Response of Personal Exposimeters for Exposure Assessment in the GSM900 Downlink Band

Arno Thielens, Sam Agneessens, Günter Vermeeren, Leen Verloock, Hendrik Rogier, Luc Martens, and Wout Joseph
Department of information technology, Ghent University/iMinds
Gaston Crommenlaan 8, 9050, Belgium
Arno.Thielens@intec.ugent.be

Abstract- **The response of personal exposimeter in the GSM900 downlink (DL) band is studied using numerical simulations and measurements on human subjects. Both the numerical simulations and the measurements show that a personal exposimeter will on average underestimate the incident electric fields in the GSM900 DL band and that the variation (expressed in terms of the 95% confidence interval and the interquartile distance) on its response is relatively large: a 95% confidence interval of 22 dB and an interquartile distance of 7.3 dB are found in a realistic environment using numerical simulations, while the calibration measurements show interquartile distances up to 12 dB. In terms of variation there is an excellent agreement between simulations and measurements.**

I. Introduction

The number of radio frequency (RF) sources has increased in the last decade. This gave rise to a public concern about possible adverse health effect induced by RF radiation. Up till now, the only proven mechanism of an effect of RF radiation on the human body is tissue heating by absorption of electromagnetic (EM) energy. The quantity used to describe this, in the RF region, is the specific absorption rate (SAR, the ratio of the amount of power absorbed in a certain mass) for which basic restrictions have been defined [1]. Because the SAR cannot be measured inside a living human, reference levels on the incident EM fields have been defined [1]. These fields can be assessed using EM measurement equipment such as personal exposimeters (PEMs). The World Health Organization (WHO) has indicated the need for a correct exposure assessment of RF radiation as one of the priorities in the research regarding RF radiation [2]. This exposure assessment is crucial for a correct description of the EM environment in which employees and the general public live and work.

The currently existing PEMs have some clear advantages over other EM measurement devices such as broadband probes or spectrum analyzers. First, they are worn on the body and will thus measure on the same location and time as the subject who is wearing the PEM. Secondly, they can measure simultaneously in different frequency bands. Therefore, PEMs are frequently used in measurement campaigns of RF exposures [3-8] and a protocol has been developed for a correct use of PEMs for personal exposure assessment [9]. However, PEMs are also faced with relatively large measurement uncertainties due to shadowing of the body [10-13]. Moreover, they measure the electric fields on the body instead of the incident fields, which are typically used to represent exposure and for which reference levels exist. Additionally, they exhibit an unwanted dependence on polarization of the incident fields, while their recordings should only depend on the field strength [13]. Considering these uncertainties a calibration of PEMs on the body has to be carried out.

The distribution of the electric fields recorded by a PEM has already been studied using numerical simulations [10-12,14], but has not yet been compared to actual measurements with PEMs. In [13], a calibration method for PEMs worn on the body is proposed. Calibration measurements are however only reported for one subject and have not yet been compared with numerical simulations. Numerical simulations could serve as a replacement for the more time- and work-consuming calibration measurements if they can provide the same results as calibration measurements.

The goal of this paper is to numerically determine the distribution of electric fields registered by a PEM used for the Global System for Mobile Communications (GSM) around 900 MHz (GSM900) downlink (DL) band and compare these with calibration measurements of PEMs worn by real human subjects.

II. Materials and Methods

Finite-difference time-domain (FDTD) simulations are carried out using the Virtual Family Male (VFM) [15]. This is a heterogeneous human body model consisting of 81 different tissues, based upon magnetic resonance imaging of a healthy volunteer with a BMI (body mass index) of 22.3 kg/m². The dielectric properties assigned to the phantom's tissues are taken from the Gabriel database [16]. A grid step of 1.5 mm is chosen inside the phantom to ensure stability and provide an acceptable spatial resolution. FDTD simulations of the phantom under single plane-wave exposure at 950 MHz, a frequency in the GSM900 DL band, are carried out. Using the methods presented in [11] and [17] the fields inside and surrounding the phantom can be determined for (realistic) exposure situations, using these simulations. In this study two exposure scenarios are considered: one realistic multipath environment: the 'Indoor Pico-cell' environment [11, 17] and one exposure scenario, named 'Angular Average'. This second scenario is chosen to compare numerical simulations with measurements using the calibration setup. In this scenario, a subject is under single plane wave exposure, with an elevation angle of the incident fields equal to 90° and an azimuth angle between 0° and 360°. Only two polarizations are considered in the 'Angular Average' scenario: vertical polarization (parallel to the phantom's/subject's rotation axis) and horizontal polarization (perpendicular to the phantom's/subject's rotation axis).

To model the positioning of a PEM, a surface at 1 cm from the phantom is determined. This surface is discretized by the FDTD algorithm and reduced further for computational purposes. There are no measurement points selected in front of the phantom's face and on the phantom's legs. Placement of a PEM on the phantom's head might seem unrealistic using the existing PEMs, but is feasible using newer technologies such as wearable and miniaturized antennas [12]. This reduction results in a set of 401 possible measurement positions on the upper body.

Calibration measurements in an anechoic chamber are executed using the same approach as the 'Angular Average' scenario. Two 25 year old male subjects wearing a personal exposimeter (subjects A and B) with a BMI of 22±1 kg/m are placed on a platform that is 1.4 m lower than the center of a transmitting horn antenna (TX). The platform is in the far-field of the TX (distance = 4.5 m) and the absorbing walls of the anechoic chamber ensure that there is only line of sight exposure. The TX is rotated so that both vertical and horizontal exposure can be recorded and emits between 920-960 MHz, the GMS900 DL band, at a constant input power. The subjects can be rotated over 360° in their transverse plane when standing in upright anatomical position. The PEM is worn on two positions with minimal separation from the body: on the left hip and the back.

Afterwards, free-space measurements of the electric field E_{RMS} are performed on different heights (h) of the rotation axis of the platform. These fields are measured using a spectrum analyzer (R&S FSL6) with a tri-axial antenna. The fields are measured at different heights because they should be averaged over the whole-body [1]. The free-space incident electric field (E_{RMS}^{free}) is determined from these measured electric fields using:

$$E_{RMS}^{free} = \sqrt{\frac{1}{h_{tot}} \int_0^{h_{tot}} E_{RMS}^2(h)\, dh} \qquad (1)$$

The studied quantity is the PEM's response (R): this is the ratio of the electric field recorded by the PEM (E_{RMS}^{PEM}) and the free-space incident electric field (E_{RMS}^{free}):

$$R = \frac{E_{RMS}^{PEM}}{E_{RMS}^{free}} \qquad (2)$$

Ideally a PEM should record E_{RMS}^{free} and R should thus equal 1. In this paper the distribution of R is studied using the the 95% confidence interval of R (c_{95}): the ratio of the 97.5% and 2.5% percentiles of R, and the interquartile distance (c_{50}) which is the ratio of the 75% and 25% percentiles of R.

III. Results and Discussion

A. Numerical Simulations

A set of 5000 exposure samples is generated in the 'Indoor Pico-cell' scenario using the methods presented in [11, 17]. This number of samples is associated with an average value of the 95% confidence interval on the percentiles of R smaller than 16 % (between the 1% and 99% percentiles).

The PEM's response R is determined for every sample in all studied measurement locations on the body. This results in a distribution of R in the 'Indoor Pico-cell' environment. The arithmetic average R_{av} and median value R_{median} of this distribution are listed in Table I. The average value of R_{av} at 1 cm from the body is 0.77, while the median value is 0.66. A PEM will thus on average underestimate the incident electric fields emitted in the GSM900 DL band.

TABLE I
Response of a single exposimeter at 950 MHz

	Indoor Pico-cell	*Angular Average*
frequency	*950 MHz*	
R_{av}	0.77	0.85
R_{median}	0.66	0.81
$C_{95,ideal}$*	[0.40,1.8] 12.9 dB	[0.47,1.4] 9.5 dB
$C_{95,realistic}$*	[0.16,2.06] 22 dB	[0.13,2.3] 25 dB
$C_{50,ideal}$*	[0.59,0.79] 2.6 dB	[0.70,0.96] 2.7 dB
$C_{50,realistic}$*	[0.44,1.0] 7.3 dB	[0.47,1.3] 8.8 dB

*The lower and upper boundaries of the intervals are provided between brackets; c_{95}= 95% confidence interval; c_{50}=interquartile distance.

Two analyses can be performed to estimate R and c_{95} for a measurement point on the body. In a first analysis the median values of 5000 simulated values in every studied point where a measurement could take place at 1 cm from the body are determined and divided by the corresponding E_{RMS}^{free}. This results in one median R value in every possible measurement point. The c_{95} and c_{50} of these R are measures for the variance in the recordings of a single PEM when it is worn on exactly the same unknown position (on the upper body) during all measurements. This can be interpreted as an intrinsic uncertainty using a perfect single PEM in an ideal measuring scenario.

Table I lists the $c_{50,ideal}$ and $c_{95,ideal}$ for PEMs at 950 MHz. Table I also lists the same characteristics for the 'Angular Average' exposure scenario.

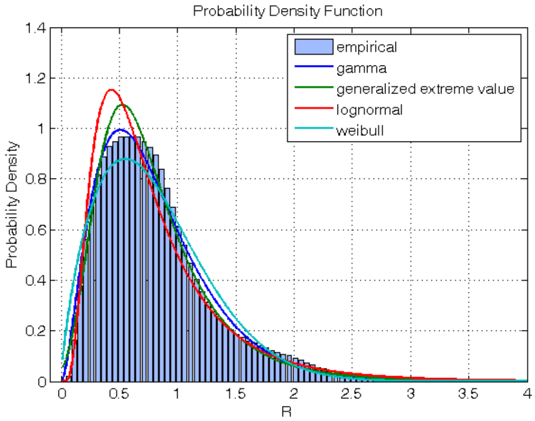

Fig. 1. *PDF of R for a single PEM at 1cm from the upper body of the VFM in the Indoor Pico-cell scenario at 950 MHz, together with the 4 best fits (in descending order) for a PEM.*

A second analysis can be performed to estimate a more realistic variation in R. Here no median value is calculated in every measurement point. R is calculated in every point for 5000 samples. The distribution of these samples is then studied. The c_{50} and c_{95} of these data are measures of the variance in the recordings of a single PEM when it is worn on varying unknown positions on the (upper) body. This can be interpreted as a more realistic estimate of variability using a single PEM, because in reality the PEM will never be worn on the same spot on the body by different subjects or even by the same subject when characterizing an environment. Figure 1 shows the probability density function (PDF) of all R values (all studied locations on the body and all exposure samples) at 1cm from the body. Four distributions are fitted to this data. A gamma function with a shape factor of 2.749 ± 0.005 and a scale factor of 0.2897 ± 0.0006 is found as a best fit for these data. In [6], a lognormal distribution was found as best fit to the electric-field strengths measured in a single point on the body. In [11] a lognormal distribution is fitted to the response of PEMs placed on different positions on the body. However, no other distributions are tested in [11]. The lognormal distribution is the third best parametric fit we found in this study. The incident electric field [11, 17] and the electric-field strengths on a single point on the body [6] are lognormally distributed but this does not imply that the responses in the set of multiple points located on the body considered in this study should also follow a lognormal distribution.

Table I lists the results for R, $c_{50,realistic}$, and $c_{95,realistic}$ in the 'Indoor Pico-cell' environment and as an 'Angular Average' at 950 MHz. The confidence intervals $c_{50,realistic}$ and $c_{95,realistic}$ are obviously considerably larger than $c_{50,ideal}$ and $c_{95,ideal}$. This underlines the importance of wearing a PEM on a fixed position on the body.

In [14] different possible locations of a PEM on the human body are investigated on a human body phantom in a simulated multipath environment at 946 MHz. This led to an R_{av} = 0.76, R_{median}= 0.7, which is in excellent agreement with our simulations. In the same study a $c_{50,realistic}$ and a $c_{90,realistic}$ of 8 dB and 18 dB, were determined, respectively. Our simulations show a $c_{50,realistic}$ and a $c_{90,realistic}$ of 7.3 dB and 19 dB on R in the 'Indoor Pico-cell' environment, which is in very good agreement with the values found in [14]. A $c_{95,realistic}$ of 18.5 dB is estimated for a single PEM at 900 MHz in realistic environments in [11], which is smaller than the c_{95} reported in this study. We attribute this difference to a smaller number of positions considered in [11]: only positions on the torso and back of the phantom, while the full upper body (without the face) is considered in this study.

The results of our numerical simulations, which are in good agreement with literature, show that a PEM will on average underestimate E_{RMS}^{free} and will estimate this E_{RMS}^{free} with a relatively large c_{50} and c_{95} in realistic scenarios. This means that a calibration on the body will be necessary.

B. Measurements

Calibration measurements are carried out in an anechoic chamber using the aforementioned methods, where the PEM is worn on two positions: the left hip and the back of two subjects. First, E_{RMS}^{free} is determined for the two polarizations of TX. An E_{RMS}^{free} of 0.18 V/m and 0.19 V/m are measured for horizontal and vertical polarization, respectively, with an input power of 10 mW at the TX. Both subjects (A and B) are rotated in the anechoic chamber under exposure at the same input power at TX. E_{RMS}^{PEM} is recorded as a function of the rotation angle, the two orthogonal incident polarizations, and the two different positions on the body. Fig. 2 shows a boxplot of the resulting PEM responses R for two subjects as a function of the position on the body. For every subject these values are also shown taking into account all samples measured in both positions. The red line indicates the median response, the blue box indicate the c_{50}, and the whiskers indicate the upper and lower adjacent values. Outliers in the measured responses are indicated by a red cross.

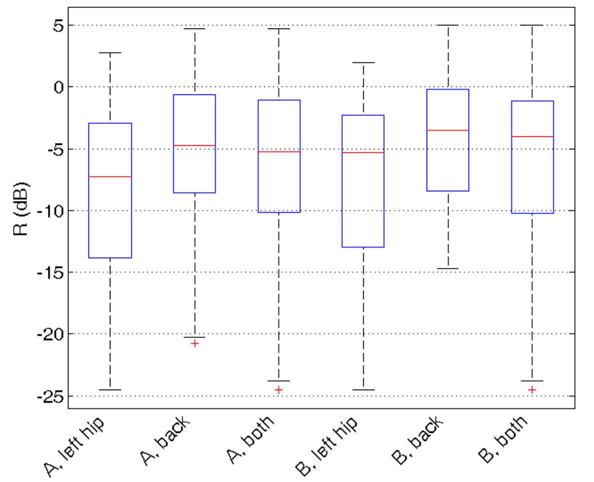

Fig. 2. *Boxplot of R for different measurement locations on two subjects under exposure in the GSM DL band.*

Fig. 2 shows that the results are comparable for both subjects. Regarding the individual positions the relative differences between the median values measured for both subject are smaller than 1.7 dB. Note that the subjects have a comparable BMI and the same age, so a small difference was expected. Table II shows the median values of R and the measured interquartile distances. The underestimation of the free space electric fields is smaller in subject B compared to subject A.

TABLE II

Calibration of a PEM worn by two subjects exposed in the GSM900 DL band

	Subject A			***Subject B***		
	Left hip	*back*	*both*	*Left hip*	*back*	*both*
R_{median}	0.45	0.58	0.55	0.55	0.66	0.62
c_{50}	11 dB	7.9 dB	9 dB	12 dB	8.2 dB	8.9 dB

The distribution of R for these two positions is also studied using (the same) numerical simulations of the VFM under exposure at 950 MHz in the 'Angular Average' scenario. Table III lists R_{median} and c_{50} for the VFM (a c_{95} could not accurately be determined in the measurements).

TABLE III

Response of a single PEM worn on the left hip and back of the VFM at 950 MHz in the 'Angular Average' scenario

	VFM	
	Left hip	*back*
R_{median}	0.83	0.78
c_{50}	10 dB	9.2 dB

The underestimation is larger than predicted by the FDTD simulations using the VFM for both subjects. For a PEM worn on the left hip R_{median}= 0.45 and 0.55 for subjects A and B, respectively, while it is 0.83 for the VFM. This is a difference of 5.3 dB between subject A and the VFM. The difference is smaller for the PEM located at the back R_{median}= 0.58 and 0.66 for subjects A and B, respectively, while it is 0.78 for the VFM (2.5 dB difference between subject A and the VFM). We attribute this to the fact that in numerical simulations the antennas in the PEM are considered perfect and will register the full E_{RMS}^{PEM} value, which in reality will not be the case, and the different morphology of the human subjects compared to the VFM. Moreover, some of the radiation emitted by the TX will be recorded in other bands than the GSM900 DL band by the PEMs [18], which will also lower the response.

For subject A, the difference between R_{median} measured on the left hip and on the back is 2.5 dB, while for subject B this is 1.8 dB. This is larger than the difference of 0.54 dB found for the VFM. However, the c_{50} measured for both subjects are in excellent agreement with those found for the VFM: for example, c_{50} = 11 dB and 12 dB for a PEM worn on the left hip of subjects A and B, while c_{50} = 10 dB for a PEM on the left hip of the VFM. The FDTD simulations using the VFM will give a good estimation of the variance of R (difference in c_{50} < 2 dB), but might not be accurate in predicting the underestimation of a PEM. To compensate for underestimation by the PEM, calibration measurements on the body will be necessary.

The interquartile distances determined for the measurement results where both sensors are considered (see Table II), are comparable to the interquartile distances determined using FDTD simulations in the same environment (8.8 dB). In [13] a PEM on a subject's hip was calibrated in an open area test site for two incident polarizations, this resulted in a c_{50} of 6.5 dB and 15.5 dB for horizontally and vertically polarized incident fields, respectively. These values are of the same order of magnitude as the values we measured for a PEM worn on the left hip in this study: 5.3 dB and 19 dB, for horizontally and vertically polarized incident electric fields recorder by a PEM worn by subject A and 4.4 dB and 18 dB for horizontally and vertically polarized electric fields recorded by a PEM worn by subject B. A median underestimation of the incident electric field was measured in [13] as well: R_{median} = 0.85 and 0.48 for horizontally and vertically polarized incident electric fields, respectively. For subject A these values are 0.55 and 0.31, while for subject B these are 0.60 and 0.29, for horizontally and vertically polarized incident electric fields. We thus observe the same difference between both polarizations. An (unwanted) polarization dependence of the PEM. However, the median responses measured in this study are lower than those measured in [14]. This difference in median response is attributed to the different subjects used in this study.

IV. Conclusions

The response (R) of personal exposimeters (PEMs) in the GSM900 downlink (DL) band is studied using finite-difference time-domain simulations using a heterogeneous phantom and calibration measurements using two male subjects. The numerical simulations show that a PEM, on average, underestimates the incident electric fields and that R has a relatively large 95 % confidence interval: 22 dB in a realistic environment is found using numerical simulations. The calibration measurements also show that a PEM will underestimate the incident electric fields in the GSM900 DL band. The measured interquartile distance of the PEMs' responses is in good agreement (differences smaller than 2 dB) with the ones found using FDTD simulations.

V. References

[1] International Commission on Non-Ionizing Radiation Protection, "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)", *Health Physics* 74: 494-522, 1998.

[2] World Health Organization, "WHO Research Agenda for Radiofrequency Fields", Switzerland, 2010.

[3] Bolte JFB, Eikelboom T, "Personal radiofrequency electromagnetic field measurements in the Netherlands: Exposure level and variability for everyday activities, times of day and types of area", *Environment International* 48: 133-142, 2012.

[4] Frei P, Mohler E. Neubauer G, Theis G, Burgi A, Frohlich J, Braun-Fahrlander C, Bolte J,Egger M, Roösli, M, "Temporal and spatial variability of personal exposure to radiofrequency electromagnetic fields", *Environmental Research* (109):779–785, 2009.

[5] Joseph W, Vermeeren G, Verloock L, Heredia MM, Martens L, "Characterization of personal RF electromagnetic field exposure and actual absorption for the general public", *Health Phys* 95(3):317-30, 2008.

[6] Joseph W, Vermeeren G, Verloock L, Martens L, "Estimation of whole-body SAR from electromagnetic fields using personal exposure meters", *Bioelectromagnetics* 31(4): 286-295, 2010.

[7] Neubauer G, Feychting M, Hamnerius Y, Kheifets L, Kuster N, Ruiz I, Schuz J, Uberbacher R, Wiart J, Röösli M, "Feasibility of future epidemiological studies on possible health effects of mobile phone base stations", *Bioelectromagnetics* 28:224-230, 2007.

[8] Röösli M, Frei P, Mohler E, Braun-Fahrländer C, Burgi A, Fröhlich J, Neubauer G, Theis G, Egger M, "Statistical analysis of personal radiofrequency electromagnetic field measurements with nondetects", *Bioelectromagnetics* 29(6):471-8, 2008.

[9] Röösli M, Frei P, Bole J, Neubauer G, Cardis E, Feychting M, Gasjek P, Heinrich S, Joseph W, Mann S, Martens L, Mohler E, Parslow RC, Poulsen AH, Radon K, Schüz J, Thuroczy G, Viel J, Vrijheid M, "Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol", *Environmental Health* 2010, 9-23, 2010.

[10] Iskra S, McKenzie R, Cosic I, "Factors influencing uncertainty in measurement of electric fields close to the body in personal RF dosimetry", *Radiat Prot Dosimetry* 140 (1): 25-33, 2010.

[11] Iskra S, McKenzie R, Cosic I, "Monte Carlo simulations of the electric field close to the body in realistic environments for application in personal radiofrequency dosimetry", *Radiat Prot Dosimetry* 147(4): 517-527, 2011.

[12] Thielens A, De Clerq H, Agneessens S, Lecoutere J, Verloock L, Declerq F, Vermeeren G, Tanghe E, Rogier H, Puers R, Martens L, Joseph W., "Distributed on Person Exposimeters for Radio Frequency Exposure Assessment in Real Environments", Bioelectromagnetics 34 (7): 563-567, 2013.

[13] Bolte J.F.B., Van der Zande G., Kamer J, "Calibration and uncertainties in personal exposure measurements of radiofrequency electromagnetic fields", *Bioelectromagnetics* 32(8): 652-663, 2011.

[14] Neubauer G, Cecil S, Giczi W, Petric B, Preiner P, Fröhlich J, Röösli M, "The association between exposure determined by radiofrequency personal exposimeters and human exposure: a simulation study", *Bioelectromagnetics* 31: 535-545, 2010.

[15] Christ A, Kainz W, Hahn EG, Honegger K, Zefferer M, Neufeld E, Rascher W, Janka R, Bautz W, Chen J,Kiefer B, Schmitt P, Hollenbach HP, Shen J, Oberle M, Szczerba D, Kam A, Guag JW, Kuster N, "The Virtual Family - development of surface-based anatomical models of two adults and two children for dosimetric simulations", *Phys Med Biol* 48:N23-N38, 2010.

[16] Gabriel C, Gabriely S, Corthout E, The dielectric properties of biological tissues, *Phys Med Biol* 41: 2231-2293, 1996.
[17] Vermeeren G, Joseph W, Olivier C, Martens L, “Statistical multipath exposure of a human in a realistic electromagnetic environment”, *Health Physics* 94: 345 – 54, 2008.
[18] Lauer O, Neubauer G, Röösli M, Riederer M, Frei P, Mohler E, Fröhlich J, “Measurement setup and protocol for characterizing and testing Radio Frequency Personal Exposure Meters”, Bioelectromagnetics 33, 75-85, 2012.