Study of the Correlation between Outdoor and Indoor Electromagnetic Exposure near Cellular Base Stations in Leuven, Belgium

Abstract

A measuring campaign for the assessment of electromagnetic radiation near base stations in the city center of Leuven, Belgium, has been carried out. The main objective of this assessment is to study the correlation between the outdoor and the indoor exposure produced by cellular base stations and to investigate the changes of electromagnetic exposure within a typical day and over 1 month in the vicinity of these base stations. The study was also carried out as a function of location and time using highly precise measurement equipment. The measurements were performed in both public and private areas in sixty (30 indoor and 30 outdoor) different locations in Leuven. The measurement was focused on mobile communication networks: GSM (Global System for Mobile Communication, 900 MHz and 1800 MHz) and UMTS (Universal Mobile Telecommunications System, 2110 MHz) were the frequency bands of interest. The data at these frequencies were extracted from raw measurements in the 824 MHz to 2170 MHz frequency band. The results show that all analyzed locations are in compliance with the exposure limits recommended by ICNIRP (International Commission on Non-Ionizing Radiation Protection) and that the (maximum) indoor exposure correlates to the outdoor exposure with a factor of about 0.5.

Keywords: electromagnetic exposure; base stations; mobile communications

1. Introduction

The fast changing world of mobile telecommunications [1], [2] has raised concern amongst many local communities over possible health effects from exposure to electromagnetic radiation from cellular base stations. If not properly managed, this can lead to debates or litigations between the residents and the service providers. The keen attention of residents to exposures is related to the dense deployment of base stations, which are mounted on buildings in residential environments. Electromagnetic fields produced by mobile phones are classified by the International Agency for Research on Cancer (IARC) as possibly carcinogenic to humans [3]. Therefore, electromagnetic

fields produced by base stations have been questioned a lot, and are seen by the common people as a (possible) threat.

Exposures of the general public to electromagnetic fields generated by wireless systems is mostly within the radio frequency range (3 kHz to 300 GHz). These frequencies are used in broadcasting stations (radio and television), mobile phone base stations (GSM - Global System for Mobile Communications, UMTS - Universal Mobile Telecommunications System, and LTE – Long-Term Evolution), Digital Enhanced Cordless Telecommunications (DECT) base stations, radio frequency (RF) tagging systems (RF identification systems and anti-theft alarms), and wireless communication applications such as wireless local area networks (WLAN), wireless fidelity (WiFi) systems, and worldwide interoperability for microwave access (WiMax). These applications require radio waves or in more general terms ElectroMagnetic (EM) waves. An EM wave when transmitted from an antenna is also known as EM radiation.
There are two types of EM radiation, ionizing radiation and non-ionizing radiation. Non-ionizing radiation does not alter the molecular structure of living tissues [4]-[6], but it could affect human cells in manners that are not fully understood yet [4], [7]. Ionizing radiation is able to directly alter the molecular composition of matter / living tissues. All radiation used in the 3 kHz – 300 GHz band is non-ionizing.

In order to evaluate the possible impact of exposure to electromagnetic radiation from mobile communication systems, studies have been carried out in the area of exposure field measurements using basic standards, for example in [8]. Techniques for exposure measurements in the immediate environment of mobile communication systems have been developed, for example in [9] - [13]. EM radiation measurements with large numbers of measuring points distributed within Italy and Greece were conducted by implementing monitoring networks [14]-[16].

RF measurement campaigns in the vicinity of base stations using personal field meters have been carried out in previous studies [17]-[23]. Large scale measurements have also been performed in countries like China [24], Ghana [25], Spain [26], Turkey [27] and Korea [28]-[29], using personal exposure meters (exposimeters). A comparison of outdoor mean exposure levels across four European cities: Amsterdam, Basel, Ghent and Brussels was done within three different outdoor areas [30]. RF and microwave exposures from mobile telephone antennas mounted on rooftops were investigated in Malaysia [31]. Alanko *et al.* presented an assessment of occupational exposure from several rooftop mounted antennas [32].

In Austria [33], field strength measurements within the bedrooms of 366 households near base stations (with a mean electric field strength for the urban area 0.08 V/m while that of the rural area was 0.13 V/m) showed that base stations in rural environments transmit higher power over larger distances. Another spot measurement campaign involving 226 households: the RF field from mobile base stations was maximally 1.36 V/m while the highest field of 3.1 V/m was caused by DECT base stations [34]. Investigations of residential exposure to EM radiation from mobile phone base station carried out by Goiceance and Dannlescu [35] in different locations of the house such as living room, balcony, loggia and roof-terrace showed that the EMF level in the living room was up to 1.4 V/m. Massive residential exposure measurements were carried out in more than 1000 rooms in [36] and [37].

Different countries made reviews of electromagnetic field exposure from base stations (indoor and outdoor environments, respectively) and concluded that in some cases electromagnetic field exposure can be high, but in most cases it is well below standard reference levels, see Tables 1 and 2.

Within the context of compliance verification of base stations to exposure limits, a number of researches has been carried out in urban and rural macro environments, but very limited information is available for electromagnetic radiation exposure in correlated outdoor and indoor environments, i.e. for example indoor and outdoor in the same city.

In this study a measurement campaign was carried out in 60 (30 indoor and 30 outdoor) different locations in the city center of Leuven, Belgium. The goals were 1) to study the exposure as a function of location in the city center and as a function of time during the day, with 2) professional highly precise measurement equipment, and not the much less accurate exposimeters used in other studies [38], [39], 3) to study the correlation between the exposure outside and the exposure inside, and 4) to check the stability of the exposure by comparing different measurements over a time span of about one month. To the best knowledge of the authors a study combining all these different aspects has not been performed before.

This study thus presents a general and systematic assessment of radio frequency electromagnetic exposure in correlated indoor and outdoor environments, in this case in Leuven, Belgium, using a dedicated professional measuring system for the actual field values. It further compares the results with both international and local legal safety limits. Note that although several organizations have defined safety guidelines for the general

public, the levels of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [40], i.e. 41, 58 and 61 V/m for GSM 900 MHz, GSM 1800 MHz and UMTS, respectively, have been adopted in most European countries. Some countries (like Belgium), regions and cities set stricter limits. The Flemish (region of Belgium) legal limits specified for the general public are 3, 4.2, and 4.5 V/m for GSM 900 MHz, GSM 1800 and UMTS respectively [41].

Reference	**Country**	**Legal limit (V/m)**	**Measurement environment**	**# locations**	**Equipment**	**Measured E_{min} (V/m) for GSM 900**	**Measured E_{max} (V/m) for GSM 900**	**Spread (V/m)**	**Type of environment**
[35]	Romania	41	Iasi	4	SA	0.250	9.700	9.450	City
[38]	Belgium, Netherlands Sweden	41	Stockholm, Amsterdam	243	SA	0.290	1.900	2.587	Urban & rural
[42]	Austria	6	Salzburg	37 (indoor + outdoor)	FM, SA	0.037	3.864	3.827	City
[43]	UK	41	N/A	20	FM, SA	---	3.543	---	City
[44]	Australia	27.5	Across 5 cities	60	SA	---	1.715	---	City
[45]	Colombia	28	Bucaramanga	33	FM, SA	0.800	2.000	1.200	City
[46]	Saudi Arabia	41	Riyadh	60	SA	0.005	2.293	2.288	City
[47]	Palestine	41	Tulkarm	150	FM	< 1.940	2.460	≈ 0.520	City
[48]	Serbia	24.4	N/A	276 (outdoor + indoor)	FM, SA	< 20.00	70.00	≈ 50.00	City
[49]	Germany	26	N/A	11	SA	0.004	5.400	5.396	City

Table 1: Measured outdoor exposures in different countries and legal limits. FM = Field Meter, SA = Spectrum Analyzer, EM = ExposiMeter, and # locations = number of locations.

Reference	**Country**	**Legal limit (V/m)**	**Measurement environment**	**# locations**	**Equipment**	**Measured E_{min} (V/m) for GSM 900**	**Measured E_{max} (V/m) for GSM 900**	**Spread (V/m)**	**Type of environment**
[35]	Romania	41	Iasi	4	SA	0.250	1.400	9.450	City
[38]	Belgium, The Netherlands and Sweden	41	Stockholm, Amsterdam	68	SA	0.100	0.910	0.810	Urban & rural
[48]	Serbia	24.4	N/A (office)	276 (outdoor + indoor)	FM, SA	< 5.400	12.000	≈ 6.60	City
[50]	Spain	26.6	Santander (geriatric residence)	---	FM, SA	---	2.605	---	City
[51]	France	41	Doubs	---	EM	0.050	0.780	0.730	Urban & rural
[52]	Belgium and Greece	41	N/A	55	EM, SA	---	1.100	---	Urban & rural
[53]	Italy	6	Torino	38	FM, SA	0.410	0.840	0.430	City
[54]	Poland	19	N/A	45	EM	0.040	1.800	1.760	Urban & rural

[55]	Turkey	30.9	Central Malatya	---	FM	1.890	3.300	1.410	City
[56]	Turkey	30.9	Samsun 1 mall	1	FM	---	7.880	---	City
[57]	Romania	41	2nd floor of a building	1	SA	0.070	0.090	0.020	City
[58]	Lithuania	41	N/A	---	FM	---	5.317	---	City

Table 2: Measured indoor exposures in different countries and legal limits. FM = Field Meter, SA = Spectrum Analyzer, EM = ExposiMeter, and # locations = number of locations.

2. Measurement Protocol

The measurements discussed and analysed in this work were carried out between September and December 2017 during working days. Outdoor measurements were performed at 9.00 am, 12.00 noon, 14.00 pm, 17.00 pm, 19.00 pm, 21.00 pm, and at midnight. Indoor measurements were carried out at 9.00 am, 12.00 noon, 14.00 pm, 17.00 pm, and 19.00 pm, excluding 21.00 pm and midnight as offices and shopping centres are closed then.

The measured frequency band ranges from 824 MHz to 2170 MHz. Most widely used radio communication bands, used for cellular transmission, are located in this band (GSM 900, GSM 1800, and UMTS 2110 MHz). The measurements consisted of a broadband measurement, in order to characterize the environment in terms of total radiation levels contributed by cellular communication systems in the area. LTE (Long-Term Evolution) was not considered in this campaign as the first trial measurement conducted prior to the measurement campaign showed that LTE base stations were only installed in few locations in the city centre of Leuven. Comparative measurements were carried out with two spectrum analyzers in order to obtain good results. The detection limit of these spectrum analyzers is about -90 dBm and the power levels measured were sufficiently high. Power levels below the noise floor (-65 dBm) of the measurement settings were neglected.

Measurements were performed with a dipole antenna mounted on a tripod and connected to one of the two spectrum analyzers. The person operating the measurement equipment was at least 2.5 m away from the tripod. The influence of body proximity on measured fields was also avoided for the public. This was done by a visible notice displayed at the measurement sites indicating that people should not walk close to the equipment as a measurement was going on. At first, test measurements were carried out at three heights (1.1, 1.5 and 1.7 m) above the floor. The maximum value was always obtained at 1.5m. As a result this height was used for all measurements, according to CENELEC [59]. Both indoor and outdoor measurements were carried out for the three orthogonal polarizations (vertical, in-plane horizontal and normal horizontal polarization) shown in Figure 1. During the exposure measurement, the maximum-hold setting was kept during a time interval of 6 minutes until the spectrum analyzer reading stabilized. The used equipment consisted of the following:

•two antennas including a penta band dipole antenna IR-GSMPB-02-C5 (gain 2 dBi in the 824 - 960 and 1710 - 2170 MHz frequency ranges) and a hyperLOG 7040 antenna (gain 4 dBi in the frequency band 700 MHz - 4 GHz),
• two portable spectrum analyzers: Anritsu MS2721A and Keysight N9344C,
• RF coaxial cable with SMA - SMA connectors,
• a tripod.
The settings of the spectrum analyzers were:
• Trace mode: MaxHold and RMS detection,
• Duration of each measurement: 6 minutes.
All electric field strengths were calculated with a resolution of 0.01 V/m.

2.1 *Measurement Uncertainty*

There are three dominant sources of uncertainty in the used measurement procedure: the spectrum analyzer, any mismatch errors, and the antenna performance. Most of the measurements were performed with the Anritsu MS2721A spectrum analyzer. According to its specifications the amplitude accuracy in the band of interest is ±1.25 dB [60]. Regarding the matching, the VSWR linked with the input port of the spectrum analyzer based on its settings during the measurements is 1.5 and the one linked with the receiving antenna is below 2 in the frequency band of interest. These two parameters allow to estimate the variation of the reflection coefficients (Γ_L,Γ_G) at the two ports, namely the load (spectrum analyzer) port and the generator (antenna) port. The standard power uncertainty (linear) can then be directly calculated using the approach introduced in [61, 62]. A conventional multiband dipole antenna was used in this campaign. The main reason is that larger dipole antennas have a considerably better sensitivity in comparison with an isotropic transducer containing short tri-axis probes. However, the radiation pattern of a larger dipole antenna deviates from the pattern of an infinitesimal dipole, leading to a deviation from isotropy. This is caused by the fact that the received power used to determine the field strength depends not only on the electric field strength as such but also on its phase distribution along the dipole. This effect was theoretically modeled in order to estimate the uncertainty following from this. CST Microwave studio was used to explicitly take into account the phase variation over the finite length dipole as a function of the incident wave direction and polarization. By considering both the known incident field strength (without the receiving antenna) with the simulated field strength in the presence of the receiving antenna, a relative error can be determined. This error increases with the frequency due to a

higher deviation of the dipole pattern from the sine pattern. The standard uncertainty (67%) estimated in this way varies from 0.4 dB for a half wavelength dipole at 950 MHz with normal broadside pattern to 1.1 dB at 1.8 GHz for the used multiband dipole where the main beam direction is tilted by 16 degrees away from broadside (normal to its axis). This tilt was measured in an anechoic chamber. A detailed explanation of the used algorithm is beyond the scope of this paper and will be reported in a dedicated technical journal. Note that an isotropic transducer containing 3 short orthogonal dipole antennas also suffers from a deviation from isotropy [63], but the origin of this deviation is of a different nature [64].

The total standard uncertainty taking into account the contribution from the various uncertainty sources, which are assumed to be statistically uncorrelated, is about 1.35 dB. The expanded uncertainty (95%) calculated using the coverage factor $k_p = 1.96$ is about 2.48 dB. A detailed overview is given in Table 3.

Cause of uncertainty	**Quantity/ Formula**	**Assumed probability distribution**	**Uncertainty**
Amplitude accuracy of spectrum analyzer	± 1.25 dB	Rectangular	0.75 dB
Power mismatch	$u(\Gamma_G, \Gamma_L) = 1.414 \bullet \Gamma_G \bullet \Gamma_L$	U-shape	0.39 dB
Antenna gain & pattern		Assessment based on simulations	1.1 dB

Table 3: Uncertainty for the electric field strength measurements.

2.2 *Measurement Locations*

The choice of the measurement locations was driven by the concentration of the base stations installed in the city center of Leuven, Belgium. The base stations seen in the course of this measurement, were building mounted and rooftop ones, as shown in Figure 2. Figure 3A shows the map of the base stations in Leuven. The ones which were operational within the period of the measurement campaign are in red, see [65]. The measurements were performed in thirty (30) outdoor locations and thirty (30) indoor locations spread out over the city center. This means that all base stations in the city center were covered in the measurement campaign. A permit was obtained from the city council in order to have official access to all public areas.
The choice of the exact measurement position was based on the proximity to a selected base station, as the intensity of the radiation decreases rapidly with distance from the emitting source. The horizontal component of the distance between a measurement spot and the closest base station was determined for all the measurements.

For the outdoor measurements, the exact measurement position in the immediate neighborhood of a specific base station was chosen in such a way that it corresponds to the position with the highest level of radiation exposure to which a person might be subjected, in conformity with [66]. This was achieved by performing measurements in a zone of about 10 m diameter at a certain distance from the base station location, thereby selecting the spot with the highest exposure. Since buildings, trees and other solid objects may significantly absorb, reflect or scatter the RF signals, the outdoor locations were based on the line-of-sight criterion and further specified in detail by checking the levels using the measuring equipment in the neighborhood of the base stations. For outdoor locations measurement spot coordinates were recorded by using the Global Positioning System (GPS), see Figure 3B.
The indoor environments considered include residential homes, offices, event centers, the Leuven railway station, shopping centers, and colleges. Broadband measurements were performed in all the rooms of chosen homes (including bed room, sitting room, and kitchen). Measurements were performed up to the highest floor of colleges and offices, as the maximum field is not necessarily observed on the highest floor but possibly on the floor which coincides with the height of the building in which the base station is installed. For class rooms and typical offices, the whole area was scanned for the maximum exposure. For the public areas (including shopping malls, gym center, and railway station), extensive exposure measurements were taken with the knowledge of both the closest base station and other surrounding base stations.

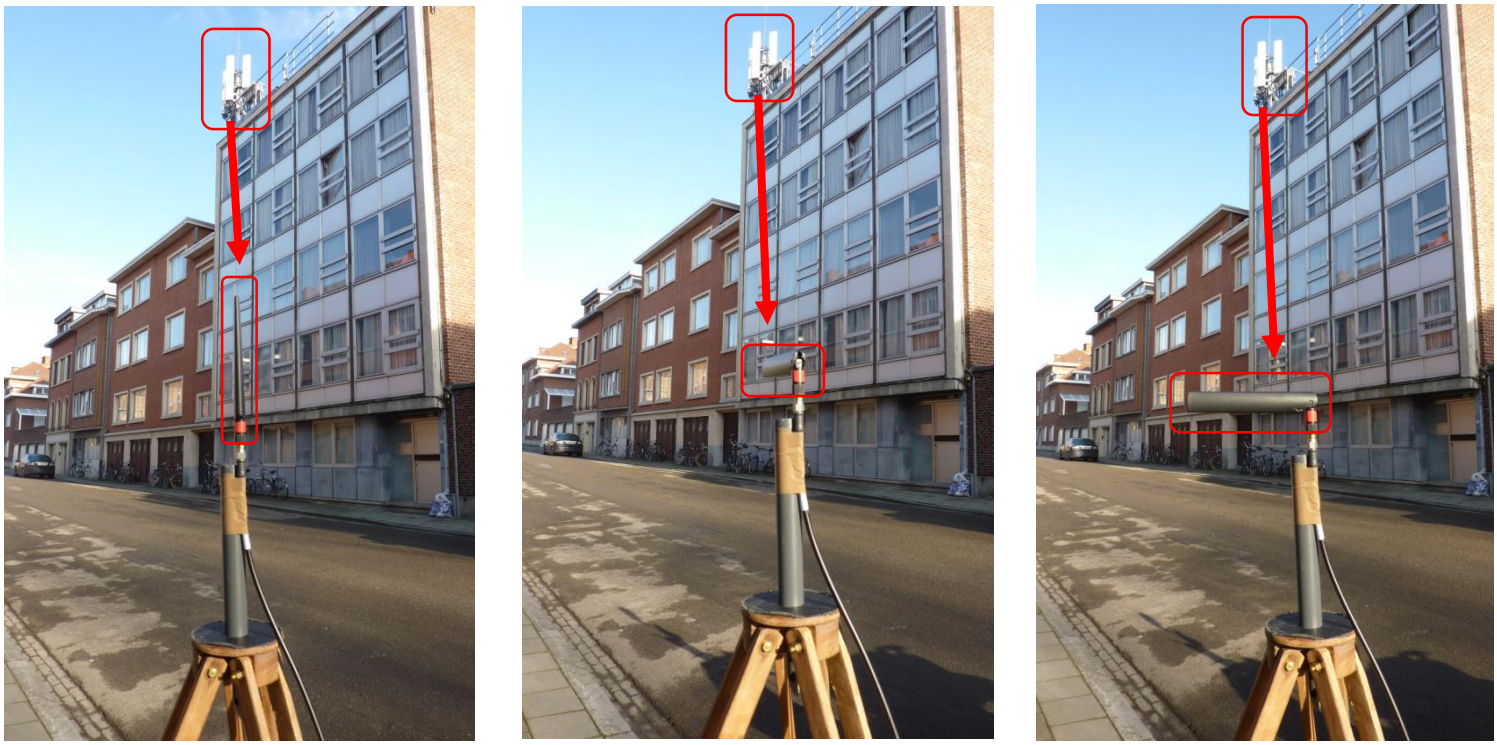

Figure 1: Example of a measurement location. The receiving antenna is in the red box close to the arrow head. The arrow is coming from the base station, which is also indicated by a red box. Left: vertical polarization, middle: in-plane horizontal polarization, right: normal horizontal polarization.

Figure 2: Building mounted base station (left), rooftop base station (middle), and mast installed on building (right)

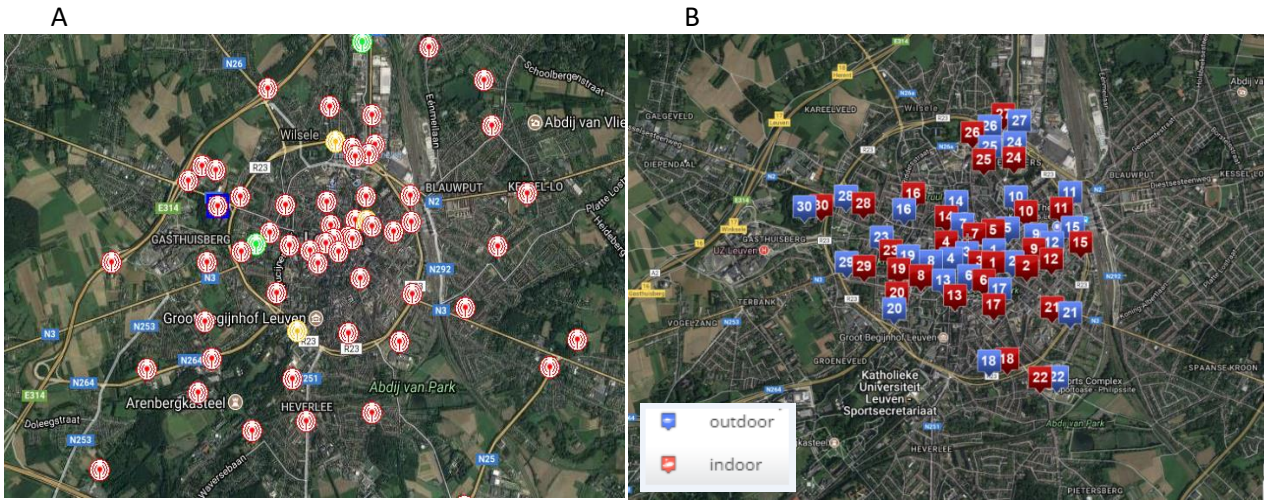

Figure 3: Map of base stations in Leuven [65] (left) & Indoor/outdoor measurement locations considered in Leuven city centre (right)

2.3 *Measurements*

During the processing of the data, in order to obtain the received power at the position of the antenna (P_{ant}), the cable losses (P_{cab}) have to be considered:

$$P_{ant} = P_{dBm} + P_{cab} \cdot l \qquad (1)$$

where l is the cable length and P_{cab} the losses, normally known in dB/m.

The cable losses are easily measured with a vector network analyzer (VNA). The incident field at the position of the antenna was obtained by taking into account the gain of the antenna in the expression (4) below. The raw data as measured by the SA (Spectrum Analyzer) are illustrated in Figures 4 and 5 for the three bands measured: GSM 900, GSM 1800, and UMTS.

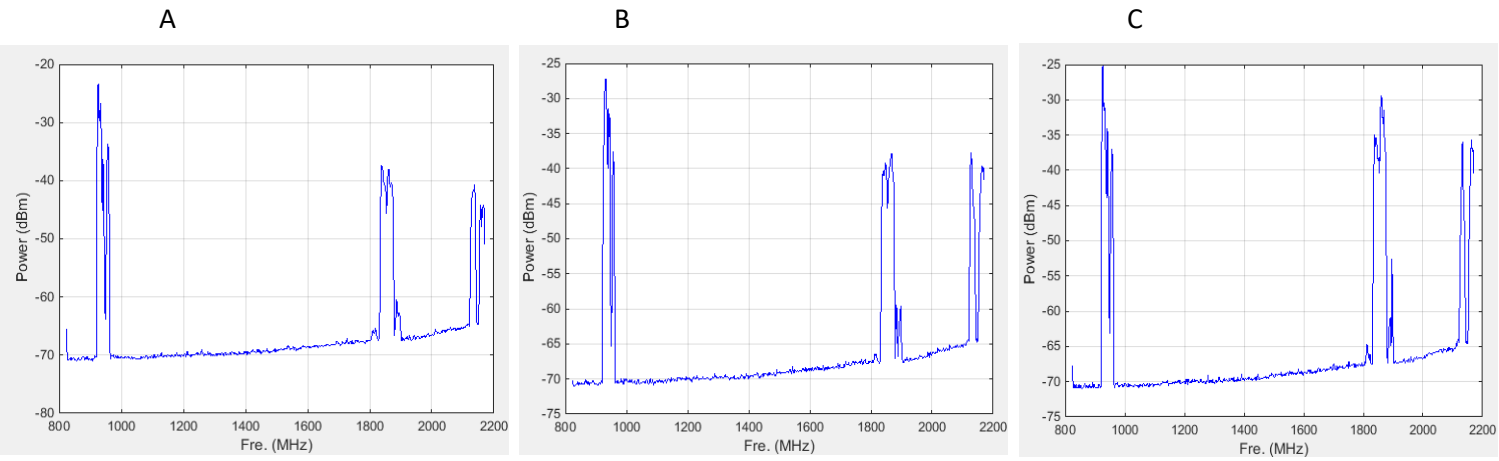

Figure 4: Raw SA outdoor measurement at Minderbroedersstraat 9: vertical polarization (A), in-plane horizontal polarization (B) and normal horizontal polarization (C).

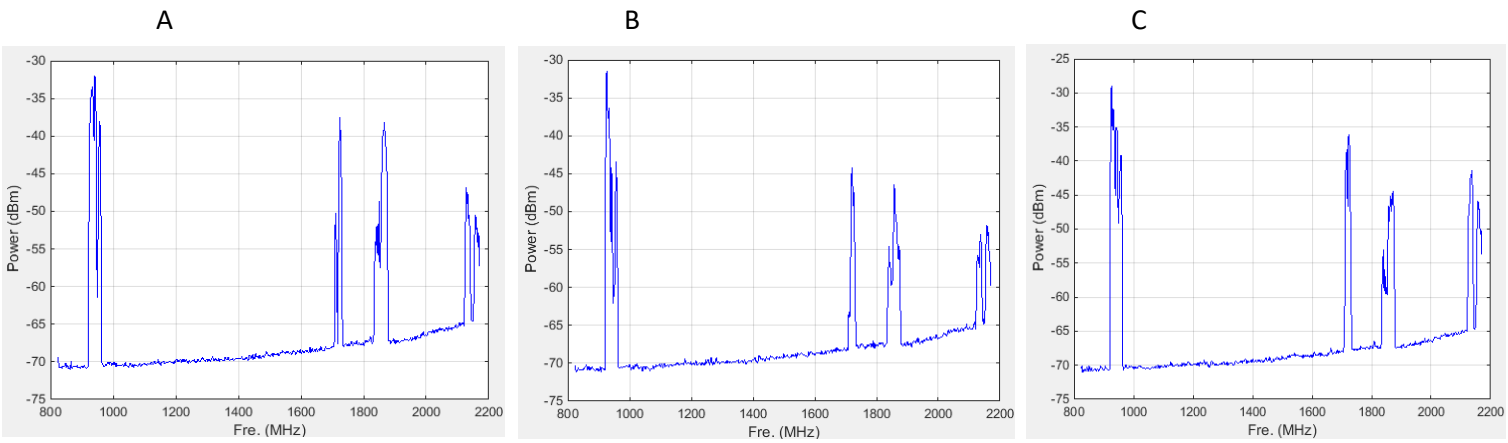

Figure 5: Raw SA indoor measurement at Minderbroedersstraat 9: vertical polarization (A), in-plane horizontal polarization (B) and normal horizontal polarization (C).

To determine the electric field strength values, expressions 2 are substituted into expression 3:

$$S = \frac{e^2}{120\pi} \quad \text{and} \quad G = \frac{4\pi}{\lambda^2} A_{eff} \qquad (2)$$

$$P_r = S.\ A_{eff} \quad (3)$$

For a plane wave which is incident on the antenna, the relationship between field strength and received power can be written as

$$e = \sqrt{\frac{480\pi^2}{\lambda^2}\frac{P_r}{G}} = \sqrt{K \cdot P_r} \quad (4)$$

with $K = \frac{480\pi^2}{\lambda^2}\frac{1}{G}$

where

e = field strength (V/m)
λ = wavelength in free space (m)
P_r = received power (W)
G = antenna gain
A_{eff} = antenna effective area (m^2)
S = power density (W/m^2)

The total field, combining the three polarizations, was obtained by summing in a "root sum square" way.

$$E = \sqrt{\sum_i e_i^2} \quad (5)$$

The total fields in the GSM 900, GSM 1800, and UMTS operational bands were obtained also by summing over the discrete measurement points in the corresponding band in a root sum square way.

The electric field strength at each specific time for the 60 measurement locations was computed and the spread over time was calculated by subtracting the lowest electric field from the highest.

The main characteristic of this measurement protocol is that it involves computing the averages of maximum exposure around base stations, both over time (6 minutes measurement interval, processed data even over a day), over space (many different locations), and frequency (several bands together). This means that it does not give any information on a specific exposure on a specific time in a specific spot for a specific base station. However, this averaging is exactly the point of the paper. Instead of being viewed as a weak point, this can thus actually

be seen as the strong point, since it gives a very good general view on exposure.

3. Results and Discussion

3.1 *Daily variation*

Since a measured value depends on the time at which the measurement was performed, it is essential to quantify the daily variations. This shows how the exposure varies during peak and off hours during day and night. The average values (over time) and the range for all 60 locations are depicted in Figures 6 and 7. Each span represents the minimum-maximum range of all measurements at a location. From all the locations considered the highest average field value measured is 1.71 V/m at location 2 in Figure 6 generated by the GSM 900 signal. It can be deduced from the graphs (Figures 6 and 7) that GSM 900 exposure mostly dominates over GSM 1800 and UMTS. For 23 outdoor locations out of 30, which is 76%, the level of GSM 900 is higher than the level of GSM 1800 and UMTS. The same is valid for 22 indoor locations out of 30, which is 73%. The lowest outdoor exposure (in percentage of legal limit for Flanders) is in the order of 7.6% for GSM 900, 2.8% for GSM 1800, and 2.9% for UMTS. The lowest indoor exposure is in the order of 4.6% for GSM 900, 2.3% for GSM 1800 and 1% for UMTS. The highest outdoor values measured represent 57% of the legal limit for GSM 900, 33.3% for GSM 1800 and 15.3% for UMTS. The highest indoor values represent 26.3% for GSM 900, 14.8% for GSM 1800, and 10.2% for UMTS.

The outdoor exposure for GSM 900 is clearly higher than the indoor exposure except in location 13 where the exposure levels for all communication systems are similar. Similarities in exposure levels for indoor and outdoor locations also exist for GSM 1800 and UMTS in about 5 locations but for 25 locations the outdoor exposure is clearly higher than the indoor exposure. In absolute levels the outdoor field is ca. the double of the indoor field exposure. In terms of average, the field intensities for both outdoor and indoor vary over the measurement time as this is much dependent on the number of mobile phone calls and data transmission.

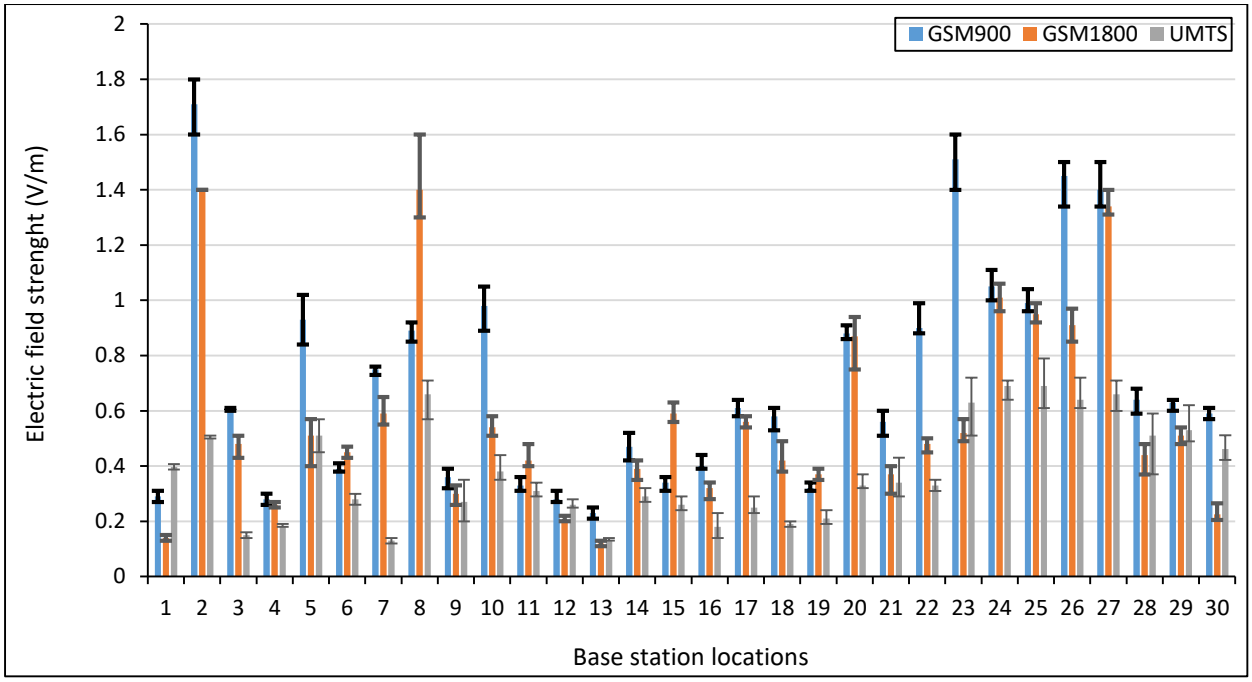

Figure 6: Average (over time, in colour) and range (max – min, as black bar) of electric field strength measured for the 30 outdoor locations near individual base stations.

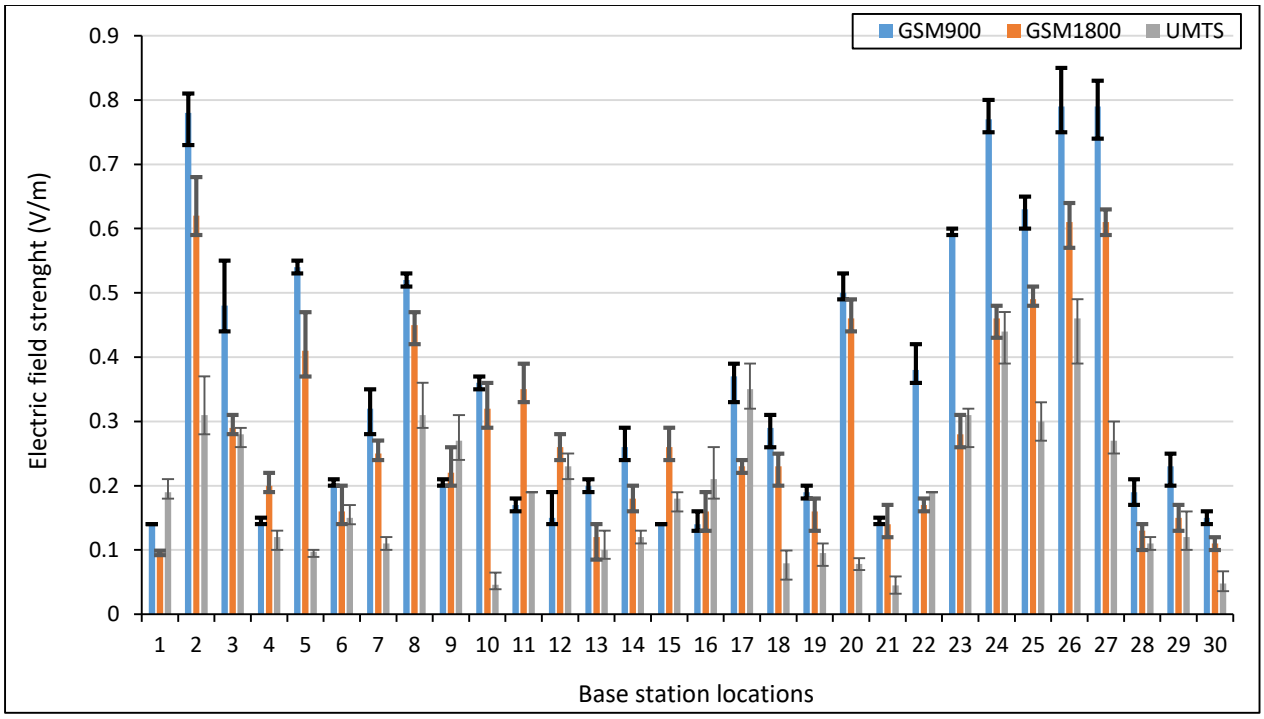

Figure 7: Average (over time, in colour) and range (max – min, as black bar) of electric field strength measured for the 30 indoor locations near individual base stations

3.2 *Reproducibility*

After the completion of the measurements at the 30 outdoor base station locations, a second measurement was performed (one month after the first measurement) at exactly the same spot as in the first measurement for three base station locations (6, 8, and 23). The results, both for the first and the second measurement, are shown in figures 8a, 9a and 10a below. The field strength level varies slightly over time for the three communication systems. The standard deviations for both measurements over time (for all three locations) are shown in Figures 8b, 9b and 10b. Also, there it can be seen that GSM 900 and UMTS behave similarly (in the 3 locations) in both measurements while GSM 1800 behaves slightly different in figure 9b. These variations in the exposure levels could be due to environmental changes and the network load at the time the measurement was performed.

It is clearly seen in figures 8, 9 and 10 that at least in this measurement campaign the field strengths are reproducible over a time span of ca. one month. For instance the field values obtained for GSM 900 during the first/second measurement at 9.00 am are 0.38/0.40, 0.80/0.70, 1.50/1.30 V/m. This last result was beyond our expectations.

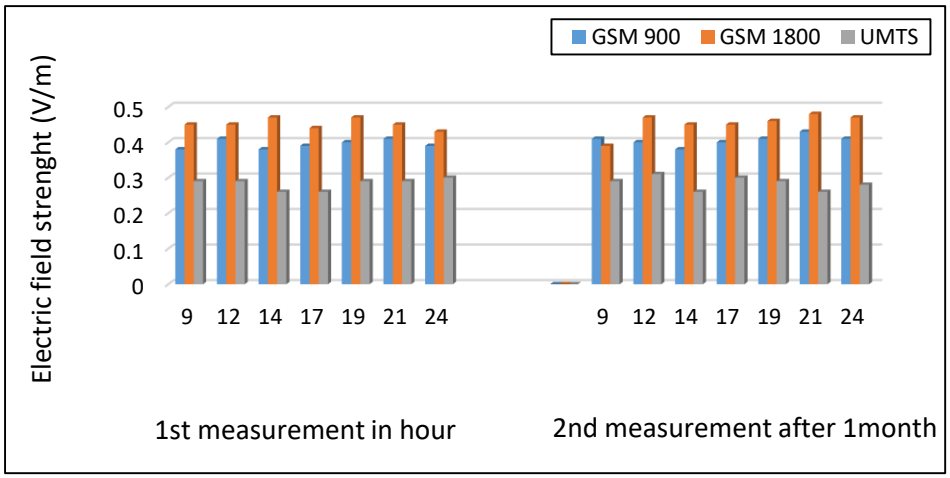

Figure 8(a): Electric field strength measurement at a specific point in location 6

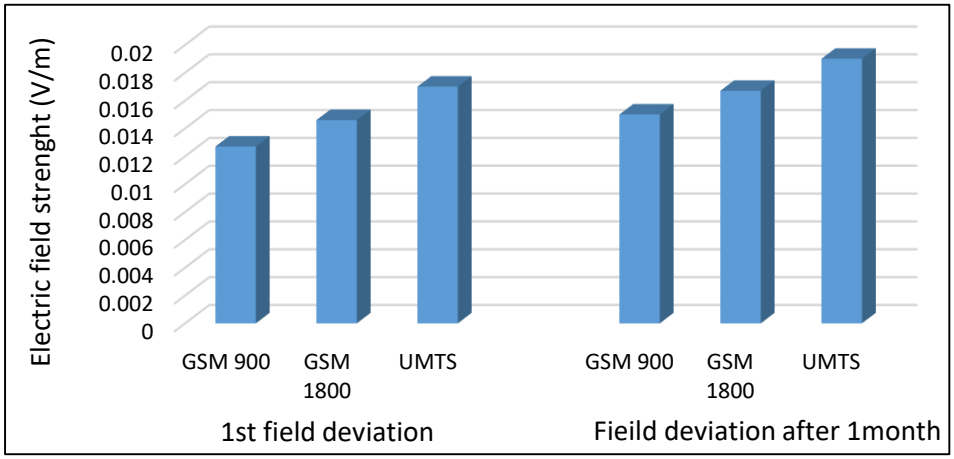

Figure 8(b): Standard deviation for all daily measurements at location 6

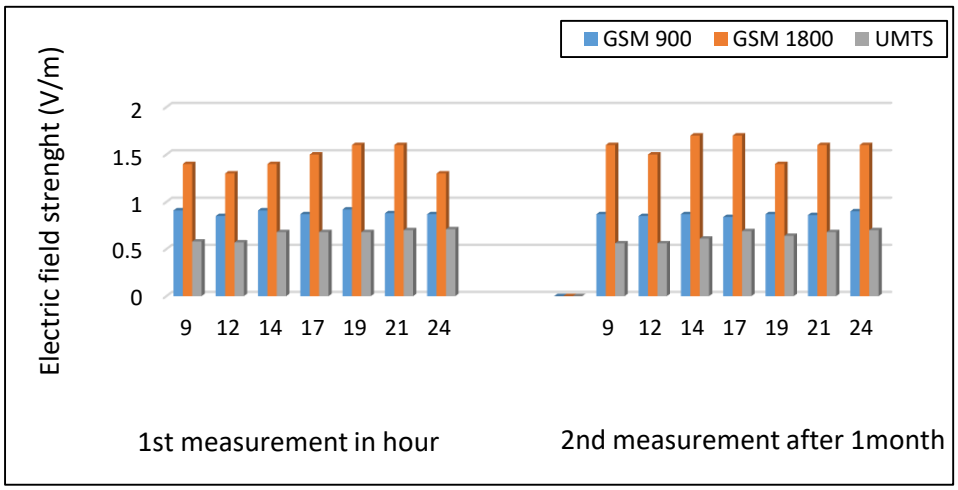

Figure 9(a): Electric field strength measurement at a specific point in location 8

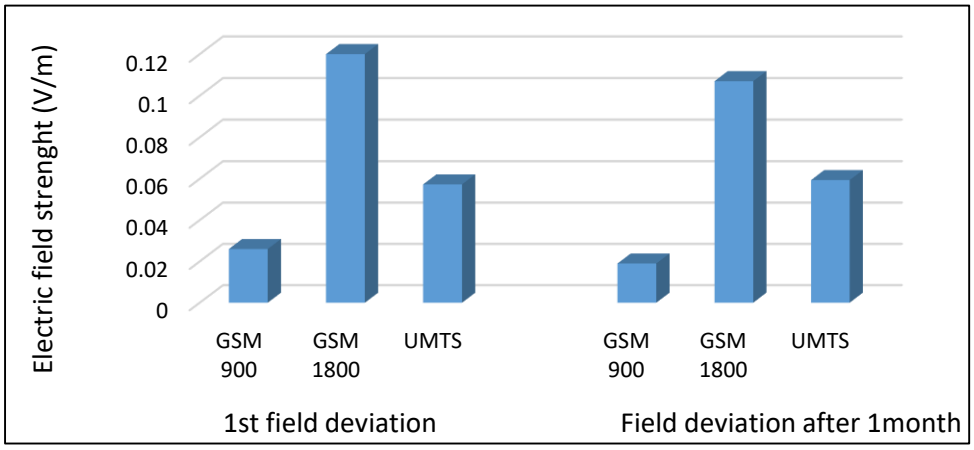

Figure 9(b): Standard deviation for all daily measurements at location 8

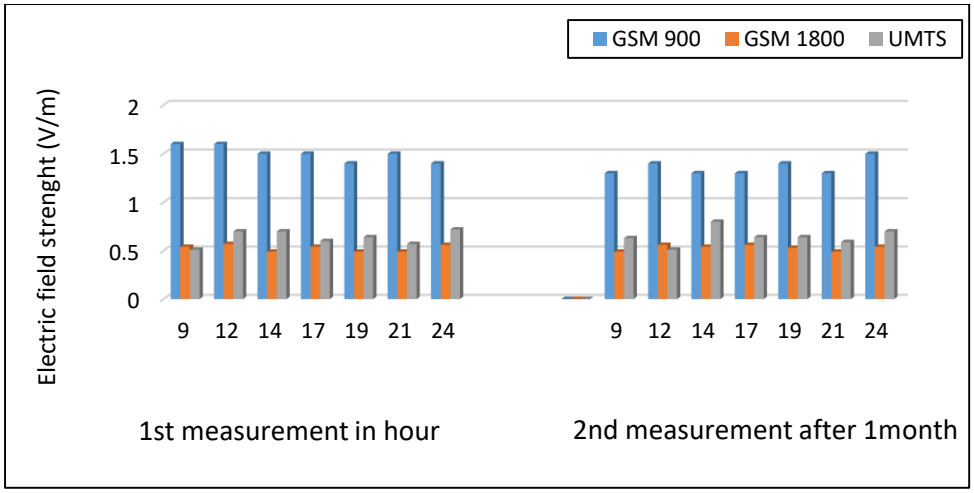

Figure 10(a): Electric field strength measurement at a specific point in location 23

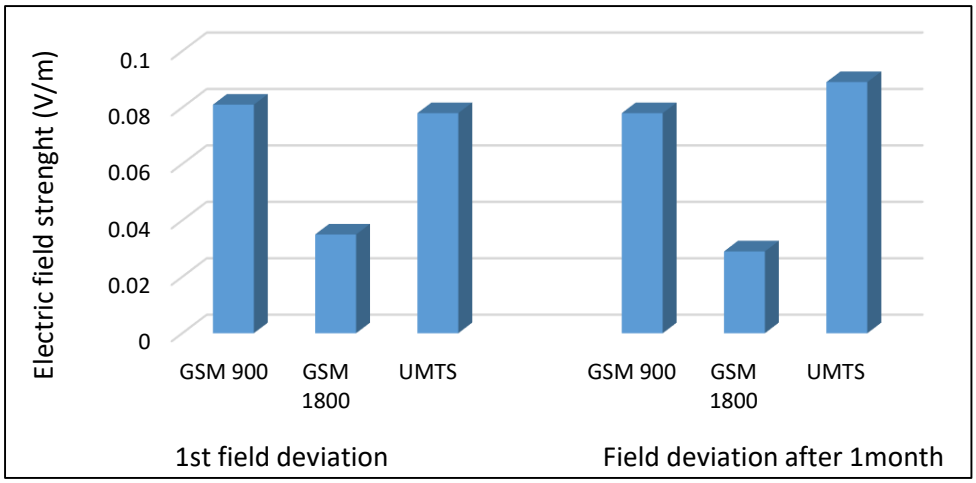

Figure 10(b): Standard deviation for all daily measurements at location 23

3.3 *Average, Standard Deviation, and Spread for the Whole City Center of Leuven at Specific Times*

In Figures 11 and 12, the exposure level averaged over the entire city center is given for both the outdoor and indoor environments, respectively. It can be seen that there is a very slight variation over time. The values for outdoor are 0.64, 0.53 and 0.33 V/m for GSM 900, GSM 1800 and UMTS respectively, and for indoor 0.32, 0.26 and 0.17 V/m for GSM 900, GSM 1800 and UMTS, respectively. The highest outdoor exposure is observed at 9.00 am for GSM 900, 5.00 pm for GSM 1800 and at midnight for UMTS. For the indoor environment, the highest exposure is observed at 12.00 noon for GSM 900, 2.00 pm for GSM 1800 and 9.00 am for UMTS. The exposure level in the outdoor environment is almost the double of the one indoors for all communication

systems. Indoor/outdoor average fields are 0.32/ 0.64 V/m for GSM 900, 0.26/0.53 V/m for GSM 1800, and 0.17/0.33 V/m for UMTS.

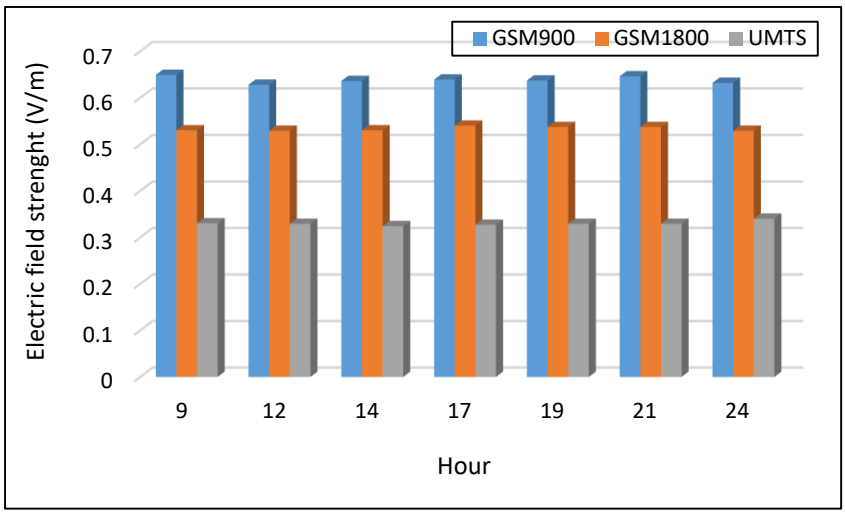

Figure 11: Average outdoor exposure for the entire city centre of Leuven versus time.

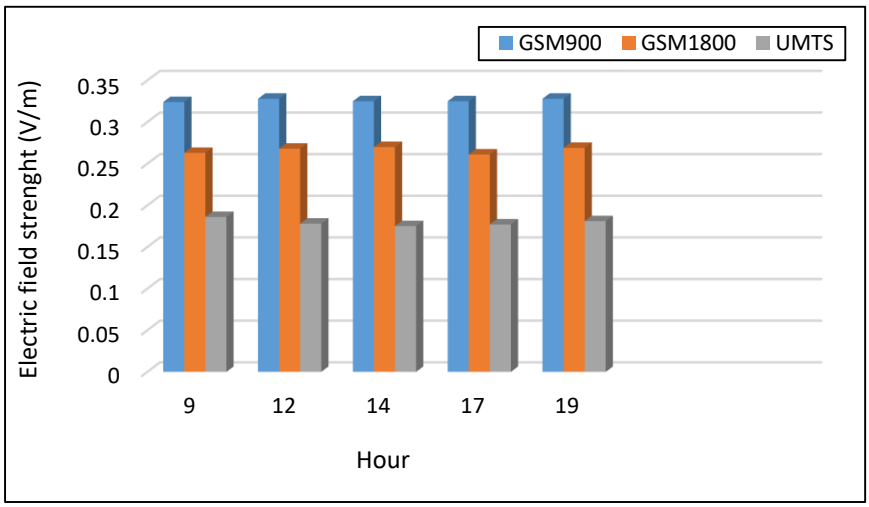

Figure 12: Average indoor exposure for the entire city centre of Leuven versus time

The standard deviation of the exposure values, which is calculated from the variation of the electric field strength over locations, versus time is given for the entire city center in Figures 13 and 14, respectively. The outdoor standard deviation/outdoor average values for GSM 900, GSM 1800 and UMTS at 9.00 am includes 0.35/0.62, 0.30/0.5 and 0.15/0.30 V/m. At 12.00 noon (0.33/0.60, 0.28/0.16 V/m), 14.00 pm (0.35/0.61, 0.30/0.50, 0.15/0.30 V/m), 17.00 pm (0.34/0.61, 0.30/0.51, 0.15/0.30 V/m) and at 19.00 pm (0.35/0.61, 0.32/0.51, 0.15/0.30

V/m). It is seen that in general the outdoor standard deviation is almost one-half of the average for all the communication systems. This is also true for the indoor exposure, except at 12.00 noon for GSM (900 and 1800) and, at 9.00 am and 7.00 pm for UMTS, when the standard deviation is slightly higher than one-half of the average.

The spread of the electromagnetic exposure given in Figures 15 and 16 is very wide for GSM 900 and 1800, while considerably lower for UMTS. From the graphs it is seen that the exposure level for GSM 900 and 1800 behave almost similarly. The high variation is due to the dynamic behaviour of the instantaneous effective power from base stations, which greatly depends on the instantaneous traffic of mobile calls and data communication. This suggests that GSM is the most used system.

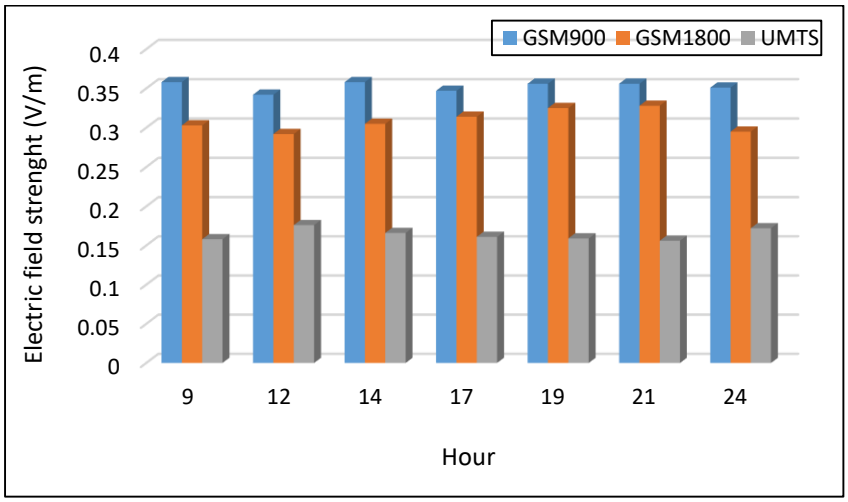

Figure 13: Standard deviation (outdoor) for the entire city centre of Leuven versus time

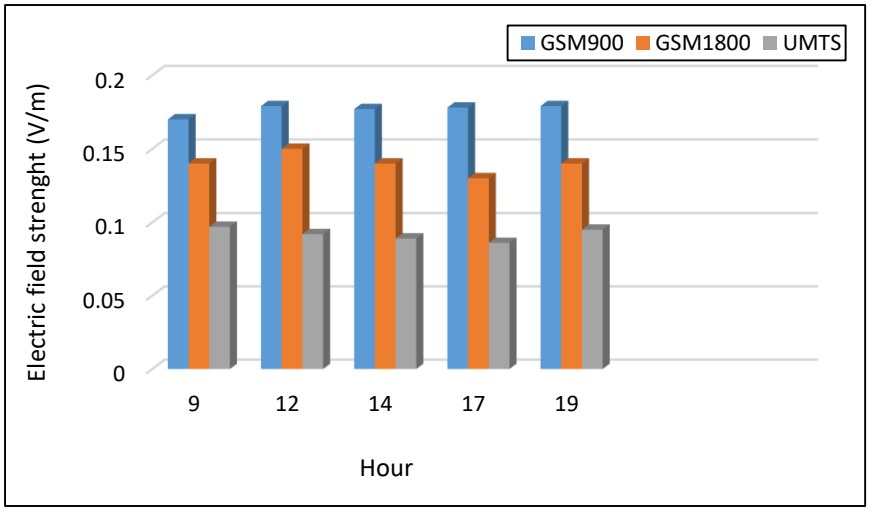

Figure 14: Standard deviation (indoor) for the entire city centre of Leuven versus time.

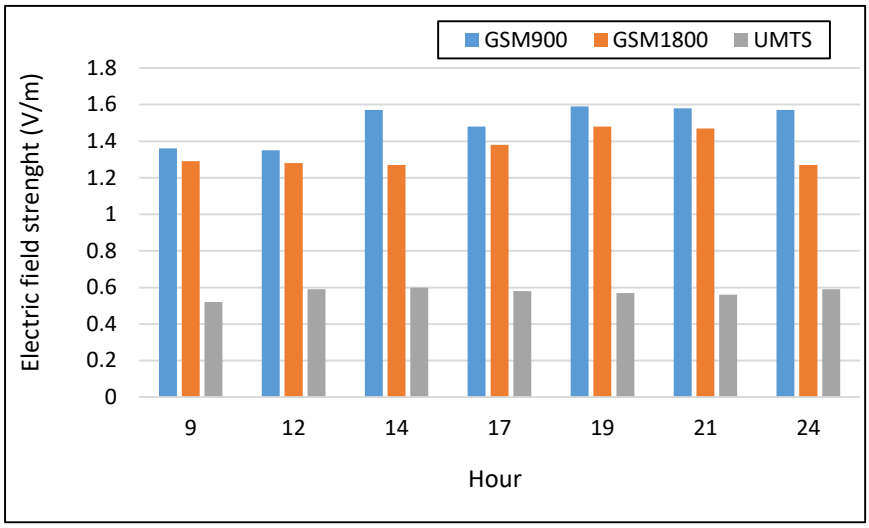

Figure 15: Spread of outdoor electric field for the entire city centre of Leuven versus time.

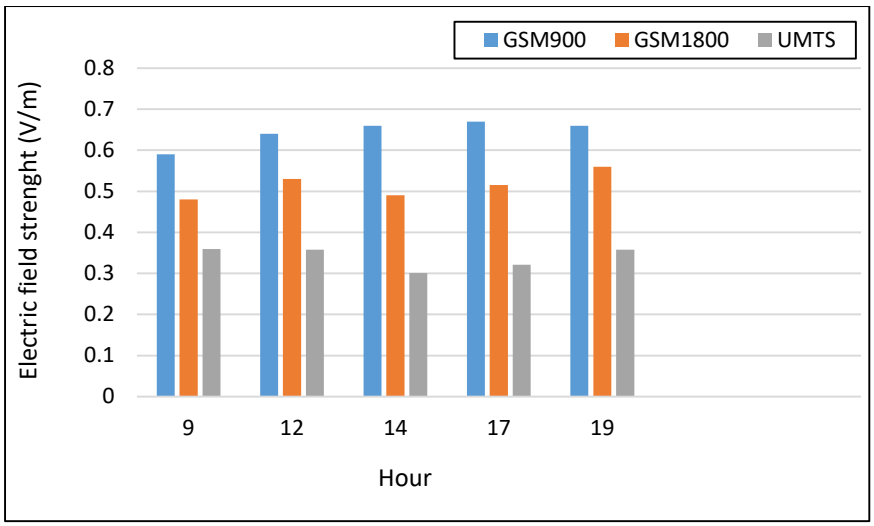

Figure 16: Spread of indoor electric field for the entire city centre of Leuven versus time

3.4 *Correlation between Indoor and Outdoor Exposure*

A more detailed analysis of Figure 7 learns that 26.7%, 30% and 53.3% of the indoor locations yielded an average value smaller than 0.2 V/m for GSM 900, GSM 1800 and UMTS respectively. For the outdoor locations shown in Figure 6; these numbers were 0% for GSM 900, 6.7% for GSM 1800 and 13.3% for UMTS. Further, in Figures 11 and 12 it is clearly seen that there is a strong correlation between the (quasi constant) average exposures over

time for GSM 900, GSM 1800, and UMTS between outdoor and indoor. For GSM 900, GSM 1800 and UMTS the ratio outdoor over indoor average exposure is about 2. The same ratio for the standard deviation, as seen in Figures 13 and 14, is about 2. This suggests that the variation of the exposure outside and inside is similar. The spread, as depicted in Figures 15 and 16, yields a ratio of about 2 for GSM 900 and 1800, and a bit less than 2 for UMTS.

The exposure ratio, which is defined as the maximal field over the ICNIRP reference field level, is given in Table 3. These ratios of about 2 are in correspondence with the ratio that one would expect based on the attenuation through the average walls used in houses.

	Indoor			**Outdoor**		
	Variation over 30 locations			**Variation over 30 locations**		
RF signal	**E_{min} [V/m]**	**E_{max} [V/m]**	**Exposure ratio ER^i [%]**	**E_{min} [V/m]**	**E_{max} [V/m]**	**Exposure ratio ER^o [%]**
GSM 900	0.14	0.83	2.02	0.21	1.80	4.39
GSM 1800	0.09	0.68	1.17	0.11	1.60	2.76
UMTS	0.04	0.49	0.80	0.13	0.79	1.29
Total signal	0.17	1.18	-	0.27	2.53	-

Exposure ratio indoor ER^i = indoor maximal field value / ICNIRP exposure limit
Exposure ratio outdoor ER^o = outdoor maximal field value / ICNIRP exposure limit
Table 3: Variation of electric field strength for 60 measurement locations and exposure ratio.

4. Conclusions

The electromagnetic radiation exposure of the general public generated by base stations in Leuven, Belgium, was duly assessed using spectrum analyzer measurements at 60 locations and at several moments during the day. All measured values are considerably below norm levels for Flanders, which means that they are far below the ICNIRP exposure limits for the general public. The average levels over time and over the whole city center are: outdoors about 0.64 V/m for GSM 900, 0.53 for GSM 1800, and 0.33 for UMTS, and indoors about 0.32 V/m for GSM 900, 0.26 for GSM 1800, and 0.17 for UMTS. To the average, the outdoor exposure levels are thus a factor of two higher than the indoor levels. In general, the dominating source of exposure is GSM 900. The maximum field value measured was equal to 1.80 V/m, due to the GSM 900 signal. In this study, the average effect of

absorption and reflection, typically used to explain the lower values indoors, is in agreement with the average attenuation through walls used in propagation models.

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