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Low EMF Exposure Future Networks

D2.1 Current metrics for EMF exposure evaluation

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Abstract	This deliverable provides an overview of current metrics and methods to assess exposure to radio-frequency electromagnetic fields as found in science, standards, and regulations. This deliverable serves as basis for the global exposure index developed within the LEXNET project.
Key words	Exposure metrics, specific absorption rate, power density, electric field, magnetic field, electromagnetic field, dose

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Executive Summary

LEXNET aims at reducing the total human exposure to radio-frequency electromagnetic fields used for cellular and wireless local area networks in the frequency range of 700 MHz to 6 GHz without compromising the user's perceived quality. A key task in the project is the definition of the global exposure index which will take into account downlink as well as uplink exposure. The present deliverable D2.1 will serve as basis for the definition of the global exposure index by providing an overview of current exposure metrics.

Deliverable 2.1 discusses current metrics as well as the methods used for the assessment of exposure to radio-frequency electromagnetic fields. In addition, this deliverable highlights differences in regulation across several European countries.

We divided the current exposure metrics into four categories: (1) incident field metrics (such as electric field, magnetic field and power density), (2) exposure ratios (which are a measure for the proportion of the exposure of a single wireless communication technology into the total exposure), (3) absorption metrics (specific absorption rate), and (4) dose metrics (this metric takes the time into account by multiplying the absorption or incident field metric with time).

Different methods exist to assess the exposure depending on the aim of the assessment. In general, compliance testing aims at worst-case exposure assessment, while epidemiological studies focus at realistic exposure assessment.

Finally, this deliverable also discusses the different devices currently used to measure the exposure: broadband probes, spectrum analyzer combined with tri-axial probe, and dosimeters (used for personal exposure assessment).

1 INTRODUCTION

This report gives an overview of current metrics for evaluating radio-frequency (RF) electromagnetic field (EMF) exposure in the frequency range of 700 MHz to 6 GHz. In this frequency range, several quantities are used to express exposure: incident field levels (E and H), incident power density (S) and specific absorption rate in the human body (SAR) are the most common quantities. International guidelines issued by the international commission on non-ionizing radiation protection (ICNIRP) and the federal communications commission (FCC) limit the levels of these quantities to protect people against adverse health effects from exposure to EMF. Basic measures to protect people from exposure to EMF are independently defined for the base station (BS) and for the personal mobile devices. On the one hand, we have compliance testing for base station (BS) when put into service, which means a lot of measurements in the vicinity of base station locations. On the other hand, we have compliance testing for personal devices, which leads to defining maximum transmitting power of the device. In neither case realistic exposure is assessed. Recently, new quantities are defined in scientific literature, such as dose and exposure ratios, to determine realistic exposure of people to RF EMF. The nature of electromagnetic fields (frequency, intensity, duration of exposure) offers a large variety of quantities which can be used as exposure metrics [1]. Moreover, a wide range of exposure conditions can exist: individual or multiple source exposure, near- or far-field exposure, short- or long-term exposure, etc. So far, multiple methods to assess the exposure are present in the epidemiological literature.

First, we will discuss the most often used quantities and mention their usage. Next, we will give an overview of the current methods for assessing these metrics. Finally, we will discuss differences in metrics encountered in science, guidelines, standards and regulations across Europe.

2 POWER DENSITY, ELECTRIC FIELD AND MAGNETIC FIELD

The exposure to incident radio-frequency electromagnetic fields is assessed in terms of power density, electric field and / or magnetic field. These quantities are easy to measure as opposed to the induced fields in a human body.

2.1 Definition

In the far-field of a source, the power density, electric field and the magnetic field are related through the characteristic impedance in free space:

$$S = \frac{E_{\mathrm{rms}}^2}{Z_0} = Z_0 H_{\mathrm{rms}}^2 \tag{1}$$

with Z_0 the characteristic impedance in free space, E_{rms} the root-mean-squared (RMS) electric field and H_{rms} the RMS magnetic field.

2.2 Methods of assessment

When assessing the exposure the aim can be twofold: (1) to test if the field strengths comply with exposure limits, and (2) to assess the typical exposure of a person which is mainly of interest for epidemiological studies.

The assessment also depends on the measurement position with respect to the antenna(s), scatterers and absorbers. In the far field of an antenna, scatterers and absorbers, it is sufficient to measure the incident electric field or the power density. However, in the near field of an antenna the magnetic field also has to be measured because there the electric and magnetic field are not related by the free-space impedance.

The exposure to incident electromagnetic fields (in the further text “incident exposure”) is mainly assessed by measurements. Broadband and frequency-selective measurement equipment is typically used for in-situ measurements. In epidemiological studies incident exposure is mainly assessed by personal exposure meters (PEM). (PEMs are usually denoted as "dosimeters" and in the following text both terms will be used interchangeably.) Numerical investigation of the incident exposure is limited. 3D ray-tracing tools are used to predict the exposure in a certain area during the network design stage. In the near field of antennas, such as base station antennas, 3D electromagnetic solvers are employed to investigate the incident exposure. Simulations provide detailed information of the field distribution around and inside the body, but numerical tools have the drawback of always being an approximation of the real world and often require long runtimes and large amount of processing power.

2.2.1 Broadband vs narrowband

Radio-frequency electromagnetic fields span a wide range of frequencies. Cellular and local area networks typically operate in the frequency range from 700 MHz to 6 GHz. Every communication technology operates in its designated frequency band. When measuring the exposure, we distinguish between broadband and narrowband measurements. Broadband measurements span several GHz at once and are performed using a field meter and a broadband probe. A single exposure value is obtained for the whole frequency range. Narrowband measurements are band-selective or frequency-selective measurements using a combination of an antenna (e.g., conical dipole or tri-axial isotropic antenna) and spectrum analyzer. In case of narrowband measurements, an exposure value is obtained for each of the considered frequency bands. Frequency-selective measurements allow identifying the importance of a communication technology in the total exposure.

In epidemiological studies personal exposure meters are used. PEMs are also narrowband devices that measure the exposure in multiple bands at the same time. Commercially available PEMs are the EME Spy 120/121/140 (Satimo, Brest, France [2,3]) and the ESM 140 (Maschek Elektronik, Bad Wörishofen, Germany [4]). These devices are worn by a person to assess the personal exposure to RF EMF. Personal exposure meters are easy to handle but require a measurement protocol [5,6], have a limited dynamic range with a maximum value of typically 5 V/m, and suffer from a large number of measurements below the detection limit (non-detects) of the device. To handle these large number of non-detects in data analysis, Roösli [7] et al propose the robust regression on order statistics (robust ROS) to determine summary statistics.

2.2.2 Temporal variations

Temporal variations and measurement procedures for temporal exposure assessment due to RF signals are investigated in [8–12]. In [11], the daily distribution of the RF field strength is determined for FM Broadcasting (FM), Television (TV), Global System for Mobile Communications (GSM900 at 900 MHz and GSM1800 at 1800 MHz), Universal Mobile Telecommunications Systems (UMTS) and High Speed Downlink Packet Access (HSDPA) services. The proposed method assigns to the different signals a conservative extrapolation factor to determine the maximum real exposure during a day using a statistical method developed on different measurements performed over 24h. Erlang data, representing average mobile phone traffic intensity during a period of time, is related to RF exposure using temporal measurements during a week in [9]. Diurnal variations of fields of mobile telecommunication and broadcasting systems are studied in [12].

2.2.3 Averaging

The incident exposure varies in time and space. Different methods exist to assess average exposure as well as peak exposure values. In addition, a weighted-average field level is appropriate for optimization purposes.

2.2.3.1 Spatial averaging

The peak-spatial exposure can be assessed by sweeping an area or by taking the maximum value in a given area (raster). In the sweeping method, a small area (volume) is scanned for maxima, with the antenna being moved in every direction and polarization, and connected to a spectrum analyzer on maximum-hold [13–16]. In the raster method, a number of spot measurements are performed in a given raster (area), after which the maximum field value is retained [14].

To assess the whole-body exposure according to CENELEC standard EN 50492 [8], a field-averaging protocol is required. The isotropic field values shall be determined at N measurement points. For measurements in special environments, e.g. in kindergartens or bedrooms, additional measurements may be performed at alternative locations in an adequate manner. Three measurement points are recommended, but depending on the location (relative to the measurement point) and the accuracy required, the number of measurement points to average may be increased to six. The uncertainty of the estimation of the mean value with three measurement points is about 3 dB, uncertainty with six measurement points is about 2 dB.

IEC 62232 [17] defines measurement grids for reference spatial-average measurements and alternative spatial-average measurements. The grids are shown in Figure 1.

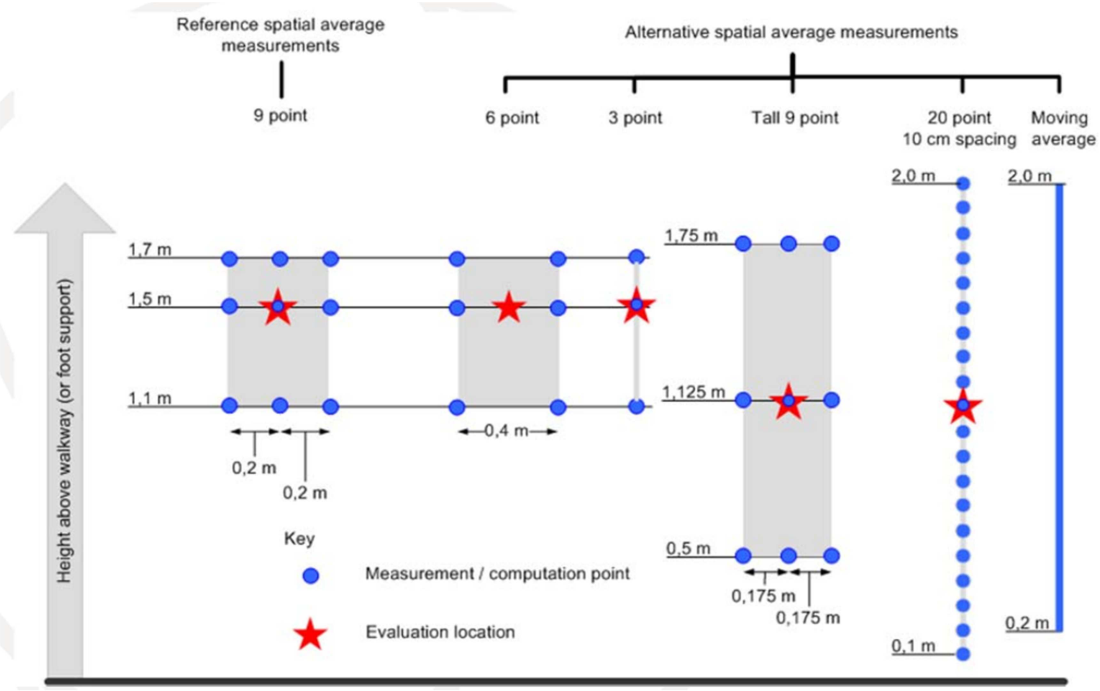
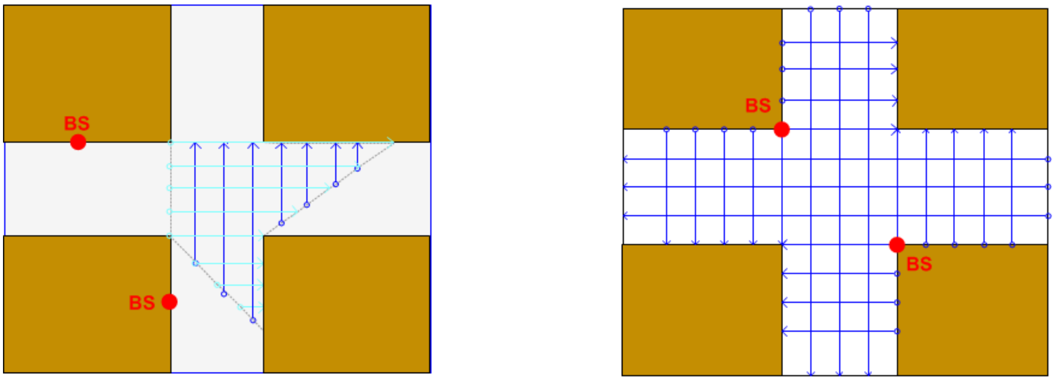


Figure 1: Measurements grids for spatial averaging in IEC 62232.

The Portuguese monIT Project developed a practical method to assess compliance with exposure to the E-field thresholds in the presence of multiple radiation sources. A spatial analysis grid is defined according to the position of the sources, as seen in Figure 2 [18].



(a) (b)

Figure 2: Examples of analysis grid for (a) non-line of sight (NLOS) and (b) line of sight (LOS) (extracted from [18])

2.2.3.2 Time averaging

ICNIRP specifies a time-averaging period of 6 minutes for the squared RMS field levels (E^2_{rms}, H^2_{rms}, and B^2_{rms}) and the power density (S) [19]. FCC specifies a 6 minutes averaging period for occupational exposure and 30 minutes (or no averaging time if this would prove impractical) for general population exposure for the squared

RMS electric field (E_{rms}^2) or the power density (S) [20]. However, in practice, the averaging time is shortened to less than one minute [21].

2.2.4 Weighted field level

Plets et al. [22] defined an exposure metric for minimizing the exposure in indoor office environments. The exposure metric E_M equals the average of the median electric-field strength (E_{50}) and the 95%-percentile value (E_{95}) of the field strengths in the building:

$$E_{\mathrm{M}} = \frac{w_1 E_{50} + w_2 E_{95}}{w_1 + w_2} \tag{1}$$

with w_1 and w_2 weighting factors for the 50%-percentile value E_{50} and the 95%-percentile E_{95}, respectively. E_{50} accounts for the median exposure on the building floor, and E_{95} accounts for the maximal exposure values. They assume an equal impact of E_{50} and E_{95} on the metric by setting both weighting factors equal to 0.5.

2.3 Implementation in science, guidelines, standards and regulations

2.3.1 In science

2.3.1.1 Compliance testing versus assessment of realistic exposure

In compliance testing the aim is to evaluate the maximum possible exposure and compare it with reference levels. This assumes transmitters operating at maximum power, the traffic load of BSs is at maximum and the measurements are focused on peak field values, which often lead to overestimation. Also, in compliance testing expanded uncertainty with a confidence interval of 95 % must be added to measurement results.

Realistic exposure can be measured by different means: spot measurements with spectrum analyzer [13,16,23–25] or personal exposure measurement campaigns [6,26–37].

2.3.1.2 Exposure prediction models

Exposure measurements can be combined with theoretical prediction models for optimization and validation of the exposure. These theoretical models rely heavily on base station parameters and use personal exposure meter [38–41] or spectrum analyzer measurements [42,43]. These models assist in interpolating dosimeter [44,45] or broadband measurements [46] at randomly, uniformly or sequentially chosen locations.

2.3.2 In regulations

In [47], Stam distinguishes three approaches for the EMF policies within the member states of the European Union: (1) the Recommendation transposed in binding national legislation, (2) the limits based on the Recommendation or ICNIRP are not binding, and (3) stricter limits then the Recommendation or ICNIRP.

In France, public exposure to EMFs is regulated by the decree n°2002-775 of 3 May 2002, which adopts the European Council recommendation on the limitation of public exposure to EMFs based on ICNIRP guidelines. Nevertheless some cities like Paris have adopted specific charters on base stations deployment defining average EMF exposure levels of Parisians.

In Belgium, every region (the Flemish region, the Walloon region, and the Brussels-Capital region) defined its own exposure limits, which are amongst the most restrictive requirements throughout the world. But, there are many exceptions [48]. In the Flemish region, the exposure limit at 900 MHz equals 3 V/m per antenna at residences and 20.6 V/m for cumulative exposure since January 2011 [49]. In the Brussels-Capital region, an exposure limit of 3 V/m at 900 MHz was proposed in 2007 [50] for all locations. In April 2014 this limit was increased to 6 V/m at the reference frequency of 900 MHz [51]. The limit accounts for the total exposure radiated by almost all transmitting antennas with a large number of exclusions. The limit became valid in September 2009 [52]. In residences in the Walloon region, an exposure limit of 3 V/m per operator and per antenna is valid since April 2009 [53]. In contrary to the Brussels-Capital region, there is no limit for the total exposure (radiated by all antennas) measured at an arbitrary location.

Portugal adopted the European Council Union recommendation relatively to the limitation of public exposure to EMFs [54] based on ICNIRP’s guidelines. The Portuguese regulations are mandatory according to Law No. 151-A/2000 of 20 July 2000 [55].

Serbia regulates this area by the “Law on Non-Ionizing Radiation Protection” (Official Gazette of the Republic of Serbia No. 36/2009) and several Regulations under this low. “Regulation on limits of exposure to non-ionizing radiation” (Official Gazette of the Republic of Serbia No. 104/2009) defines basic restrictions and reference levels described by the same functions but more strict than ICNIRP. According to this regulation, reference level at 900 MHz equals to 16.5 V/m for residential areas, schools, homes, preschools, maternity wards, hospitals, tourist facilities and playgrounds. By the “Regulation of non-ionizing radiation sources of interest, the types of source, the method and time of their testing” (Official Gazette of the Republic of Serbia No. 104/2009) requirements for measurement in the vicinity of base stations is defined. This law and related regulations were adopted in 2009.

In Spain, public exposure to EMFs is regulated by Royal Decree 1066/2001 of 28 September 2001 [56], which adopts the criteria established in the European Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields. Additionally, the Spanish regulation provides guidelines for the periodic technical assessment and monitoring of the exposure levels by both operators and public authorities.

In Montenegro the “Low on Non-Ionizing Protection” has been adopted. However, it will be applied as from 1st July 2015. In the meantime, special working groups have been working on necessary bylaws that will among other things precisely define the limits for EMF levels taking into account sources per frequency ranges, still not for SAR. At the moment, old ex-Yugoslavia standards, more strict than the EU ones, are applied. These standards give just limits for the cumulative EMF levels without making any difference with respect to the sources of EMF or the operational frequency ranges. The measurements procedures for EMF levels are based upon ECC Recommendation (02)04 (“Measuring non-ionising electromagnetic radiation“).

Exposure limits for the remaining European countries as well as countries outside the European Union are thoroughly discussed in [47].

Table 1: Radio-frequency exposure limits at 900 MHz within the member states Belgium, France, Montenegro, Portugal, Serbia, and Spain of the European union.

Country / Region	**Limit on the RMS E-field strength (V/m)**
Belgium	
Flemish Region	3 V/m (per antenna in residences)
	20.6 V/m (cumulative exposure, outdoor)
Brussels-Capital region	6 V/m (cumulative exposure)
Walloon region	3 V/m (per operator and per antenna in residences)
France	41.25 V/m
Montenegro	27.45 V/m (cumulative exposure)
Portugal	41.25 V/m
Serbia	16.5 V/m
Spain	41.25 V/m

3 EXPOSURE RATIOS

In case of multiple-source exposure, other metrics can be defined, based on the contribution of each source to the total exposure. Guidelines and standards, such as ICNIRP [19] and CENELEC [57], defined ratios to evaluate compliance in case of simultaneous exposure to fields of different frequencies.

Other definitions of exposure ratios are found in scientific literature. The authors in [25], or in [58], provide exposure ratio metrics, like the average contribution (AC), and the maximal contribution (MC) of different sources to the total exposure value. For instance, for power density, the AC and the MC contributions of each signal to the total exposure, are defined as follows, for $X = AC$ or MC:

$$X = u\left(\frac{S_{signal}}{S_{tot}}\right) 100\ [\%] \tag{8}$$

where u( ) is a function of S for a RF signal (e.g., GSM, LTE, …), i.e., S_{signal}, and S_{tot} is the total exposure due to all RF signals at the measured point.

4 SPECIFIC ABSORPTION RATE (SAR)

The specific absorption rate (SAR) is a measure for the induced electromagnetic fields inside the human body. The SAR is defined as:

$$SAR(r) = \frac{\sigma(r)E_{\mathrm{rms}}(r)^2}{\rho(r)} \tag{2}$$

with σ the conductivity (S/m) and ρ the mass density (kg/m^3).

4.1 Whole-body averaged SAR (wbaSAR)

The whole-body averaged SAR is the basis for the ICNIRP reference levels on the exposure. Hazardous exposures may occur above a whole-body averaged SAR value of 4 W/kg, as averaged over the entire mass of the body.

4.1.1 Methods for assessment

The whole-body averaged SAR can be assessed in closed environments (i.e., rooms) by measuring the reverberation time with and without people inside the room. From the difference in reverberation time, the whole-body SAR can be calculated [59]. This measurement methodology is based on room electromagnetics theory [60].

Measuring the induced fields is impossible in a living human. Therefore we have to turn to numerical analysis for characterizing the whole-body SAR in a human. Characterizing the SAR in the human body requires realistic models of humans. A number of realistic heterogeneous body models are currently used for electromagnetic field simulations, consisting of large datasets obtained from Magnetic Resonance Imaging (MRI), Computer Tomography (CT), and anatomical images. Data is represented by voxel images of thin slices of the body, and each voxel corresponds to a particular type of the body tissue. An example of heterogeneous body models are those from a Virtual Family [61]. The various tissue electric parameters can be obtained (i.e., for required frequency band) from the 4-Cole-Cole Model described in [62]. Several human models are developed especially during the last decade. The Virtual Family [61] and Virtual Class Room [61] are a family of magnetic resonance imaging (MRI) models. There are also the Japanese models (male and female model [63]), Korean models [64,65], Chinese adult models (male and female models [66]), Norman and Naomi models [67,68], Zubal adult model and Visible human model [69,70].

4.1.2 Averaging

The wbaSAR is averaged spatially over the mass of the body (M) and, hence, equals the ratio of the total absorbed power in the body and the mass of the body – this mass averaging is also used for calculating the peak-spatial SAR (IEEE-C95.3). The wbaSAR is given by:

$$wbaSAR = \langle SAR \rangle_M = \frac{1}{M}\int_R SAR(r)dm = \frac{1}{M}\int_R \sigma(r)E_{\mathrm{rms}}(r)^2 dV = \frac{P_{\mathrm{abs}}}{M} \tag{3}$$

with M the total mass of the human body model, V the total volume of the tissues of the human body model, and R the region of the body.
For comparison with ICNIRP guidelines the wbaSAR is averaged over a 6 minute period.

4.1.3 Implementation in science, guidelines, standards and regulations

Science distinguishes between compliance testing and realistic or typical exposure. Compliance testing in terms of whole-body SAR is solely performed using numerical techniques, such as 3D electromagnetic solvers. For example the whole-body SAR induced in mast workers exposed in front of the base station antenna. Recently, Bamba et al [59] developed a methodology to assess experimentally the whole-body SAR in a closed environment (indoor) based on the room electromagnetics theory.

ICNIRP [19] and FCC guidelines specify a limit on the whole-body SAR of 0.4 W/kg for occupational exposure and of 0.08 W/kg for general public exposure.

4.2 Peak-spatial averaged SAR

Exposure guidelines not only limit whole-body absorption but also localized absorption. Compliance to these guidelines requires compliance to both limits and basic restrictions.

4.2.1 Methods for assessment

Evaluating the compliance of RF mobile devices can only be performed in certified laboratories equipped with a dosimetric measurement setup. This dosimetric setup consists of a dosimetric probe (calibrated for measuring electric fields in tissue-simulating liquid), a phantom filled with tissue-simulating liquid and a robot for moving the probe in the tissue. During compliance testing the RF mobile devices are driven in a test mode and radiate at maximum power.

Certification of mobile devices requires measurements, but numerical methods, such as the popular finite-difference time-domain technique, are used to investigate and characterize the localized SAR in (realistic) human body models under different exposure conditions.

4.2.2 Averaging

Guidelines on EMF exposure define the duration of averaging and the averaging mass. In Europe, the SAR is averaged over a 6 minute period and over any 10 g of contiguous tissue according to the ICNIRP guidelines [19]. Standards [71,72] describe the procedures for compliance testing and calculating the localized SAR (e.g., how to build a ten gram cube of tissue).

4.2.3 Implementation in science, guidelines, standards and regulations

The European Commission adopted the limits proposed in the ICNIRP guidelines. ICNIRP distinguished between the head and trunk region and the limbs. In the head and the trunk of the body – where the most vital organs reside – the basic restriction on the peak SAR in 10 g of tissue is 2 W/kg. In the limbs, the basic restriction is 4 W/kg. These values apply to general public exposure. For occupational exposure, the limits are 5 times larger, i.e. 10 W/kg in the head and trunk, and 20 W/kg in the limbs.

4.3 Organ-specific averaged SAR (osaSAR)

The organ-specific averaged SAR ($osaSAR$) is defined as the mass average of the SAR in a certain organ or tissue in the (human) body and is used to study the localization of absorption of electromagnetic fields in the body.

4.3.1 Methods for assessment

The organ-specific SAR can only be assessed by numerical simulations.

4.3.2 Averaging

The osaSAR is averaged spatially over the mass of a certain organ or tissue in the body (M_{organ}). The osaSAR is given by [73]:

$$osaSAR = \frac{1}{M_{\text{organ}}} \int_{\text{organ}} SAR(r)dm = \frac{1}{M_{\text{organ}}} \int_{\text{organ}} \sigma(r)E_{\text{rms}}(r)^2 dV = \frac{P_{\text{abs}}}{M_{\text{organ}}} \quad (4)$$

4.3.3 Implementation in science, guidelines, standards and regulations

The organ-specific SAR only recently gained interest from the scientific community. Hence, only a limited number of publications are available in literature. Studies investigating the organ-specific SAR were conducted for near-field exposure conditions [74–77], exposure from base-station antennas [78,79], single-incident plane wave exposure [80] and realistic exposure in multi-path environments [73,81,82].

4.4 SAROTA

The recent trend towards assessment of real exposure induced by devices motivates the need for a comparative metric evaluating both exposure and radiating performances of the device. Indeed, while maximum SAR is relevant for compliance assessment, the real SAR is closely related to the radiated power of the device which is controlled by the connected base station.

The base station controls the power emitted by the mobile to ensure a satisfying signal-to-noise ratio (called the Ec/N0_target) and a good received power (Ec). The mobile emitted power is monitored using an algorithm called the power control. In this case, the gain and the radiation pattern become very important as this can affect the power received at the base station level.

The idea behind this approach is to avoid comparing mobiles considering the maximum SAR but to introduce the gain as an important parameter that should be taken into account to efficiently and fairly compare devices in terms of real exposure.

In this scope, a new metric named SAR_{ota} is being prepared by France Telecom. It is defined as:

$$SAR_{OTA}^{UL}\ (\text{W/kg}) = \frac{SAR_{norm}^{UL}}{\text{G}\ (\theta,\varphi)}\ (\text{W/kg}) \quad (5)$$

The methodology was applied and tested for comparing two different mobile phones and it shows that the mobile compensate lower gains by a higher transmitted power (see figure below) as soon as the power does not reach the maximum. Figure 3 shows that, depending on the mobile phone gain, the variation of the mobile phone SAR with the radiated power can be completely different. On the figure on the left, when the gain of Mobile 1 is less than the gain of Mobile 2, whatever the radiated power, the SAR of Mobile 1 is always higher than the SAR of Mobile 2 and inversely when the gain of Mobile 1 is greater than the gain of Mobile 2.

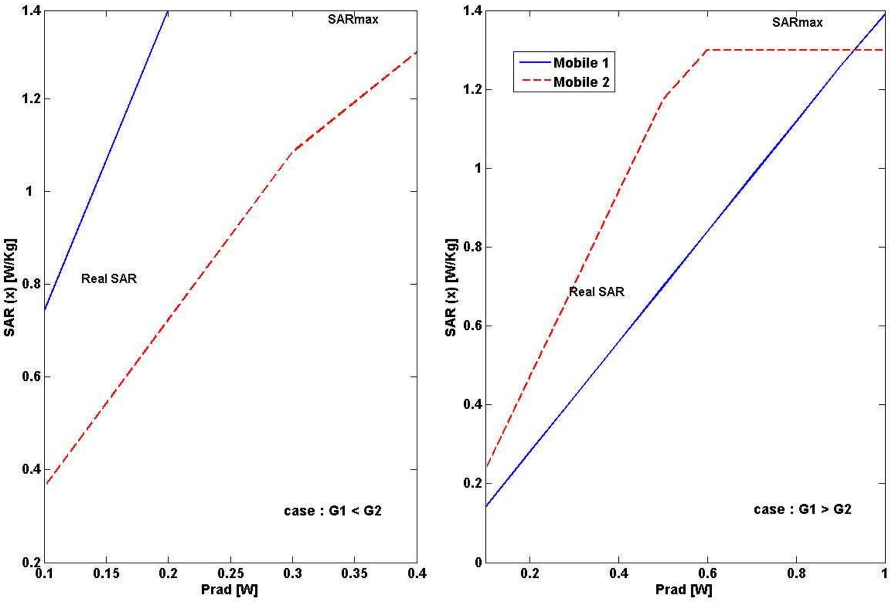


Figure 3: SAR evolution as a function of the radiated power for two different mobiles phones (Mobile 1 and 2) with different maximum average SAR values over 10g of tissues ($SARmax_{mobile1}$ > $SARmax_{mobile2}$) in two cases: the gain of mobile 1 (G1) is less than the gain of mobile 2 (figure on the left) and G1 is greater than G2 (figure on the right)

Furthermore, authors in [83] discuss the designing conditions to achieve optimum SAR and OTA performances, and present some preliminary results. A similar approach is followed in [84], taking into account the effect of the user’s hand.

4.5 SAR/kbps

The SAR/kBps, [85], can be calculated (e.g., for the maximum data throughput rates of the system) in order to normalize the subsequently determined SAR results obtained for the individual communication systems as proposed by Federal Office of Public Health (FOPH) in Switzerland.

5 DOSE

A recent trend in EMF exposure assessment is to take into account the exposure time (t), using as the metric, the actual absorbed dose.

5.1 Dose based on SAR : Dose = SAR * t

Multiplying wbaSAR or psaSAR (W/kg) with the exposure time, T_{exp} (s), results in an actual absorbed dose (J/kg). This has been done by Aerts et al. [86] and Lauer et al. [87]. Using dose as exposure metric has the advantage that (whole-body) exposure to downlink and uplink sources can be added and compared for various scenarios.

5.1.1 Methods for assessment

The SAR values are simulated [87], or calculated from power measurements performed with a mobile device (performed using specific tools or applications on the mobile), as in [88], and using additional formulae found in [89].

The whole-body averaged dose, D_{wba}, can be split in two contributions: the dose due to uplink exposure (D_{UL}) and the dose due to downlink exposure (D_{DL}).

The SAR_{wba} due to downlink exposure (e.g., from a base station or transmitter antenna) can be calculated as follows:

$$SAR^{\mathrm{DL}}_{\mathrm{wba}}\ (\text{W/kg}) = \frac{S_{\text{inc}}\ (\text{W/m}^2)}{1\ (\text{W/m}^2)} \times SAR^{\mathrm{DL}}_{\mathrm{wba,\,norm}}\ (\text{W/kg}), \tag{6}$$

with S_{inc} the incoming power density (which can be calculated from the received power of e.g., a mobile device), and $\text{SAR}^{\text{DL}}_{\text{wba, norm}}$ the normalized (to a power density of 1 W/m^2) SAR_{wba} due to exposure to the specific downlink signal.

The downlink dose, D_{DL}, is then

$$D_{\mathrm{DL}}\ (\text{J/kg}) = SAR^{\mathrm{DL}}_{\mathrm{wba}} \times T_{\mathrm{exp}}, \tag{7}$$

with T_{exp} the total exposure time to the downlink signal.

The SAR_{wba} due to uplink exposure (e.g., from a mobile phone) can be calculated as follows:

$$SAR^{\mathrm{UL}}_{\mathrm{wba}}\ (\text{W/kg}) = \frac{TX\ (\text{W})}{1\ (\text{W})} \times SAR^{\mathrm{UL}}_{\mathrm{wba,\,norm}}\ (\text{W/kg}), \tag{8}$$

with TX the power emitted by the source, and $\text{SAR}^{\text{UL}}_{\text{wba, norm}}$ the normalized (to an output power of 1 W) SAR_{wba} due to exposure to the source's uplink signal.

The uplink dose, D_{UL}, is then

$$D_{\mathrm{UL}}\ (\mathrm{J/kg}) = SAR^{\mathrm{UL}}_{\mathrm{wba}} \times T_{\mathrm{use,}} \tag{9}$$

with T_{use} the total time of the uplink activity of the device.

Finally, the total whole-body averaged dose is $D_{wba} = D_{UL} + D_{DL}$.

In case of localized exposure (e.g., to the uplink radiation of a device), the dose, D_{loc}, can be calculated as follows:

$$D_{\mathrm{loc}} = T_{\mathrm{use}} \times SAR_{\mathrm{psa}} \times \frac{p_{\mathrm{UL}}(W)}{p_{\mathrm{UL,max}}(W)} (J/kg), \tag{10}$$

with $p_{UL,max}$ the maximum power emitted by the mobile (approximately 2 W for GSM900, 1 W for GSM1800, and 0.2 W for UMTS [89], p_{UL} is the power emitted by the mobile, and T_{use} the total use time of the device. SAR_{psa} for a specific mobile device can be found on http://www.sardatabase.com/.

5.1.2 Averaging

When opting for power measurements, at various measurement locations, the transmitted and received powers are monitored with a tool or application on the mobile device, and captured when stabilized. These measurements are repeated along four orthogonal orientations at every measurement location, and the average of the four orientations is retained. This is done in order to account for the influence of the mobile antenna directivity [88].

In order to calculate the average dose during a certain exposure scenario, the transmitted powers (TX, and P_{UL}) and received power densities (S_{inc}) , or simulated SAR values, are further spatially and temporally averaged.

5.2 Dose = E * t

In the context of navy crew exposure to radars and high-frequency antennas, [90] define two other *doses*, namely the annual exposure dose, D_{ann} (Vh/m) and the annual exposure dose (ICNIRP), $D_{ann,\ ICNIRP}$ (h).

The first is defined as:

$$D_{\text{ann}}\ (\text{Vh/m}) = E_{\text{spatial}} \times 365 \times 24\ (\text{h}) \times t_{\text{transmit}} \times t_{\text{mission}}\,, \tag{11}$$

with $E_{spatial}$ the spatially averaged E-field strength over a number of spot measurements. $t_{transmit}$ is the average transmission time of the equipment (e.g., if the antenna would transmit 15 minutes per hour, then $t_{transmit} = 0.25$), and $t_{mission}$ is the average mission time of the exposed crew member (e.g., if the mission lasts 9 months per year, then $t_{mission} = 0.75$).

The second is defined as

$$D_{\text{ann, ICNIRP}}\ (\text{h}) = \left(\frac{E_{\text{spatial}}}{E_{\text{ref}}}\right)^2 \times 365 \times 24\ (\text{h}) \times t_{\text{transmit}} \times t_{\text{mission}}\,, \tag{12}$$

with E_{ref} the ICNIRP reference level for the specific frequency of the corresponding antenna equipment.

The doses depend on the used equipment and the total time of the crew’s mission.

This approach is based on the LF exposure assessment in [91], and similar approaches can be found in [92] (for a 27 MHz source) and [93], a validation study of the INTERPHONE study, in which a “cumulative power” (in mWs) of a phone call is introduced.

5.2.1 Methods for assessment

For each equipment, electric-field spot measurements are performed on different parts of the boat (e.g., afterdeck) and (spatially or linearly) averaged per part.

5.2.2 Averaging

Linear averaging of the measured electric-field values:

$$E_{\text{linear}}\ (\text{V/m}) = \frac{1}{\text{n}}\sum E \qquad (13)$$

with n the number of spot measurements.

Spatial averaging of the measured electric-field values:

$$E_{\text{spatial}}\ (\text{V/m}) = \sqrt{\frac{1}{\text{n}}\sum E^2} \qquad (14)$$

with n the number of spot measurements.

6 CONCLUSIONS

This deliverable presented current exposure metrics used in compliance testing and realistic exposure assessment for frequencies ranging from 700 MHz to 6 GHz. This deliverable D2.1 will serve as basis for the definition of the global wireless exposure index. We focused on the definition and the methodology to assess current metrics for different wireless communication technologies and which are found in guidelines, standards and scientific literature. Finally, we mentioned briefly the regulations valid in different countries and regions within the European Union.

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APPENDIX 1: INTERNAL REVIEW

	Reviewer 1: Milos Tesanovic			**Reviewer 2: Aleksandar Nešković, Mladen Koprivica**		
	Answer	**Comments**	**Type***	**Answer**	**Comments**	**Type***
1. Is the deliverable in accordance with						
(i) the Description of Work?	☒ Yes ☐ No		☐ M ☐ m ☐ a	☒ Yes ☐ No		☐ M ☐ m ☐ a
(ii) the international State of the Art?	☒ Yes ☐ No		☐ M ☐ m ☐ a	☒Yes ☐ No		☐ M ☐ m ☐ a
2. Is the quality of the deliverable in a status						
(i) that allows to send it to EC?	☒ Yes ☐ No		☐ M ☐ m ☐ a	☒ Yes ☐ No		☐ M ☒ m ☐ a
(ii) that needs improvement of the writing by the editor of the deliverable?	☒ Yes ☐ No	Please see my comments above.	☐ M ☒ m ☐ a	☒ Yes ☐ No		☐ M ☒ m ☐ a
(iii) that needs further work by the partners responsible for the deliverable?	☐ Yes ☒ No		☐ M ☐ m ☐ a	☐ Yes ☒ No		☐ M ☐ m ☐ a

* Type of comments: M = Major comment; m = minor comment; a = advice