMs are faced with measurement uncertainties caused by the presence of the human body, because PEMs are calibrated in free-space while they are used on body. This results in deviations of the measured fields from the actual incident fields for which reference levels exist [6].

People spend most of their time indoor and are exposed to EM radiation continuously. According to the room electromagnetics' theory [7], the total power in an indoor environment is composed of specular and diffuse multipath components (DMC), which result from coherent and non-coherent reflections (multiple sets of diffracted waves), respectively. The contribution of DMC to the total power may increase up to 95% [8]. Therefore, it is necessary to assess the exposure of humans to DMC (in indoor environments). In the previous studies on personal exposimeters, the PEMs' response in *diffuse fields* is not addressed yet. Currently, the existing calibration procedures are executed in an anechoic chamber. This calibration is studied for specular exposure, but it is uncertain whether this can be used under exposure to DMC.

In this paper, we report on-body calibration measurements and simulations of the response of a PEM, under *diffuse field exposure* i.e., in a reverberation room. We will compare the results of these measurements with a calibration measurement

in an anechoic room. The methodology is described in Section II. Section III presents the results. Finally, Section IV concludes the paper.

II. METHODOLOGY

The goal of this study is to assess the incident electric fields corrected for the effect of human body using PEMs in indoor environments. A PEM of type EME SPY140 (Satimo, Brest, France) with maximum sample rate of 0.25 Hz is used. The frequency bands of this PEM are listed in Table I (Lower and upper LTE bands and UMTS/HSPA are not measured by the PEM). The detection limit of the PEM depends on the frequency band and is between 0.005 to 0.02 V/m.

TABLE I
THE STUDIED FREQUENCY BANDS USED FOR SIMULATIONS AND MEASUREMENTS.

RF signal	Range (MHz) (f_j)	f_c (MHz)	L (mm)
TV	470-862	666	205.7
Lower LTE-1*	791-821	806	168.4
Lower LTE-2*	832-862	847	160.3
GSM 900-UL	880-915	897	151
GSM 900-DL	925-960	950	142.6
GSM1800-UL	1710-1785	1748	73.7
GSM1800-DL	1805-1880	1843	69.9
DECT	1880-1900	1890	67.4
UMTS/HSPA ¹	1900-1920	1910	66.7
UMTS-UL	1920-1980	1950	65.3
UMTS-DL	2110-2170	2140	59.1
WiFi-2G	2400-2483.5	2450	50.5
Upper LTE*	2500-2570	2600	47.2
	2575-2690		
WIMAX	3400-3600	3500	33.8
WiFi-5G	5150-5875	5500	21.2

* Only used for simulations; not in the range of PEM
 f_c is the center frequency and L the optimized length of the dipole.

A. Numerical Simulations

To study measurement of PEM on body, the finite-difference time-domain (FDTD) simulations are performed using the SEMCAD-X simulation platform [9]. The PEM is modelled numerically as a dipole. In order to estimate what a PEM will measure in diffuse fields, we determine numerically the distribution of the received RF power on a dipole worn on

the body in diffuse fields. We consider 14 frequency bands in the range of 666-5500 MHz (from TV up to WiFi 5 GHz in Belgium [10], see Table I). The location of the PEM on the body is also studied since it can affect its measurements. Fig. 1 shows the details of the proposed numerical model for simulations. For each frequency band, a dipole antenna is placed next to a heterogeneous (81 tissues) virtual family male (VFM) body model [11] with body mass index (BMI) of 22.3 kg/m² (see Fig.1(a)). The dielectric properties used for this model are taken from [12] and a maximum grid step of 1.5 mm is used to resolve the skin of the model, appropriately. The front and back of the torso are chosen for mounting the PEM since in reality, the measurement of a PEM at these locations are less affected by the user's movements. The distance between the dipole and the numerical body model is 19 mm (half of the width of the EME SPY140).

Fig. 1. The proposed model for numerical simulations. (a) Location of the optimized dipole on the front and the back of the VFM. (b) 3D directivity of the dipole optimized for WiFi 2 GHz. (The dipole has a total efficiency of 64.3% and a return loss equal to 27.7 dB at 2450 MHz, in presence of the body. The directivity is scaled to the maximum directivity in dB.

Firstly, a dipole antenna is designed and optimized at a separation of 19 mm from a lossy homogeneous phantom ($40 \times 20 \times 15$ cm³) with dielectric properties of muscle at each center frequency [12] to ensure that the antenna has a return loss lower than -10 dB. The optimized length of the antenna

(L) is in good agreement with the results of [13] (0.47λ for the dipoles near a body phantom at 2.4 GHz). These values are listed in Table I. Secondly, in order to simulate exposure to diffuse fields, FDTD simulations are performed for the VFM equipped with a dipole.

To model diffuse indoor fields, we use the model and distributions of [7]. According to [7] uniform distributions are defined and are listed in Table II. The amplitude of the electric fields is assumed to be 1 V/m [7].

TABLE II
PROPOSED PARAMETERS FOR SIMULATION

Parameter	distribution	range
azimuth angle (ϕ)	uniform	$[0, 2\pi]$
polar angle (θ)	uniform	$[0, \pi]$
polarization (ψ)	uniform	$[0, \pi]$
phase (α)	uniform	$[0, 2\pi]$
No of plane waves (N_{pw})	–	2000

In order to obtain a distribution of dipoles' received power in indoor diffuse fields, a huge number of FDTD simulations should have to be performed. To avoid this, we use the following method. Simulations are performed at each center frequency for the dipole radiating on the front and on the back of torso as shown in Fig. 1(b). Then the 3D directivity of the dipole is determined on the body.

The on-body aperture AA_i of the dipole i (front or back) is determined for two orthogonal polarizations (θ and ϕ) from the directive gain D_i of each antenna (for ϕ and θ angles) from numerical simulations as:

$$AA_i(\phi, \theta) = \eta_{rad}(1 - |S_{11}|^2)D_i(\phi, \theta) \frac{\lambda^2}{4\pi} \quad (1)$$

where η_{rad} and $|S_{11}|^2$ are the radiation efficiency and the power reflection coefficient of the dipole, respectively and λ is the wavelength. $AA_i(\phi, \theta)$ can be determined for two orthogonal polarizations of the incident electric fields: θ and ϕ , which are parallel to the unity vectors $\bar{1}_\theta$ and $\bar{1}_\phi$. These antenna apertures are denoted $AA_i(\phi, \theta, 0^\circ)$ and $AA_i(\phi, \theta, 90^\circ)$. The received power P_r on an antenna i (front or back) can be determined from its aperture [14]:

$$P_{r,i}(\phi, \theta, \psi) = AA_i(\phi, \theta, \psi) \times S_{inc} \quad (2)$$

where S_{inc} are the incident power density from azimuth (ϕ) and polar (θ) angles with a ψ polarization, respectively. $AA_i(\phi, \theta, \psi)$ can be calculated for any polarization angle ψ :

$$AA_i(\phi, \theta, \psi) = AA_i(\phi, \theta, 90^\circ) \cdot \cos^2(\psi) + AA_i(\phi, \theta, 0^\circ) \cdot \sin^2(\psi) \quad (3)$$

Next, a stochastic approach [15] is applied to combine different single plane waves using sets of multiple plane waves to calculate the received power on the dipole and determine the exposure in realistic environments. For multiple plane waves incident on an antenna, the incident plane waves can interfere with each other. Therefore, the received power on a dipole is not necessarily equal to the sum of the induced powers

induced by each single plane wave. The received power on each antenna i is obtained as a function of the incident electric fields:

$$P_{r,i} = \frac{1}{|Z_i|} \left| \sum_{j=1}^{N_{pw}} AF_i(\theta_j, \phi_j, 0^\circ) \cdot (\bar{E}_{inc,j}(\theta_j, \phi_j, \psi_j) \cdot \bar{I}_\theta) \cdot e^{i\alpha_j} \right|^2 + \frac{1}{|Z_i|} \left| \sum_{j=1}^{N_{pw}} AF_i(\theta_j, \phi_j, 90^\circ) \cdot (\bar{E}_{inc,j}(\theta_j, \phi_j, \psi_j) \cdot \bar{I}_\phi) \cdot e^{i\alpha_j} \right|^2 \quad (4)$$

where $|Z_i|$ is the magnitude of the input impedance of the dipole i , $\bar{E}_{inc,j}(\theta_j, \phi_j, \psi_j)$ is the incident electric field of plane wave j with azimuth angle ϕ_j , polar angle θ_j , polarization ψ_j , amplitude $|\bar{E}_{inc,j}|$, phase α_j and N_{pw} is the number of incident plane waves. The antenna factor $AF_i(\theta_j, \phi_j, \psi_j)$ is obtained as:

$$AF_i(\theta_j, \phi_j, \psi_j) = \sqrt{AA_i(\theta_j, \phi_j, \psi_j) \times \frac{|Z_i|}{377}} \quad (5)$$

B. On-body calibration measurements

The on-body calibration consists of two steps and is performed in a reverberation chamber (RC). A RC is a closed metallic cavity in which diffuse fields are uniformly distributed. Fig. 2 shows an illustration of the measurement setup. A metallic stirrer is placed in the chamber to stir the EM waves and rotates from 0° to 360° with steps of 1° during the measurements. A constant power of 10 mW is delivered to the horn antenna (TX) at each center frequency. Performing measurements in the TV band was not possible due to the dimensions (vs. λ_{TV}) of the RC.

In the first step, the free-space incident electric field is measured using a broadband field meter (NBM-550, NARDA, NY, USA) at different heights (53-203 cm) from the RC's floor and are averaged over the total measured height. The uniformity of diffuse fields is checked by changing the polarization of the TX and repeating the measurements.

In the second step, a 27-year old male subject with a height of 1.81 m and a mass of 75 kg (BMI 22.9 kg/m²) is positioned in the RC (see Fig. 2) wearing a PEM on the front and back of his torso. The electric field strength is measured by the PEM on his body during one complete rotation of the stirrer. The response (R_{ij}) is defined for the PEM at location i (i = front or back) and frequency range f_j :

$$R_{ij}(f_j) = \left(\frac{E_{RMS,ij}^{on-body}(f_j)}{E_{RMS,ij}^{free}(f_j)} \right)^2 \quad (6)$$

where E_{RMS}^{free} and $E_{RMS}^{on-body}$ are obtained from steps 1 and 2, respectively. The obtained responses are then averaged over the front and the back:

$$R_{avg,j}(f_j) = \frac{(R_{front,j}(f_j) + R_{back,j}(f_j))}{2} \quad (7)$$

In order to compare the results with previously proposed calibrations, on-body calibration measurements are executed

in an anechoic room similar to the above mentioned steps and based on the routines proposed in [16].

Fig. 2. On-body calibration measurement setup in RC. (Length= 5.7 m; width= 4.1 m; height= 2.8 m)

III. RESULTS AND DISCUSSION

Fig. 3 shows the median of the simulated received power of the dipole on the front and back of the VFM and for the average over front and back. The best fit for these data is obtained for a second order exponential function ($y = ae^{bx} + ce^{dx}$) where a, b, c and d are the coefficients. The received power on the dipole decreases with increasing frequency. This can be explained by equations (2) and (1): λ decreases with increasing frequency, which results in a lower AA_i and consequently a lower $P_{r,i}$ for a constant S_{inc} .

Fig. 3. Fitted curves to the median of the simulated received power on the dipole on the front and back of the body and average over front and back.

Fig. 4(a) shows the 50% prediction interval (PI_{50}), i.e., the ratio of 75% to 25% percentiles, for the response of the

Fig. 4. The prediction intervals of the response obtained from **simulations** (bars without pattern) using dipole and **measurements** (bars with pattern), using PEM, in **front** (dark gray) and **back** (white) of the body and **average** (light gray) over front and back.

simulated dipole and the response of PEM for on-body calibration measurements in RC in the range of 897–5500 MHz. Both front and back positions are considered. For **simulations** (bars without pattern), the values of PI_{50} for the dipole on the front or the back are in the range of 6.5–7.2 dB. Maximum PI_{50} values are found for the lower LTE-1 (dipole on the front) and upper LTE band (dipole on the back). A minimum PI_{50} of 6.5 dB is obtained from simulations for lower LTE-2 (dipole on the front) and UMTS-UL (dipole on the back). The averaged response for front and back of the VFM results in a PI_{50} of 4.3–4.8 dB. The minimum and maximum PI_{50} values for the average over both positions of the dipole are for lower LTE and DECT, respectively. Averaging over two positions reduces the PI_{50} approximately 2 dB for all frequency bands.

The results for on-body calibration **measurements** (bars with pattern) in the RC are as follows: a minimum PI_{50} of 2.8 dB (GSM1800-DL) for the PEM on the front and 2.9 dB (WiFi-5G) for the PEM on the back is obtained. The maximum values obtained for the PI_{50} are 4.5 dB (UMTS-UL) and 5.1 dB (GSM900-DL) for the PEM on the front and

on the back, respectively. For the average over two positions, the PI_{50} is reduced to about 3 dB for all frequency bands.

The PI_{50} is underestimated by the numerical simulations (approximately 2 dB). We attribute this difference to the imperfect modeling of the fields.

Fig. 4(b) shows the 95% prediction interval (PI_{95}), i.e., the ratio of 97.5% to 2.5% percentiles. For the dipole (**simulations**, bars without pattern) on the front, it is in the range of 21 dB (UMTS-DL) to 22.7 dB (WiFi-2G). For the dipole on the back, it is in the range of 20.4 dB (lower LTE) to 23.1 dB (WiFi-5G). For the average over two positions, the PI_{95} is reduced to approximately 13 dB (UMTS-UL) to 14.2 dB (TV). Averaging over two positions improved the PI_{95} with approximately 8 dB for all frequency bands.

For on-body calibration **measurements** (bars with pattern) in the RC the obtained minimum and maximum PI_{95} values are 10 dB (WiFi-5G: PEM on the front and on the back) and 13.7 dB (GSM900-DL: PEM on the front; GSM900-UL: PEM on the back), respectively. For the average over two positions, PI_{95} is reduced to 8 dB (4 dB improvement).

The median of the response for the PEM (on the front), as well as the ratio of the median response $(RC/AN)^{-1}$ are listed in Table III. The ratio of the response indicates that using the on-body calibration in anechoic room underestimates the actual exposure in indoor diffuse fields 2-4 times (except WiFi-5G) for the PEM on the front. According to the results, the on-body calibration in RC is advised to assess the exposure in indoor diffuse environments.

TABLE III
RATIO OF THE MEDIAN RESPONSE FOR ON-BODY CALIBRATION MEASUREMENTS FOR RC VERSUS AN FOR THE PEM ON THE FRONT OF SUBJECT'S BODY.

RF signal	$p_{50}(F_{RC})$	$p_{50}(F_{AN})$	$(RC/AN)^{-1}(F)$
GSM 900-UL	0.06	0.13	2.1
GSM 900-DL	0.06	0.13	2.1
GSM1800-UL	0.11	0.28	2.5
GSM1800-DL	0.09	0.28	3.1
DECT	0.008	0.02	2.5
UMTS-UL	0.09	0.22	2.4
UMTS-DL	0.08	0.27	3.4
WiFi-2G	0.12	0.5	4.1
WIMAX	0.07	0.16	2.3
WiFi-5G	0.13	0.13	1

F = front; $(RC/AN)^{-1}$ is the ratio of the median response.

IV. CONCLUSION

The response of a PEM is studied in indoor diffuse environments. Numerical simulations are performed based on the FDTD method and a stochastic approach is applied to model the response to diffuse fields. On-body calibration measurements are performed in a reverberation chamber under diffuse fields exposure. We show that existing on-body calibration routines that are executed in anechoic chambers underestimate the actual diffuse exposure in indoor environments.

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