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Analysis of Electromagnetic Waves Spatio-Temporal Variability in the Context of Exposure to Mobile Telephony Base Station

Mame D. Bousso-Lo N'Diaye[1, 2], Nicolas Noe[1, *], Pierre Combeau[2], Francois Gaudaire[1], and Yannis Pousset[2]

Abstract—With the increasing number of mobile phone users, new services and mobile applications, the proliferation of radio antennas has raised concerns about human exposure to electromagnetic waves. This is now a challenging topic to many stakeholders such as local authorities, mobile phone operators, citizen and consumer groups. The study of the spatial and temporal variability of the actual downlink exposure is a very important requirement to find an accurate exposure assessment. In this paper, a concept of exposure areas linked to specific variations of the electric field is introduced. Then a measurement campaign of the temporal variability of the electric field in urban environment is presented, considering different technologies and mobile operators in the previously defined exposure areas. This study allowed to determine updated daytime and nighttime exposure profiles. A second result yielded the averaging duration needed to reach a stable evaluation of the electric field exposure levels, inside each exposure area and according to each technology.

1. INTRODUCTION

The exposure to radiofrequencies is still a topic under investigation, because of the increasing use of smart objects. The major exposure sources of people are these objects themselves (and especially mobile phones), and there exists no evidence yet of harm. Nevertheless, the mobile telephony base stations antennas can worry people living in the neighbourhood, and environmental associations are actively lobbying against the installation of new equipments. By the end of 2016, more than 7 billion mobile phone subscribers contract worldwide (see Figure 1) according to the ITU (International Telecommunication Union). As far as France is concerned there are 73 million mobile phone contracts subscribed to this day according to ARCEP (French Electronic Communications Regulation Authority). In this context, more and more people are demanding precautionary measures and a reduction of the existing exposure limits.

The subject of EMF (electromagnetic fields) exposure has been widely addressed in the literature during the past ten years. The only proven risk to this day is the increase of temperature of human tissues. As a consequence, standards and recommendations have been established by committees from all over the world, such as ANSI (American National Standards Institute) in North America or ICNIRP (International Commission on Non-Ionizing Radiation Protection) guidelines in European countries. These standards and guidelines have been frequently improved to take into account numerous aspects of exposure and to tackle emerging issues.

There are still debates concerning EMF exposure. These debates are fueled by the increasing penetration of radio technologies in the everyday life (mobile phones, wi-fi, ...) and devices (electricity meters, ...). Several stakeholders are concerned by the exposure question: state ministries, state

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* Corresponding author: Nicolas Noe (nicolas.noe@cstb.fr).
[1] CSTB, Lighting and Electromagnetism Division, Nantes, France. [2] CNRS, Université de Poitiers, XLIM, UMR 7252, F-86000 Poitiers, France.

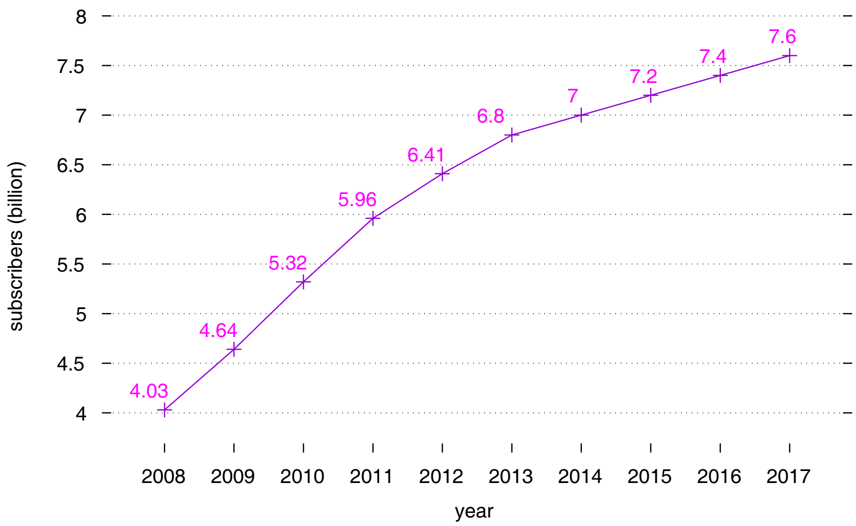


Figure 1. Worldwide mobile cellular subscribers (billion).

agencies, technical and research centers, mobile telephony operators and companies, environmental and users associations, ... These actors may have divergent agendas, hence general agreement and objective views of the existing situation are hard to reach. As a consequence, there is still a need for widely accepted exposure indicators, and research has to be carried out for building knowledge of real exposure levels, taking into account current and future radio technologies.

The goal of this paper is to improve the evaluation of human exposure, focusing on the electric field variability, both in time and space. The paper is divided into five sections. Section 1 is this introduction. Section 2 is a state-of-the-art study of EMF exposure quantification. This section introduces the physical quantities of EMF exposure (SAR, electric field) and the exposure indicators found in the literature. This will allow us to identify exposure quantification issues. Section 3 is dedicated to the concept of exposure area. First propagation regions in a radio link are described, then these exposure areas are defined. They will be the basis of the exposure variability analysis in this paper. Section 4 details the methodology used in this study. It deals with the technical goals, the study data and the processing of results. Section 5 is dedicated to hourly profiles of instantaneous exposure over a day. Existing profiles are discussed, and a new profile is proposed. Section 6 addresses the question of averaging duration, in terms of radio technologies and exposure areas. Finally, Section 7 summarizes the contributions of this paper to the radiofrequencies (RF) exposure community.

2. ANALYSIS OF EXISTING APPROACHES AIMED AT QUANTIFYING THE EXPOSURE

We describe here the physical quantities used to quantify EMF exposure in existing norms and guidelines. These quantifies are as the follows:

- **Electric field**,
- **SAR** (Specific Absorption Rate, the power absorbed per mass of tissue)

Electric field can only be used to measure far field exposure levels, whereas SAR can be used both for near and far fields, and is to this day the only way to characterize near field exposure. These two quantities differ on the measurement and simulation processes. These quantities are used as thresholds for regulation enforcement, but there is a need to have dedicated tools to study real exposure.

A large body of work has been done in previous years to quantify real exposure. In [1], Ghanmi investigated this subject, dealing with variability and uncertainties in dosimetry. It led to advanced statistical techniques in numerical dosimetry for SAR evaluation. French publicly funded project DICER [2] studied methodologies in order to propose relevant indicators of RF electric field. This project led to a general agreement of technical bases to use in current debates, and eased in France the comparison between heterogeneous exposure situations (domestic, industry, ...). A main contribution concerning mobile telephony was the definition of a Global Exposure Indicator (GEI). This indicator aggregates SAR and electric field in a single value, depending on user's behavior (duration of "voice" and "data" usages). The major step forward with this indicator is that this single value handles the exposure from both downlink (base stations antennas) and uplink communications (phone). This GEI indicator was also used in a European project called LEXNET [3]. Its goal was to achieve efficient solutions to reduce RF human exposure by 50% without damaging the quality of service. This indicator enabled the analysis of the performance and relevance of low emission radio technologies.

All these studies illustrate the importance of the propagation region (near field, far field) on the exposure characterization. In this paper we will focus on the analysis of far field exposure to mobile telephony base stations. We will study the hypothesis that the variability of the electric field is characterized by the relative emitter/receiver location and visibility. This leads to the definition of exposure areas in the forthcoming section.

3. CONCEPT OF AREA OF EXPOSURE

3.1. Propagation Area

We recall in this section the importance of propagation regions in the radio transmission link. As a matter of fact, the properties of electromagnetic waves depend on the propagation region around the emitter. There are four propagation regions, depending on the distance to the emitter:

- **Reactive near field**
  This is a very "thin" region, and it is located within a distance to the emitter shorter than $\frac{\lambda}{2\pi}$, with λ being the wavelength. This is roughly 5 cm for a 900 MHz emitter. Waves are evanescent in this region, i.e., propagation phenomena are negligible compared to radiation phenomena. This region cannot be simulated accurately with wave propagation tools.
- **Rayleigh region**
  This region ranges between $\frac{2\lambda}{2\pi}$ and $\frac{D^2}{2\lambda}$, with D being the largest dimension of the antenna. For a one-meter-long 900 MHz GSM antenna, $\frac{D^2}{2\lambda} = 1.5\,\text{m}$). The electromagnetic power is confined within a cylinder around the radiating aperture. The wave might exhibit a cylindrical character as shown in [4].
- **Fresnel region**
  This is an intermediary region between $\frac{D^2}{2\lambda}$ and $\frac{2D^2}{\lambda}$ from the emitter. The wave naturally diverges. On the upper limit of the Fresnel region, the aperture, as seen from the antenna, is equal to the angular aperture of the main lobe $\frac{2\lambda}{D}$. The combination of Fresnel and Rayleigh region is the **near field region** of the antenna.
- **Fraunhoffer region**
  This region is beyond a distance of $\frac{2D^2}{\lambda}$ and is also called **far field region** of the antenna. The radiated power is confined into a conic beam, and the waves are locally almost plane waves.

In an urban environment (exposure generated by base station antennas, on the ground or on facades of neighbouring buildings), we only deal with the far field region, for both measurements and simulations. Consequently, the far field region will be segmented into three exposure areas, defined in the following section.

3.2. The Concept of Exposure Areas

A spatial decomposition of exposure will be used to characterize the variability of electric field. Simulation tools are used to define the concept of exposure area. Asymptotic methods (ray optics) are well suited to simulate EMF exposure in urban environment. Firstly, details of buildings coming from geographical information systems (GIS) are coarse compared with mobile telephony wavelengths, fulfilling the asymptotic development. Secondly, far field radiation patterns can be used, as opposed to exact methods (such as method of moments) for which emitters must be designed as set of dipoles, and we only have interest in far field. Thirdly, asymptotic methods are very fast in 2.5D urban environments [5–7]. Finally, the contributions from each emitter to each receiver can be identified as direct, reflected and diffracted paths.

This identification of direct, reflected and diffracted paths leads to the definition of exposure areas using geometrical criteria only. For a given emitter, three exposure areas are identified:

- Z_{direct} is the area where most of the emitted power is collected, coming mainly from direct paths. The electric field in this area mostly depends on emitter characteristics. Reflected and diffracted paths might exist in this area, but their contributions are negligible with respect to the direct paths.
- $Z_{\text{reflection}}$ is the area where the collected power mostly comes from reflected paths. The electric field in this area mostly depends on the shape and the electromagnetic properties of the building surrounding the emitter. There is no direct path in this area.
- $Z_{\text{diffraction}}$ is the area where the collected power only comes from diffracted paths. The electric field in this area mostly depends on the diffraction model and the height profile of the paths. A receiver is in $Z_{\text{diffraction}}$ when it is in neither Z_{direct} nor $Z_{\text{reflection}}$ areas.

Figure 2 illustrates these exposure areas.

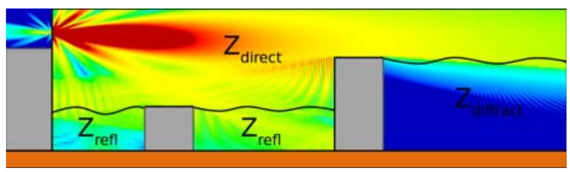


Figure 2. Exposure areas (areas can be identified during ray-tracing computation).

As shown in [8], the variability of the electric field is correlated to the main contribution, so to the exposure areas. Thus we propose to study electric field variability in each of them. The next section describes the used methodology.

4. METHODOLOGY

4.1. Goals

Current standards and guidelines (ICNIRP, ANSI) require measurements to be continuously averaged over 6 minutes in order to evaluate short-term exposure. This duration only relies on health risk and has no other explanation than thermal hazard. Russia and Ukraine use an exposure threshold close to ICNIRP, but the threshold is a continuous function of the exposure duration [9] (concept of dose). In France, ANFR (National FRequency Agency) is responsible for EMF exposure protocols establishment. The French protocol, based upon ICNIRP standards, allows for a shorter measurement duration as long as the RMS (Root Mean Square) value is stable, but the stability criterion is not defined. A French study on public exposure to base stations showed that the exposure level, whatever the time of the day, is close to the one that would be measured and averaged over 6 minutes [10]. More recently, the LEXNET indicator [3] took into account the large-scale temporal variability of the exposure by segmenting day according to the human activities, leading to daytime and evening slots.

The goal of this study is to analyze temporal variability of public exposure to mobile telephony base station antennas. More specifically, we address the uncertainties on the temporal variability of the instantaneous exposure level, and so on the averaging duration to apply. Therefore, daily exposure for different mobile communication technologies is studied as the temporal variation of exposure in each different exposure area.

The analysis of temporal variation performed in this body of work leads to a more selective study than in [10]. Actually this project aims at improving the knowledge of personal exposure to EMF generated by base station antennas with a statistical approach. The real exposure level over a day is analyzed for each telephony downlink band. Then a comparison of raw levels, averaged over 6 minutes and over longer time periods is analysed. We have initiated our study with the same methodology and then have improved it with the exposure area concept, and its effects on temporal variability. In addition to existing technologies[†] at the time of [10], we also take into account LTE (Long Term Evolution) emitters that were not available at that time.

4.2. Fixed-Point Temporal Measurements

For EMF measurement we used the Narda SRM 3006 spectrum analyzer. This analyzer offers the possibility to selectively measure the EMF, per technology (GSM, UMTS, LTE ...) and per frequency, to identify the exposure sources. It also computes the total field of all the transmitters radiating in the measurement environment. Thus two types of measures were performed:

- wide-band measurement ("safety" mode): record one value per downlink according to each frequency band allocated to operators. The "safety" mode is used to perform transient measurements;
- narrow-band measurement ("spectrum" mode): record of the detailed spectrum around a given central frequency.

In France the frequency spectrum is in the public domain. For telecommunication systems like mobile telephony, each mobile technology (GSM, UMTS, LTE) operates in a given frequency bandwidth (900 and 1800 MHz for GSM, 2100 MHz for UMTS and 2600, 800 and 700 MHz for LTE[‡]). These frequency bands are spread across four operators: Orange, SFR, Bouygues and Free. They are reserved for public mobile telephony, whereas other bands can be employed for professional, military or academic research communication purposes. In France the ARCEP is in charge of allocating the frequency spectrum to the different mobile operators, and the spectrum is presented on Figure 3 (data of 2014).

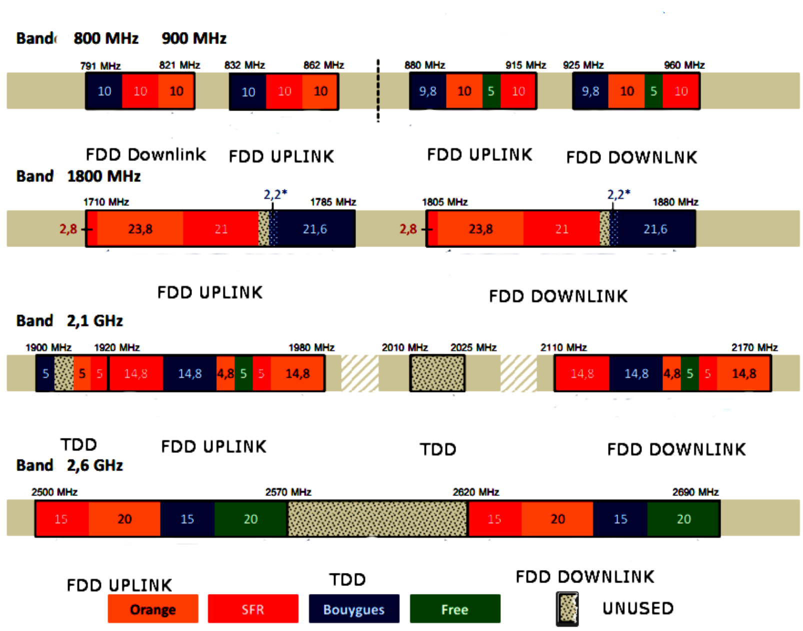


Figure 3. Frequency spectrum allocation to the different french operators (2014).

To analyze the temporal variability of the exposure, a measurement campaign was realized on the CSTB (Scientific and Technical Center for Building) site of Nantes. The measurement point is located on the ceiling of the A building, as it is illustrated on Figure 4. The base stations of Orange and SFR are also in the site. The Orange base station is installed on the B building (*cf.* Figures 4 and 5(a)), the

[†] GSM (Global System for Mobile), UMTS (Universal Mobile Telecommunication System).
[‡] notice that today there is also UMTS at 900 MHz and LTE at 1800 MHz.

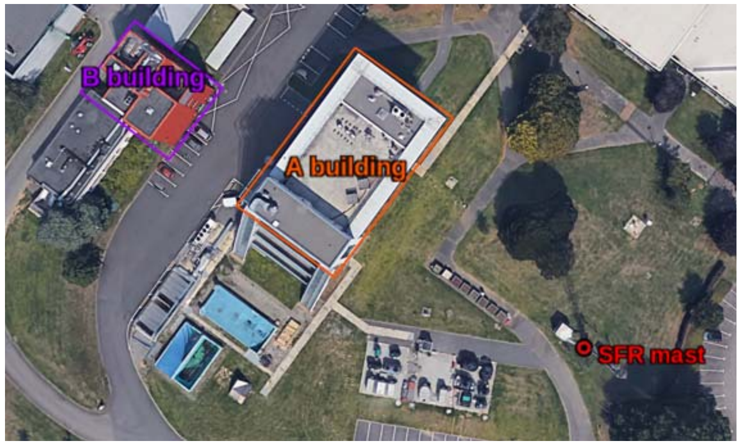
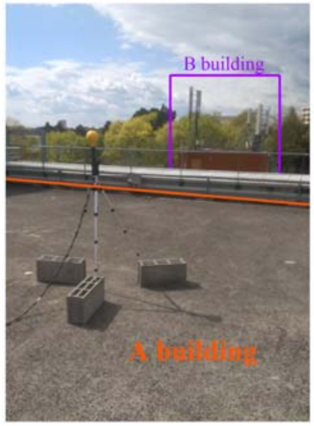


Figure 4. Measurement site of CSTB: measurement site (building A) and base stations of Orange (building B) and SFR (mast).

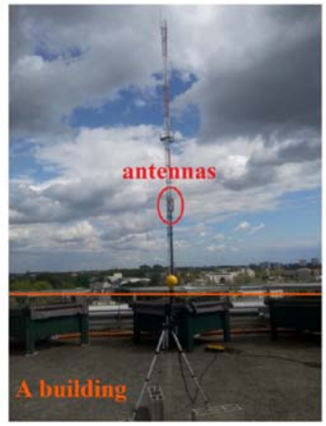
Figure 5. Base stations: (a) Orange, (b) SFR.

measurement point being in its main radiating azimuth (*cf.* Figure 5(a)), whereas the SFR base station is on a mast (*cf.* Figure 5(b)). Figures 6(a) and 6(b) show the two base stations from the point of view of the measurement point. The measurement point has been chosen to receive EMF in Z_{direct} (in the main azimuth) from the Orange transmitter which is in line of sight and EMF in Z_{direct} and $Z_{\text{reflection}}$ from the SFR transmitters.

A part of the received field also comes from other transmitters, not visible from the measurement point, as the ones of Bouygues Telecom and Free, allowing us to obtain some information about the temporal variability of the exposition when the receiver is in the $Z_{\text{diffraction}}$ of theses transmitters. The temporal behavior of EMF in the different exposure areas is more or less influenced by the environment. Indeed, in the case of Z_{direct}, the receiver being situated in height (four stories high, 15 meters above the ground), the link is less concerned by the variations of the environment. On the contrary, in the case of



(a)



(b)

Figure 6. Base stations from the point of view of the measurement point: (a) Orange, (b) SFR.

$Z_{\text{diffraction}}$, numerous external factors (moving vehicles ...) can influence the measurement. The analyzer has been configured to measure the cumulative electrical field in each downlink bandwidth affected to each operator (safety mode). Even if some frequency bands can be used by several technologies (for instance GSM and UMTS in the 900 MHz band, or GSM and LTE in the 1800 MHz for Bouygues), the knowledge of the transmitters located in the area of interest (public data from ANFR) combined with the analysis of the measured spectrum allows to identify the measured technology, which are:

- In Z_{direct} (Orange, located in the area of interest): LTE 800, GSM 900 and 1800, UMTS 2100,
- In $Z_{\text{reflection}}$ (SFR, located in the area of interest): LTE 800, UMTS 2100[§],
- In $Z_{\text{diffraction}}$ (Bouygues Telecom, not located in the area of interest, they are at about 400 m from the measurement point): LTE 800, GSM 1800, UMTS 2100.

Two types of measurements have been performed to analyze the temporal variability of the exposure:

- Measurements during 6 hours (Meas_6h): Measurements by downlink bandwidth during the day with a temporal step of 6 s, on a total duration of 6 h.
- Measurement during 24 hours (Meas_24h): Measurements per downlink bandwidth with a temporal step of 12 s at the same receiving location as for Meas_6h, on a total duration of 24 h.

To characterize the temporal variability of the exposure to EMF, we were interested in the influence of the exposure areas on the averaging duration according to each technology (GSM, UMTS and LTE), from the two previous types of measurements. We also searched to quantify the averaging duration required to obtain a better characterization of the exposure.

5. SEGMENTATION INTO DAILY EXPOSURE PROFILES

This segmentation is performed with the 24 hour-long measurements (Meas_24h).

5.1. Previous Work

Mobile telephony usage is linked to human activity, and it highly depends on the time of the day, with strong differences between day and night. As a consequence it is assumed that daily exposure can be divided into two different variation profiles. The study presented in [11] compares global average exposure to 3G (both downlink and uplink) in urban, suburban and rural areas. This leads to these two profiles:

[§] UMTS 900 transmitters are also located in the area of interest but are not treated here.

- **Day-profile: 8AM-6PM**
- **Evening-profile: 6PM-8AM**

Nevertheless when other technologies are taken into account and focusing on downlink only, we identify different segmentation profiles. This is illustrated with measurements in Z_{direct} exposure area in Figure 7. This figure displays instantaneous exposure during 24 hours for GSM, UMTS and LTE. The measurement time is on the horizontal axis (in hours, starting at 10 AM, until the next morning), and the electric field level (in V/M) in the considered downlink band is on the vertical axis. Segmentation profile proposed in [11] is also plotted in green (high part: day-profile, low part: evening-profile).

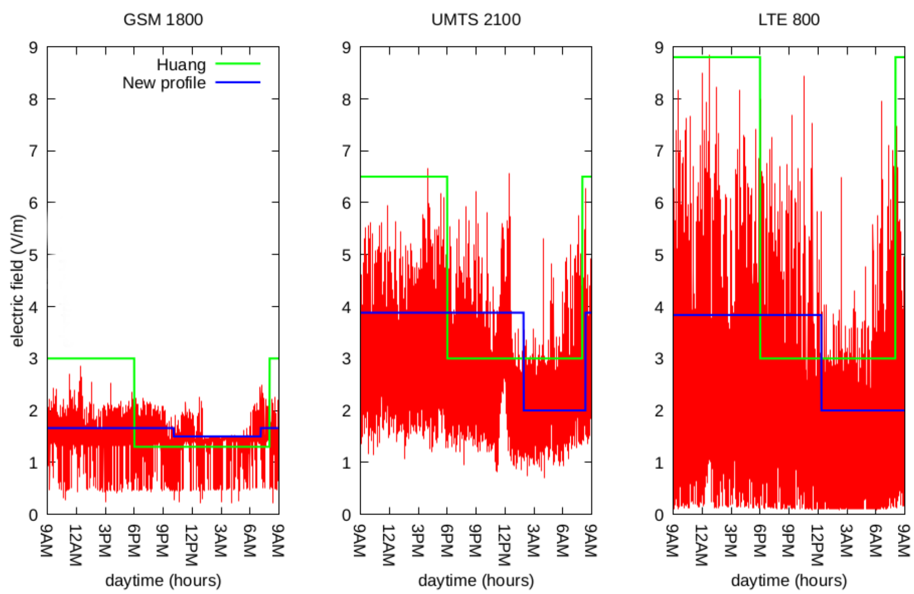


Figure 7. Time dependant exposure to an Orange base station during 24 hours.

Figure 7 obviously displays two temporal profiles: a lower exposure profile (mostly during nighttime) and a higher exposure profile (mostly during daytime). This corroborates the basic hypothesis that the exposure to base stations is directly linked to daily human activity, with higher values at daytime and lower values at nighttime.

Nevertheless even if the limit between these two profiles is hard to identify, it is also blatant that segmentation proposed in [11] does not apply to this signal. As a consequence, a segregation technique is used to compute the limit with objective criteria.

5.2. New Profiles

A new segmentation procedure is now introduced. It consists in defining two adjacent time periods, each with its own average value. We then have to look for the "breaking point" between these two parts. This breaking point should satisfy that the difference between the average levels should be as great as possible, whereas the duration of each part should be as long as possible. We can then define the E_{opt} parameter to maximize in order to fit both criteria as:

$$E_{opt} = |E_2 - E_1| * \sqrt{T_1 * T_2} \tag{1}$$

T_1 and T_2 are the respective durations of the two profiles (hence $T_1 + T_2 = 24\,\text{h}$), and E_1 and E_2 are the average electric field values on the two profiles.

By maximizing E_{opt} we deduce the breaking time between profiles, the duration and the average value of each profile. We then compare night-profile with day-profile by computing the relative error E_r (in%) and the difference E_c (in dB) between the average values of the signal on the two profiles. The relative error E_r between E_1 and E_2 is defined in Equation (2) while the difference E_c between E_1 and E_2 is defined in Equation (3).

$$E_r = \frac{E_1 - E_2}{E_2} \tag{2}$$

$$E_c = 20 \log \left(\frac{E_1}{E_2} \right) \tag{3}$$

Table 1 shows segmentation results for the three exposure areas and the three considered technologies (GSM, UMTS, LTE): time slot for each of the two profiles, relative error E_r (in%) and difference E_c (in dB).

Table 1. Comparative daily profiles according to exposure areas and technologies.

Exposure areas	**Profiles**	**LTE**	**UMTS**	**GSM**
Z direct	Day	09h10 - 00h20	08h20 - 01h55	07h05 - 22h05
	Evening	00h20 - 09h10	01h55 - 08h20	22h05 - 07h05
	E_r	38%	39%	5%
	E_c	2.83 dB	2.88 dB	0.44 dB
Z reflection	Day	07h15 - 00h55	09h55 - 23h30	Unavailable
	Evening	00h55 - 07h15	23h30 - 09h55	Unavailable
	E_r	11%	17%	Unavailable
	E_c	0.97 dB	1.41 dB	Unavailable
Z diffraction	Day	11h05 - 00h10	07h05 - 00h05	11h30 - 23h30
	Evening	23h35 - 10h05	00h05 - 07h05	23h30 - 11h30
	E_r	-4%	18%	-8%
	E_c	-0.39 dB	1.5 dB	-0.73 dB

Z_{direct}: The analysis of E_c and E_r (see Table 1) shows that LTE and UMTS technologies have larger gap than GSM in the two profiles in Z_{direct} area. In other words, the exposure to these two technologies is very different in the daytime compared with the night.

$Z_{\text{reflection}}$ and $Z_{\text{diffraction}}$: The difference between the two profiles is lower than 2 dB in the $Z_{\text{reflection}}$ and $Z_{\text{diffraction}}$ exposure areas, whatever the technology. It can also be noted that the relative error E_r is negative for LTE and GSM in $Z_{\text{diffraction}}$ area, meaning that the average night-profile signal is slightly higher than the average day-profile one. Furthermore, the E_r values for LTE (-4%) and GSM (-8%) in these areas, compared to the values in visibility area (except for GSM) show that the average variations of the two profiles are identical.

In conclusion it is mostly the Z_{direct} area that is influenced by the day and night change for LTE and UMTS technologies (38% for LTE, 39% for UMTS). We will now see if these conclusions are confirmed by studying the variation rate of the EMF as a function of the averaging duration, for each profile (day or night), in order to quantify the minimum duration needed to assess exposure accurately.

6. QUANTIFICATION OF AVERAGING DURATION

6.1. Data Processing of Measurements

Let $E[t]$ be the instantaneous measurement (sampled every 6 seconds) of the electric field for a full duration of 6 hours. ΔT is the duration (in seconds) of the time averaging window, and $N_{\Delta T}$ is the number of samples in the current time averaging window. The smoothed counterpart of signal $E[t]$ is $\bar{E}[t, \Delta T]$ with a sliding time averaging window of duration ΔT. This smoothing procedure is applied to remove transient fluctuations of the signal and to highlight long term tendencies. $\bar{E}[t, \Delta T]$ is defined as:

$$\bar{E}[t, \Delta T] = \frac{1}{N_{\Delta T}} \sum_{k=0}^{N_{\Delta T}-1} E[t-k] \tag{4}$$

6.2. Influence of Exposure Areas and Technologies

This study is based on 6 hour-long measurements (Meas_6h *cf.* Subsection 4.2).

6.2.1. Study of Signal $\bar{E}[t, \Delta T]$

Figure 8 shows that for Orange LTE 800 in Z_{direct} area, the measured signal during 6 hours as a function of time, smoothed for each of these five ΔT values: $\Delta T_1 = 60\,\mathrm{s}$, $\Delta T_2 = 360\,\mathrm{s}$, $\Delta T_3 = 720\,\mathrm{s}$, $\Delta T_4 = 1800\,\mathrm{s}$, $\Delta T_5 = 3600\,\mathrm{s}$. Time (in minutes) and electric field (in V/M) are displayed on the x and y-axes, respectively. The raw signal (sampled every 6 s) has unpredictable short time variations. As a consequence, time averaging is mandatory to make a reliable analysis of exposure. By using a sliding averaging window (of different durations), the signal becomes more and more stable. This is true for all technologies and all exposure areas. We now study the effect of ΔT according to technologies and exposure areas.

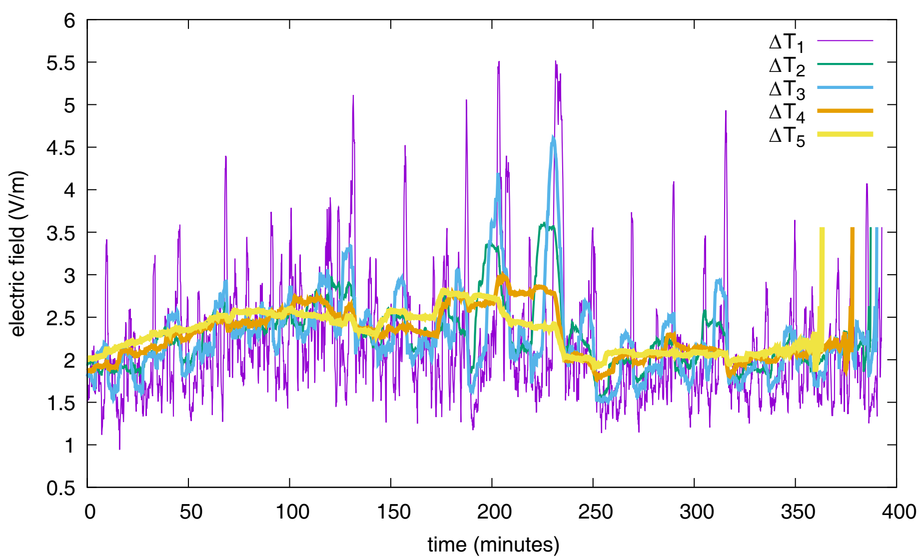


Figure 8. Effect of averaging duration on the electric field level — Orange LTE 800 — $\Delta T_1 = 60\,\mathrm{s}$, $\Delta T_2 = 360\,\mathrm{s}$, $\Delta T_3 = 720\,\mathrm{s}$, $\Delta T_4 = 1800\,\mathrm{s}$, $\Delta T_5 = 3600$ s $- Z_{\mathrm{direct}}$.

6.2.2. Influence of ΔT According to Technologies and Exposure Areas

Here the influence of technology and exposure area on the evolution of $\bar{E}[t, \Delta T]$ is emphasized. It will be done using an "error bars" graphical representation. This representation is well suited to study data variability, showing both average value as the center value and RMS value as an interval around it. It would highlight the potential significant differences in the variability of the electric field depending on the technology. These graphs show the evolution of $ES_{\Delta T}$ as a function of ΔT (see Equation (5)). $ES_{\Delta T}$ is an interval depending on $\mu_{\Delta T}$ (average value of $\bar{E}[t, \Delta T]$, see Equation (6)) and $\sigma_{\Delta T}$ (RMS value of $\bar{E}[t, \Delta T]$). If the values are distributed with a normal (Gaussian) law, 68% of these values are in the range $ES_{\Delta T}$ defined with:

$$ES_{\Delta T} = [\mu_{\Delta T} - \sigma_{\Delta T}; \mu_{\Delta T} + \sigma_{\Delta T}] \tag{5}$$

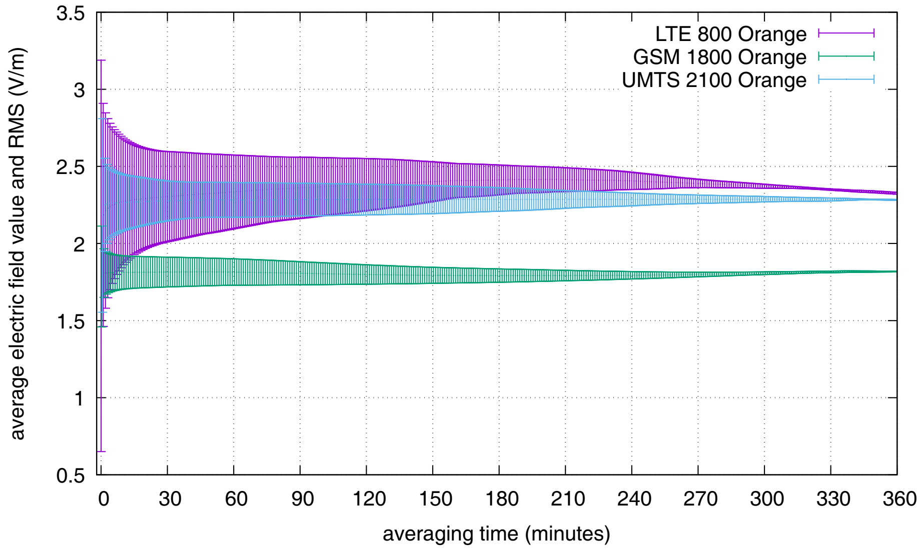


Figure 9. $ES_{\Delta T}$ according to technologies for Orange in Z_{direct}.

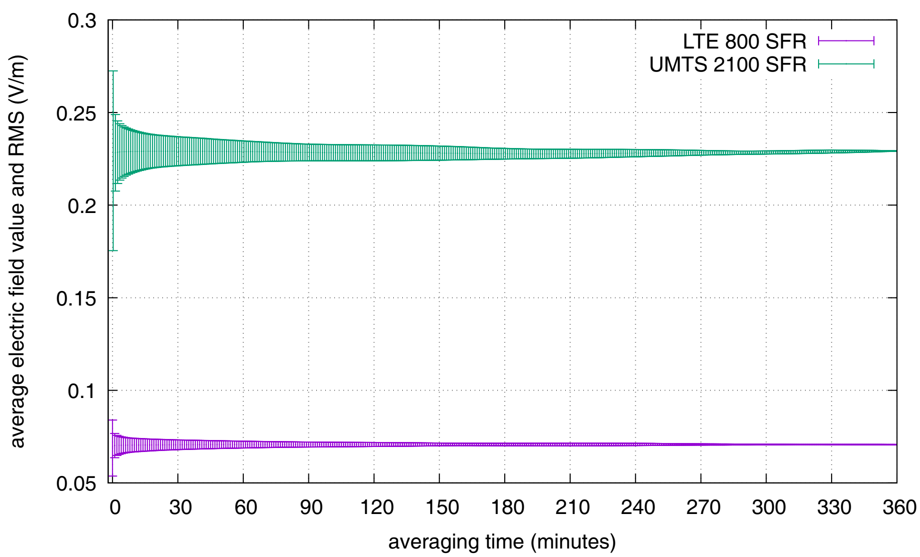


Figure 10. $ES_{\Delta T}$ according to technologies for SFR in $Z_{\text{reflection}}$.

$$\mu_{\Delta T} = \frac{1}{T} \sum_{t=0}^{T} \bar{E}[t, \Delta T] \tag{6}$$

Figure 9 represents the evolution of $ES_{\Delta T}$ according to technologies for Orange in Z_{direct}, while Figures 10 and 11 show the ones for SFR in $Z_{\text{reflection}}$ and Bouygues in $Z_{\text{diffraction}}$, respectively. Each exposure area is hence treated.

The comparison of curves of Figures 9, 10 and 11 shows that the variations of $ES_{\Delta T}$ are far greater in the Z_{direct} area where $\sigma_{\Delta T}$ goes up to 1.5 V/M, compared to $Z_{\text{reflection}}$ and $Z_{\text{diffraction}}$, where $\sigma_{\Delta T}$ is always less than 0.02 V/M. In Z_{direct} area (*cf.* Figure 9), LTE and UMTS technologies also have a higher temporal variability than GSM: 5 and 2.1 times more, respectively. This difference can be explained by the technology gap between GSM on one side and UMTS and LTE on the other side. GSM relies on a circuit-oriented connection, opening a channel between the caller and the contact person, closed down at the end of the communication. All the power is affected to a single user [12]. UMTS switched

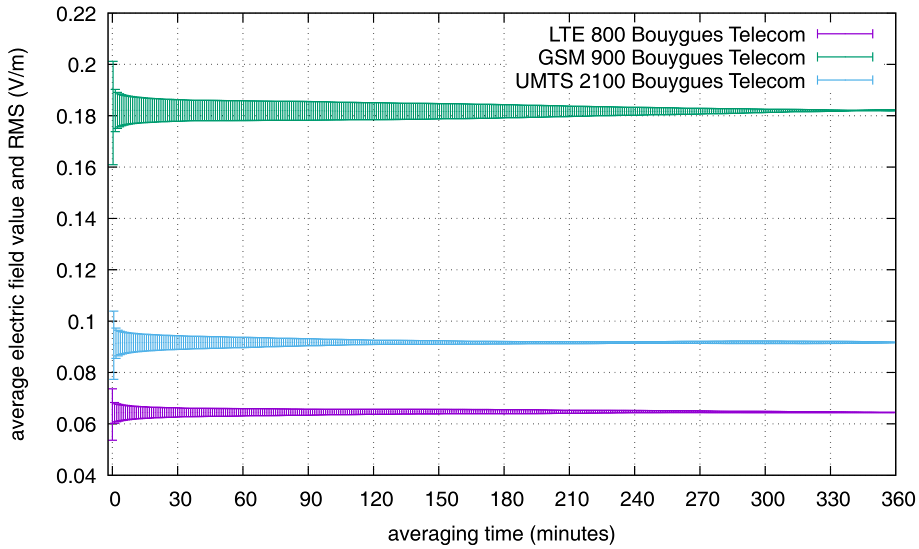


Figure 11. $ES_{\Delta T}$ according to technologies for Bouygues in $Z_{\text{diffraction}}$.

the radio technology from a circuit-oriented connection to a packed-oriented connection, hence allowing multiple users to communicate at the same time [13]. As far as LTE is concerned, its radio interface is based on multiplexing and OFDMA, allowing high flow communication with fewer interferences and a full-IP network architecture [14], which implies very fast signal variations.

The results globally show that the exposure area has a great impact on exposure evaluation. Temporal evaluation of the exposure also depends on the technology in Z_{direct} area. Beside, exposure evaluation is less affected by technologies in the $Z_{\text{reflection}}$ and $Z_{\text{diffraction}}$ areas, because of the influence of the environment. We will now focus on the averaging duration to apply, for each exposure area and each technology.

6.3. Determination of averaging duration

In this part we study the averaging duration needed to be able to quantify exposure levels. A first study led to the segmentation of exposure in variation profiles, depending on the time of the day. Then the averaging duration needed to have exposure varying less than a given variation rate is analyzed. Hence, the variation rate $TV_{\Delta T}$ given by Equation (7) is computed.

$$TV_{\Delta T} = \frac{\sigma_{\Delta T}}{\mu_{\Delta T}} \tag{7}$$

In order to assess the averaging duration for each variation profile, a criterion of signal stability is defined based on conclusions of COPIC (French's comity on mobile telephony exposure) [10]. This project concluded that, as far as mobile telephony is concerned and for current technologies (GSM and UMTS at the time of the study) and current usages, the measured exposure level during the day, whatever the time of the day, was close to the one that would be measured and averaged over 6 minutes. Furthermore, the amplitude of the variations during the day was rather low, less than 30%. As a consequence, we set our variation rate to 30%.

Table 2 displays the averaging duration ΔT found for each profile so as to reach a $TV_{\Delta T}$ (*cf.* Equation (7)) lower than 30%. The average signal value $\mu_{\Delta T}$ (*cf.* Equation (6)), averaged with ΔT, was also indicated for each profile in order to compare average differences between profiles, as a function of the variation rate.

The results from this table show that an averaging duration shorter than 1 min is always sufficient to reach a variation rate lower than 30%. French official protocol for exposure measurement (created by ANFR) reports that the averaging duration is shorter than 6 min, as soon as the RMS measured value is stable. These results show that this duration can be lowered to 1 min. They also partially confirm

Table 2. ΔT and $\mu_{\Delta T}$ for a variation rate lower than 30% according to each exposure area and technology.

Areas	Profiles	LTE		UMTS		GSM	
		ΔT	$\mu_{\Delta T}$ (V/m)	ΔT	$\mu_{\Delta T}$ (V/m)	ΔT	$\mu_{\Delta T}$ (V/m)
Z direct	Day	1 min	2.52	1 min	2.91	12 s	1.48
	Evening	1 min	1.88	1 min	2.13	12 s	1.41
Z reflection	Day	12 s	0.12	12 s	0.24	Unavailable	Unavailable
	Evening	12 s	0.10	12 s	0.20	Unavailable	Unavailable
Z diffraction	Day	12 s	0.13	12 s	0.13	12 s	0.17
	Evening	12 s	0.14	12 s	0.11	12 s	0.18

Table 3. ΔT and $\mu_{\Delta T}$ for a variation rate lower than 10% according to each exposure area and technology.

Areas	Profiles	LTE		UMTS		GSM	
		ΔT	$\mu_{\Delta T}$ (V/m)	ΔT	$\mu_{\Delta T}$ (V/m)	ΔT	$\mu_{\Delta T}$ (V/m)
Z direct	Day	24 min	2.64	54 s	2.93	1 min	1.52
	Evening	20 min	1.92	8 min	2.14	1 min	1.42
Z reflection	Day	1 min	0.12	2 min	0.23	Unavailable	Unavailable
	Evening	12 s	0.10	1 min	0.20	Unavailable	Unavailable
Z diffraction	Day	12 s	0.13	1 min	0.12	1 min	0.17
	Evening	12 s	0.14	1 min	0.11	1 min	0.18

analysis of the previous section and agree with COPIC conclusions [10]: in order to evaluate daily exposure at a given location, it is not needed to take into account the whole time slot. An averaged measurement of a few minutes is sufficient enough. Daily exposure can be evaluated with a 1 min measurement as long as the location is in $Z_{\text{reflection}}$ or $Z_{\text{diffraction}}$ area, whatever the technology (even for LTE) and the moment of the day. On the opposite, as far as Z_{direct} is concerned, day and night profiles should be taken into account since a difference of $\mu_{\Delta T}$ equal to 0.8 V/M is observed between day and night for LTE and UMTS. However if the variation rate is changed, these conclusions can change a lot as illustrated in Table 3, where the same study has been conducted with a variation rate lowered to 10%.

This example shows that the exposure area highly influences the averaging duration to be used for exposure quantification for LTE and UMTS.

When the location of the measurement point is in non-line of sight with the emitter ($Z_{\text{reflection}}$ and $Z_{\text{diffraction}}$), the averaging duration can be reduced to 2 min. For example, Figure 12 presents a zoom on the first part of Figure 11 ($Z_{\text{diffraction}}$) corresponding to averaging durations between 0 and 12 min. The result concerning UMTS 2100 (Bouygues Telecom) shows that an averaging duration of 6 min (recommended by ANFR) gives a variation rate $TV_{\Delta T}$ of 4%, which is in accordance with the objective of 10%. But it can also be observed that an averaging duration of 2 min is sufficient since it gives a $TV_{\Delta T}$ of 5.5%.

On the opposite, in line of sight of the emitter (Z_{direct}), the averaging duration can be larger than the protocol one (20 min to 24 min depending on the profile for LTE and 8 min to 9 min for UMTS). Figure 13 illustrates this point for Orange in Z_{direct}. In this case, whereas an averaging duration of 24 min almost respects the target variation rate of 10% (we have 13%), using the averaging duration of 6 min recommended by the protocol drives to a variation rate of 42%, that is almost 4 times more. This difference between exposure areas is related to the effects of the environment. This implies that the variation rate $TV_{\Delta T}$ is a very important parameter to quantify exposure, especially for LTE and UMTS. As for $TV_{\Delta T}$ of 30%, ΔT for GSM is always lower than the protocol value.

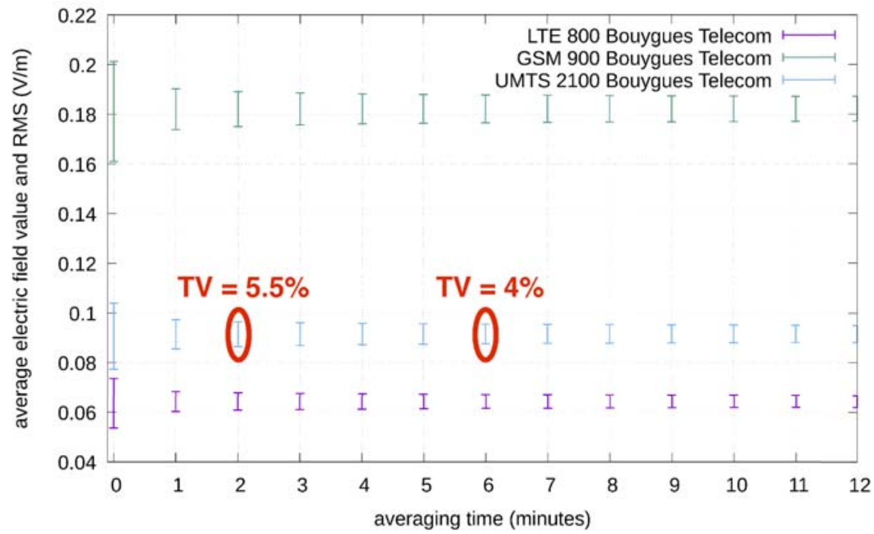


Figure 12. $ES_{\Delta T}$ according to technologies for Bouygues in $Z_{\text{diffraction}}$ (zoom of Figure 11).

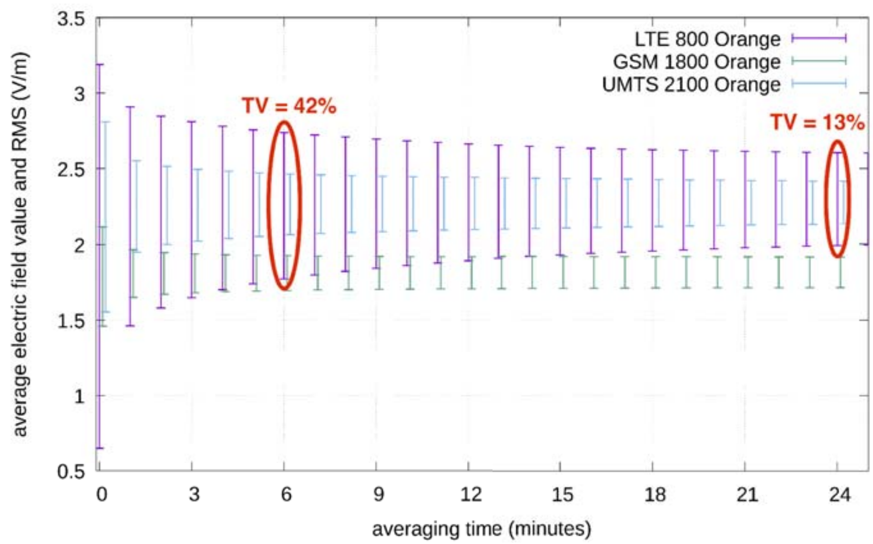


Figure 13. $ES_{\Delta T}$ according to technologies for Orange in Z_{direct} (zoom of Figure 9).

7. CONCLUSION

To bring elements of answers to the actual problematic concerning the exposure to EMF, our researches in the field of human exposure to EMF have been oriented on the spatio-temporal variability of the electric field. The hypothesis is that the relative position of the transceivers characterizes the variability of the electric field emitted by the fixed emitters of the base stations. This drove us to define the concept of exposure areas characterizing three specific behaviors of the wave propagation according to the existence of specific combinations of electromagnetic interactions. The objectives were to know if there is a specific impact of these zones on the assessment of the exposure, by taking into account several parameters like the averaging duration, the technology (GSM, UMTS and LTE) and the daily profile (day, night). For this, the exposure at a fixed location has been evaluated. The first part of the study according to the Meas_6h data has shown that Z_{direct} is the most influenced one by the temporal variations, whereas the second part on Meas_24h data has evaluated the averaging duration based on a longer measurement duration.

The influence of the evaluated point location has been studied with regard to the transmitters by taking into account the daily profile. The conclusion is that in Z_{direct}, the daily profile has to be taken into account to better characterize the exposure.

The conclusions of this paper are:

- the exposure areas can be divided in two specific ones: Z_{direct} and Z_{indirect} ($Z_{\text{reflection}}$, $Z_{\text{diffraction}}$);
- the daily profile (day/night) has to be taken into account for the mean level evaluation into Z_{direct} (LTE and UMTS);
- the duration of averaging (6 min) should be decreased to 1 min according to a variation rate of 30%.

Thus, we have verified the proposed hypothesis by showing that the exposure area influences the assessment of the real exposure, and that it has to be taken into account to better characterize the exposure. From a practical point of view, this study can be a base to achieve optimized guidelines to measure electric field exposure from mobile telephony base stations. First, the two proposed exposure areas can be easily identified on a simple geometrical criterion (line of sight of the emitter or not). Then, public data from ANFR are used to know what technology from what operator is deployed in the considered environment. Finally, Tables 1 and 2 give the good averaging duration to use according to a specific technology and the moment of the day.

This study presents some solutions to measure the exposure. Nevertheless, some aspects can be improved due to the complexity of the problem. However, we are confident to conclude that an indicator depending on the exposure area, the exposure duration and the technology should better quantify the far field exposure in a given location. For the exposure at urban scale, it would be interesting to integrate new parameters as the population density, the spatial averaging and the exposure area to provide exposure maps that would be sufficient representative of the real exposure. For indicators as in [2, 3, 15], which also integrate the near field, the consideration of exposure areas should improve the estimation of the exposure level by adapting the index according to each one.

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