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ASSESSMENT OF RF EXPOSURES FROM EMERGING WIRELESS COMMUNICATION TECHNOLOGIES IN DIFFERENT ENVIRONMENTS

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Abstract- **In-situ electromagnetic (EM) radio frequency (RF) exposure to base stations of emerging wireless technologies is assessed at 311 locations, 68 indoor and 243 outdoor, spread over 35 areas in three European countries (Belgium, The Netherlands, and Sweden) by performing narrowband spectrum analyzer measurements. The locations are selected to characterize 6 different environmental categories (rural, residential, urban, suburban, office, and industrial). The maximal total field value was measured in a residential environment and equal to 3.9 V/m, mainly due to GSM900 signals and 11**

times below the ICNIRP reference levels for electric field strength. Exposure ratios for maximal electric field values with respect to ICNIRP reference levels, range from 0.5 % (WiMAX) to 9.3 % (GSM900) for the 311 measurement locations. Exposure ratios for total field values vary from 3.1 % for rural environments to 9.4 % for residential environments. Exposures are lognormally distributed and are the lowest in rural environments and the highest in urban environments. Highest median exposures were obtained in urban environments (0.74 V/m), followed by office (0.51 V/m), industrial (0.49 V/m), suburban (0.46 V/m), residential (0.40 V/m), and rural (0.09 V/m) environments. The average contribution to the total electric field is for GSM more than 60 %. Except for the rural environment, average contributions of UMTS-HSPA are more than 3 %. Contributions of the emerging technologies LTE and WiMAX are on average less than 1 %. The dominating outdoor source is GSM900 (95th percentile of 1.9 V/m), indoor DECT dominates (95th percentile of **1.5 V/m).**

***Key Words*- RF exposure, base station, exposure of general public, measurement, telecommunication, UMTS, HSPA, LTE, WiMAX, DECT, environment, emerging technology.**

I. INTRODUCTION

The WHO International EMF Project's RF Research Agenda identified as a research topic a need for measurement surveys to characterize population exposures from all radio-frequency (RF) sources, with a particular emphasis on new wireless technologies (WHO 2010). There is a need to conduct measurements to assess the typical range of exposures from existing and emerging wireless network technologies such as WiMAX (Worldwide Interoperability for Microwave Access), HSPA (High Speed Packet Access), and LTE (Long Term Evolution) in a range of common locations (outside public areas, within buildings, homes, etc.) and compare the exposure contributions to existing exposures from e.g., FM, TV, GSM, etc.

Procedures for measurements in the vicinity of GSM (Global System for Mobile Communications) and UMTS (Universal Mobile Telecommunications System) base stations have been developed in (Kim et al. 2008, Lehmann et al. 2002, Joseph et al. 2006, Neubauer et al. 2002, Olivier and Martens 2007). Bornkessel et al. 2007 provided results of temporal and spatial measurements of GSM and UMTS signals. Measurements in the neighborhood of WiMAX base stations are investigated in Joseph et al. 2008. Foster 2007 investigated exposure of Wi-Fi access points and checked compliance with international guidelines (ICNIRP 1998, IEEE C95.1 2005, FCC 2001). Also Kühn et al. 2007, Myhr 2004, Schmid et al. 2007, and Verloock et al. 2010 investigated short-period exposures caused by Wi-Fi access points. Exposures from TV and radio transmitters have been studied in e.g., Joseph and Martens 2006 and Sirav and Seyhan 2009. Tomitsch et al. 2010 measured exposures in bedrooms of residences: highest values were caused by DECT telephone base stations (3.31 V/m or 28,979 $\mu W/m^2$) and mobile phone base stations (1.36 V/m or 4,872 $\mu W/m^2$). Finally, exposures from LTE have recently been investigated in Joseph et al. 2010b.

Procedures for RF exposure measurements in the vicinity of base stations have thus already been developed and a standard has been written for the *in-situ* measurement of electromagnetic-field strength related to human exposure in the vicinity of base stations

(CENELEC, 2008) but assessment of exposure to electromagnetic fields of emerging wireless systems such as HSPA, LTE, and mobile WiMAX and the characterization of exposure distributions and variability in different environments are missing.

Measurement campaigns of RF exposures using personal exposimeters and their results have been presented (Frei et al. 2009, Joseph et al. 2008b, 2010c, Knafl et al. 2008, Neubauer et al. 2007, Roösli et al. 2008, Viel et al. 2009). Exposimeters are not suitable for accurate field assessment and current personal exposimeters cannot measure accurately e.g., LTE and WiMAX (Bolte et al. 2011), but one can use these to obtain an idea about exposure distributions.

In this paper a methodology and design of measurement campaign will be presented to experimentally determine in-situ electromagnetic field exposure of general public due to new wireless sources in various environments. The purpose of this study is to provide a range of typical RF exposure values from base stations, investigate the exposure distributions, compare the contribution of the various RF sources, and check compliance with the ICNIRP guidelines for general public exposure (ICNIRP 1998). Moreover, LTE exposures in the first commercial deployment (Stockholm, Sweden) and mobile WiMAX exposure (IEEE 802.16e 2005) (Amsterdam, The Netherlands) were assessed during this measurement campaign. Only exposures due to base stations are considered here and not due to mobile handsets. The results, procedures, and methodologies of this paper can be used by authorities and epidemiologists to estimate the exposure from RF emitting sources and gain insight in which environments highest exposures occur and due to which sources. Moreover, the exposure variability that can be expected between different environments is presented here. Knowledge about these exposure distributions and variability is useful for the planning of future studies.

II. MATERIALS AND METHOD

A. Measurement locations

The 311 different measurement locations, spread over 35 areas or sites, are subdivided into 6 different categories depending on the type of environment, population density, the available wireless technologies (e.g., mobile WiMAX in the urban environment of Amsterdam, The Netherlands and LTE in Stockholm, Sweden), and the expected amount and time of traffic: rural, residential, urban, suburban, office, and industrial environments. Table 1 summarizes the categories and the number of indoor and outdoor measurement locations per category. Also a short description of the categories is added. These sites are geographically spread across Belgium, The Netherlands, and Sweden. 243 outdoor locations and 68 indoor locations were selected. Fig. 1 shows the measurement locations on different maps: in Fig. 1 (a) the numbers 1-35 represent areas or sites in Belgium and The Netherlands where about 8-10 measurements are performed per site (corresponding with measurements executed during a day, Joseph et al. 2008, 2010b), Fig. 1 (b) shows the 30 measurement locations in and around Stockholm, Sweden. In order to compare base station exposure of different sources, these measurement locations were randomly selected, spread over the three countries. The measurements were performed in the period September 2009 - April 2010.

B. Measurement procedure

Electromagnetic-field measurements in the band 80 MHz – 6 GHz were performed at 311 different locations with a spectrum analyzer (SA) (noted as *narrowband measurements*). "Max-hold measurements" of all present signals are executed for about 30 minutes at each location, depending on the number of frequency bands to be measured. A *max-hold measurement* is defined here as a narrowband measurement of a signal with the maximum-hold setting kept during a time interval until the SA reading stabilizes. Typically, narrowband measurements (in- and outdoor) are executed at 8 to 10 locations per site. The measurement probe is positioned at 1.5 m above the ground (CENELEC 2008).

The measurement setup of the narrowband measurements consisted of tri-axial Rohde and Schwarz R&S TS-EMF Isotropic Antennas (dynamic range of 1 mV/m – 100 V/m for the frequency range of 80 MHz – 3 GHz, and 2.5 mV/m – 200 V/m for the frequency range of 2 GHz – 6 GHz) in combination with a spectrum analyzer (SA) of type R&S FSL6 (frequency range of 9 kHz – 6 GHz) (http://www2.rohde-schwarz.com, R&S Belgium, Excelsiorlaan 31 1930 Zaventem Belgium). The measurement uncertainty for the electric field is ± 3 dB for the considered setup (CENELEC 2008). This uncertainty represents the expanded uncertainty evaluated using a confidence interval of 95 %.

Current wireless RF sources are mainly operating in the frequency range of 80 MHz up to 6 GHz. After allocating the present signals by a spectral survey, these signals were measured more in detail. Base station exposures of the 12 following different RF signals in the band 80 MHz – 6 GHz are determined (explanation of abbreviations is listed below Table 2), namely FM, T-DAB, TETRA, PMR, DVB-T, GSM900 and GSM1800, DECT, UMTS-HSPA**,** WiFi, LTE, and WiMAX. The narrowband measurements were executed during daytime at weekdays. The used setup for narrowband measurements enables the most accurate assessment of in-situ exposure from various sources (CENELEC, 2008).

Table 2 lists the different RF signals, while the sensitivities of the measurement system for the various signals are provided in Table 3: they vary from 0.002 V/m for TETRA/PMR/GSM900 to 0.013 V/m for WiMAX. These sensitivities depend upon the frequency due to the varying antenna factor (sensitivity) of the tri-axial measurement probes in the considered frequency range.

C. Settings of measurement equipment

If the SA-settings for narrowband max-hold measurements are discussed in literature, almost never all parameters (and certainly not the sweep time) are discussed or only vaguely specified. These settings have a huge influence on the measurement results. Therefore, it is very important to specify these (Verloock et al. 2010). To determine the (optimal) settings to check compliance of the different signals with the ICNIRP guidelines, the method of Verloock et al. 2010 is used. After investigations, we obtained the settings listed in Table 3 to perform exposure assessment of the various signals. The most important settings are these of detector mode (rms or root-mean-square), resolution bandwidth RBW, and sweep time SWT. Concerning the video bandwidth VBW, CENELEC 2008 recommends that VBW > 3·RBW. These settings have been determined and tested in-lab and in-situ. Methods and details for these settings can be found in CENELEC, 2008, in recommendation ITU-R. 1708 of ITU 2005, Joseph et al. 2008, Verloock et al. 2010, and Joseph et al. 2010b. These references for optimal exposure assessment of the different technologies are also provided in Table 3.

We have to remark that the use of max-hold measurements may result in larger overestimations for GSM and DECT than for other signals. The SA's maximum-hold setting retains the maximum measured values, resulting in an overestimation of e.g., hopping GSM signals because it is assumed that all maxima are simultaneously present using this setting (this is thus a kind of worst-case measurement). Also base station exposure to DECT is overestimated as DECT is a TDD system (Time-Division Duplex) and thus uplink traffic due to DECT mobile phones is also measured.

D. Data analysis

We consider in this paper as exposure metrics the electric-field strength E [V/m] of an RF signal, the total electric field E_{tot} [V/m] of all RF signals present, and the power density S [W/m^2]. Furthermore exposure ratios ER and average (AC) and maximal (MC) contributions are defined.

The exposure ratio ER of an RF signal is defined as the ratio between the maximal measured electric field value for the considered signal type over the 311 locations and the corresponding ICNIRP reference level:

$$ER = 100 \cdot \frac{\max\limits_{i=1...N}(E_{signal,i})}{L_E} \; [\%] \tag{1}$$

With *max()* the maximum value over N locations (N = 311 when considering all data), $E_{signal,i}$ [V/m] the field strength of an RF signal (e.g., FM, GSM, LTE, etc.) at location i, respectively, L_E the corresponding ICNIRP reference levels for electric-field strength in V/m. A ratio smaller than 100 % means that the ICNIRP reference levels are satisfied.

The exposure ratio can also be defined with respect to power densities (denoted as ER_S):

$$ER_S = 100 \cdot \frac{\max_{i=1...N}(S_{signal,i})}{L_S} = 100 \cdot \left(\frac{\max_{i=1...N}(E_{signal,i})}{L_E} \right)^2 \ [\%] \tag{2}$$

With *max()* the maximum value over N locations, $S_{signal,i}$ [W/m^2] the power density of an RF signal at location i, and L_S the corresponding ICNIRP reference levels for power density in W/m^2.

The exposure ratio ER_{tot}^{env} is defined as the maximal cumulative ratio between *total* electric field values in an environment and the corresponding ICNIRP reference levels:

$$ER_{tot}^{env} = 100 \cdot \max_{i=1...N_{env}} \left(\sqrt{\sum_j \frac{E_{j,i}^2}{L_j^2}} \right) \ [\%] \tag{3}$$

With *max()* the maximum value over N_{env} locations per environment (env), $E_{j,i}$ [V/m] the total field strength of RF signal j present at location i and L_j the corresponding ICNIRP reference level. ER_{tot}^{env} is thus the maximal cumulative ratio for multiple frequencies per environment in ICNIRP, 1998.

The average (AC) and maximal (MC) power density contribution [%] of each signal to the total power density value are defined as the average and maximum of the ratio of the power density of each signal and the total signal:

$$X = 100 \cdot \underset{i=1...N}{u} \left(\frac{S_{signal,i}}{S_{tot,i}} \right) \ [\%] \tag{4}$$

With $X = AC$ or MC, *u(.)* representing a function: maximum or average, $S_{signal,i}$ [W/m^2] the power density of an RF signal (e.g., FM, GSM, LTE, etc.) at a location i (i = 1,…, N), N is the considered number of measurement locations, and $S_{tot,i}$ the total power density for all signals at the considered measurement location i.

III. RESULTS AND DISCUSSION

A. General overview of measurements

Fig. 1 (a) shows the maximal measured total electric-field strengths [V/m] per area on the map Belgium and The Netherlands, respectively. The maximal total value E_{tot} is 3.9 V/m (residential site 7). Fig. 1 (b) illustrates the total electric field exposures in Stockholm (urban environment) with a maximal field value of 2.6 V/m.

Table 2 lists the ranges of the different RF exposures for all 311 measurement locations. E_{min} denotes the minimal electric field values above the sensitivity of the equipment, E_{max} represents the maximal values for each RF signal type. Total (cumulative) exposure varies between 0.023 and 3.9 V/m. Highest average fields E_{avg} are obtained for GSM900 (0.5 V/m) and GSM1800 (0.2 V/m). Average total exposures over 311 locations are equal to E_{avg} = 0.7 V/m (Table 2). Maximal contributions *MC* range from 6.9 % (T-DAB) to 100.0 % (GSM900). Average contributions *AC* range from 0.2 % (WiMAX, T-DAB) to 53.2 % (GSM900).

Table 4 summarizes the narrowband measurements for the different environments: the 50th percentile (p_{50}), 95th percentile, maximum (max) and the standard deviation (σ) of the electric-field values are listed. For each environment also the percentage of the number of locations (n) where a certain signal was above the sensitivity of the measurement system (and thus present), is mentioned. All measured electric-field values satisfy the ICNIRP guidelines (ICNIRP 1998). The maximal total value was measured in a residential environment and equals 3.9 V/m (Table 4). This value is 11 times below the ICNIRP guidelines and mainly due to the GSM900 signal (3.85 V/m). From Table 4 it can be seen that mobile telecommunication signals (GSM, UMTS-HSPA) were measured almost at all locations in each environment and dominate the RF-exposures in all environments due to the presence of the high amount of base station antennas nowadays and the common mobile phone use among people. For the GSM900 signal *n* equals 100 % in every environment and *n* is more than 70 % for the GSM1800 signal. The UMTS-HSPA signal was also measured more than 70 % in all environments except in the rural environment. GSM dominates the wireless telecommunication exposures from base stations. Because of the use of frequency hopping an overestimation is made for these signals by performing max-hold measurements (see Section II.B). Standard deviations σ of total exposures vary from 7 to 10 dB for all environments. These are typical standard deviations σ for large sets of field values (Plets et al. 2009).

B. Field distributions per environment

Fig. 2 shows the cumulative distribution functions (CDF) of the *total* exposures (all RF sources) for the different environments (i.e., Prob[E_{tot} [V/m] < abscissa]). Clearly lowest exposures occur for the rural areas, as this distribution is situated most to the left. Highest exposures occur in general in urban environments as much more RF sources and base stations are present in these environments. Differences between residential, suburban, industrial, and office environments are limited. These distributions are in between the rural (lowest) and urban (highest) exposures.

Exposure data in dBV/m (per environment) passed a Lilliefors test for normality at significance level of 5 %. (Kutner et al. 2005) The exposure values in V/m are converted to dBV/m values and maximum likelihood estimates of the mean and standard deviation of a normal distribution are calculated. Fig. 3 shows, based on this procedure, the excellent agreement between empirical and estimated lognormal CDF for E_{tot} (all data). Different distributions were compared (lognormal, exponential, Rayleigh, Rice, etc.) and for the lognormal distribution the best agreement was obtained. This results for E_{tot} in estimates $\mu_{est} = -7.4$ dBV/m of the mean value and $\sigma_{est} = 9.4$ dB of the standard deviation of the lognormal distribution function. Table 5 summarizes μ_{est}, σ_{est} for the different environments. These values are listed in dBV/m and dB because of the *log*normal behavior. The mean values vary from -4.1 dBV/m (urban) to -17.3 dBV/m (rural) and standard deviations vary from 7.0 to 10.6 dB. These distribution functions provide a basis for classification of future measurements (Tomitsch et al. 2010). Moreover, this is very useful for epidemiological studies.

C. Exposures and ER per environment

Fig. 4 shows a histogram with median p_{50} and 95th percentile p_{95} exposures for the different environments. The error bars in Fig. 4 are calculated from the uncertainties of the experimental values. Exposures are clearly the lowest in the rural environment. This can be explained by the fact that less RF (telecommunication) signals and base stations are present in rural areas due to the lower population density. For the median values, highest exposures were measured in urban environments (0.74 V/m), followed by office (0.51 V/m), industrial (0.49 V/m), suburban (0.46 V/m), residential (0.40 V/m), and rural environments (0.09 V/m). These values are comparable with those of Tomitsch et al. 2010 where median values in bedrooms of houses for the RF frequency range of 40.3 $\mu W/m^2$ (0.12 V/m) are obtained, which agrees well with the rural exposures of 0.09 V/m. The majority of the houses in Tomitsch et al. 2010 were located in rural areas (154 of the 226 houses). Tomitsch et al. 2010 also obtained significant lower exposures in rural areas.

Exposures are compared with the ICNIRP guidelines using exposure ratios *ER* (eq. (1)) in Fig. 5. Fig. 5 (a) compares the exposure ratios for the different RF signals. *ER* values, determined using maximal field values, range from 0.5 % (WiMAX) to 9.3 % (GSM900) for the 311 measurement locations. Thus individual exposures are maximally 9.3 % of the ICNIRP reference levels for field values. Highest *ER*s occur for GSM900, followed by DVB-T, FM, DECT, and GSM1800. *ER* values for emerging technologies UMTS-HSPA (2.3 %), LTE (1.2 %), and WiMAX (0.5 %) are lower as these are new systems and are deployed less than e.g., GSM. The exposure ratios are also listed in Table 2. For power densities, the highest exposure ratio ER_S occurs for GSM900 and is 0.9 %.

Fig. 5 (b) compares ER_{tot}^{env} for *total* field values per environment. In residential and urban environments the highest exposure ratios occur. For all environments exposure ratios are lower than 10 % of the ICNIRP reference values for electric fields. Again, lowest *ER*s are obtained for rural environments: the ratios for *total* exposures vary from 3.1 % for the rural environment to 9.4 % for the residential environment.

D. *Exposure per type of RF signal*

Highest exposures occur for GSM900 (p_{95} up to 2.2 V/m, suburban), followed by GSM1800 (p_{95} up to 1.4 V/m, urban), and UMTS-HSPA (p_{95} up to 1.1 V/m, urban) (Table 4). The exposure levels are lower for UMTS-HSPA than for GSM. This can be explained by the limited coverage of UMTS-HSPA in the various environments especially in the rural environment and the less usage of UMTS-HSPA by the general public. LTE was only measured in Stockholm (Sweden) in an urban, office, and suburban environment where the first commercial LTE network is deployed (Joseph et al. 2010b). LTE exposures (max 0.8 V/m) are significantly higher than the exposure due to WiMAX (max 0.3 V/m) for the urban, the suburban and the office environment. WiMAX (fixed and mobile) was mainly measured in the urban environment (n = 16.9 %) and at some locations in the suburban (n = 10.0 %), the office (n = 2.4 %), and the industrial environment (n = 1.9 %). Only in Amsterdam, The Netherlands, mobile WiMAX (IEEE 802.16e 2005) is present while elsewhere fixed WiMAX (IEEE 802.16d 2004) and WiMAX-like technologies (proprietary systems) are deployed. WiMAX causes lower exposures because coverage is limited and only for a few cities in Belgium and The Netherlands.

Exposures to WiFi (p_{95} up to 0.1 V/m, urban) and DECT (p_{95} up to 1.3 V/m, residential), which are indoor sources, were measured in each environment in- and outdoor. Exposure to DECT is overestimated here as DECT is a TDD system and thus uplink traffic is also measured (Section II.C). In Tomitsch et al. 2010 median exposures to DECT of 2.68 $\mu W/m^2$ (0.032 V/m) and to WiFi of 0.84 $\mu W/m^2$ (0.018 V/m) were measured in houses. These values agree again well with the results for rural areas in Table 4, where median values of 0.03 V/m were obtained for DECT and WiFi in rural areas.

In each environment the majority of the signals FM, T-DAB, TETRA, PMR and Analogue TV – DVB-T were measured (and thus present). From these signals, the highest exposure was obtained for the FM (maximally 1.4 V/m) and Analogue TV – DVB-T (maximally 1.7 V/m) in *residential* and *urban* environments (Table 4). Although the FM signal was present at each location in the different environments, the signal could not be measured at some locations (n does not equal 100 % in every environment, Table 4). At these locations the signal level of FM was below the sensitivity of the measurement equipment (Table 3).

E. *Exposure contributions per category/environment*

Fig. 6 shows the average power density contribution of each signal in the various environments. It can clearly be seen that the main contribution in all environments is due to the GSM signals as these telecommunication signals are most used up to now, and use typically higher powers than the newer technologies such as UMTS, HSPA, and LTE. The average contribution (AC) for GSM (900+1800) is more than 60 % (Table 2, Fig. 6). Except for the rural environment, average contributions of UMTS-HSPA are more than 3 % (from 3.7 % in residential environments to 11.4 % in urban environments). The average contributions of LTE and WiMAX are less than 1 % (Table 2) (Joseph et al. 2010b). As these technologies are new and emerging, their deployment and resulting exposures are limited.

In *residential* and *suburban* environments DECT results in the second highest exposure contributions (after GSM900) of 15.7 and 23.8 %, respectively (Fig. 6). Average contributions due to WiFi are limited and lower than 2 % for all environments. Furthermore in each environment the DECT and WiFi signals are present. Fig. 6 illustrates again that the exposure to DECT is significantly higher than to WiFi. Also in Tomitsch et al. 2010, DECT caused the highest exposures in bedrooms: a maximal value of 4872 $\mu W/m^2$ (1.4 V/m) was measured. Here we obtained values up to 2.7 V/m: in our study more different types of environments and both indoor and outdoor exposures are considered.

In each environment the FM, T-DAB, PMR, and Analogue TV – DVB-T signals were measured, these signals contribute on average less than 20 % to the total value.

F. Outdoor versus indoor exposure

In this section indoor and outdoor exposures are discussed. Table 6 lists the 50th percentile (p_{50}) and the 95th percentile (p_{95}) of the different signals in all environments. The dominating outdoor source is GSM900 (p_{95} = 1.9 V/m), indoor DECT dominates (p_{95} = 1.5 V/m). 95th percentiles for *total* indoor and outdoor exposures do not differ much and are about 2.2 V/m. Higher total outdoor values (p_{50} and p_{95}) of mobile telecommunication signals were obtained than at indoor locations (last row of Table 6). For the emerging technologies UMTS-HSPA (outdoor p_{95} = 0.6 V/m, indoor p_{95} = 0.4 V/m) and LTE (outdoor p_{95} = 0.7 V/m and indoor p_{95} = 0.1 V/m), similar conclusions can be drawn. Total outdoor exposure of mobile telecommunications is higher than indoor exposure because only exposure of base stations is considered (handset exposures are not included in the study), which are outdoor sources and are dominant outdoor. The propagation of base station signals into houses and buildings is subject to penetration losses (Plets et al. 2009).

Fig. 7 shows the average power density contribution of each signal for the indoor and outdoor measurements. Outdoor as well as indoor, the mobile telecommunication signals produce the highest contributions: on average GSM900 (out: 57.5 %, in: 42.4 %) produced the highest contribution followed by GSM1800 (out: 16.9 %, in: 7.2 %), UMTS-HSPA (out: 5.4 %, in: 3.5 %), LTE (< 1 %) and WiMAX (< 1 %). DECT is important at indoor locations (28.9 %, also Table 6).

For DECT and WiFi higher percentiles in Table 6 are obtained indoor than outdoor: DECT and WiFi signals are indoor sources and the access points for these technologies are installed indoor. The average contribution of DECT equals 6.2% outdoor while indoor the contribution is 28.9 % (Fig. 7). For WiFi the average contribution is 0.4 % outdoor while indoor 3.4 %.

Fig. 7 shows that the FM, T-DAB, TETRA, PMR and Analogue TV – DVB-T signals were measured indoor as well as outdoor. There is no significant difference between the contributions of these signals indoor and outdoor.

G. Comparison with related research

Median RF exposures in Tomitsch et al. 2010, where exposure in bedrooms of mainly rural houses was investigated, agree well with the values of Table 4 in rural areas. In Tomitsch et al. 2010 the following median exposures were obtained: 4.42 μW/m^2 (0.041 V/m) for GSM900, 0.81 μW/m^2 (0.018 V/m) for GSM1800, 0.60 μW/m^2 (0.015 V/m) for UMTS. We obtained 0.08, 0.03, and 0.02 V/m for GSM900, GSM1800, and UMTS, respectively (p_{50} values for rural environments in Table 4). According to Bornkessel et al. 2007, exposures in the surrounding of GSM and UMTS base stations are mainly in the range below 2 % of ICNIRP field strength limits and may reach more than 10 %. This agrees with our results for GSM (max 9.3 %) and UMTS-HSPA (2.3 %). Highest values of about 5 V/m were measured for both GSM and UMTS for 11 specific scenarios (not randomly as in our study). Also GSM exposures are mostly higher than UMTS in Bornkessel et al. 2007 (85 %), as in our measurements. Electric-field values for WiMAX up to 0.8 V/m were found in Bornkessel et al. 2008, which is higher than in our study (0.3 V/m, Table 2) but of the same order. The higher fields in Bornkessel et al. 2008 can be explained by the fact that fields around specific

WiMAX base station sites were investigated. Exposures to the different signals are comparable to results in literature, but will not be discussed here in detail (Lehmann et al. 2002, Joseph et al. 2006, Neubauer et al. 2002). Higher exposures to TV and radio transmitters are possible in specific regions (Sirav and Seyhan, 2009). Field distributions have not been modelled in Tomitsch et al. 2010, in contrary to our results of Section III.B.

Here we obtained significant lower exposures in rural areas. This is consistent with Tomitsch et al. 2010 and Lönn et al. 2004, where higher mobile phone output powers were found in rural compared to urban areas, indicating lower base station signal intensity in rural areas. Measurement campaigns of RF exposures using personal exposimeters and their results have been presented in Frei et al., 2009, Joseph et al., 2008b, 2010, 2010c, Knafl et al., 2008, Neubauer et al., 2007, Roösli et al., 2008, Viel et al., 2009. Exposimeters are not suitable for accurate field assessment and current personal exposimeters cannot measure LTE, but one can use these to obtain a rough idea about exposure distributions. Also in Joseph et al., 2008b and Viel et al., 2009 it was concluded that exposures and especially downlink GSM exposures are higher in urban areas than in rural areas.

IV. CONCLUSIONS

In-situ electromagnetic radio frequency exposure to existing and emerging wireless technologies is accurately assessed using spectrum analyzer measurements at 311 locations (68 indoor, 243 outdoor), subdivided into 6 different categories (rural, residential, urban, suburban, office, and industrial) and geographically spread across Belgium, The Netherlands, and Sweden. Measurement procedures and settings of measurement equipment are provided.

The maximal total value was measured in a residential environment and equals 3.9 V/m mainly due to the GSM900 signal (11 times below the ICNIRP reference levels). Exposure ratios for maximal electric-field values, range from 0.5 % (WiMAX) to 9.3 % (GSM900) for the 311 measurement locations. The exposure ratios for total exposures vary from 3.1 % for the rural environment to 9.4 % for the residential environment. Exposures are lognormally distributed and are in general the lowest in rural environments and the highest in urban environments. The dominating outdoor source is GSM900 (95^{th} percentile of 1.9 V/m), indoor DECT dominates (95^{th} percentile 1.5 V/m) if present.

The average contribution to the total electric field is for GSM more than 60 %. Except for the rural environment average contributions of UMTS-HSPA are more than 3 %. The contributions of LTE and WiMAX are on average less than 1 %.

Future research will consist of the investigation of the temporal behavior of RF signals and the influence of usage traffic. As exposures vary during time, future exposure assessment will have to take this into account. Also comparison of narrowband measurements with exposimeter data is part of future research.

References

Bolte J, Van der Zande G, Kamer J. Calibration and Uncertainties in Personal Exposure Measurementsof Radiofrequency Electromagnetic Fields. Bioelectromagnetics; 2011 DOI 10.1002/bem.20677.

Bornkessel C, Schubert M, Wuschek M, Schmidt P. Determination of the general public exposure around GSM and UMTS base stations. Radiat Prot Dosimetry (124):40-47; 2007.

Bornkessel C, Schubert M, Wuschek M. Determination of the public's exposure caused by WiMAX transmitters. German Mobile Telecommunication Research Programme (DMF); 2008. Available at www.emf-forschungsprogramm.de/akt_emf_forschung.html/dosi_HF_001.html Accessed 25 June 2010.

CENELEC European Committee for Electrotechnical Standardisation TC 106x WG1 EN 50492 in situ. Basic standard for the in-situ measurement of electromagnetic field strength related to human exposure in the vicinity of base stations; 2008.

Federal Communications Commission (FCC). Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields. Washington, DC, Tech. Rep. Suppl. C to OET Bulletin 65; 2001.

Foster KR. Radiofrequency exposure from wireless LANs using Wi-Fi technology. Health Phys 92(3):280-289; 2007.

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

International Commission on Non-ionizing Radiation Protection (ICNIRP). Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up 300 GHz). Health Phys 74(4):494-522; 1998.

Institute of Electrical and Electronics Engineers IEEE 802.16d – 2004. IEEE Standard for Local and metropolitan area networks Part 16: Air interface for fixed broadband wireless access systems. Piscataway New York: IEEE; 2004.

Institute of Electrical and Electronics Engineers IEEE 802.16e-2005. IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1 Corrigendum to IEEE Std 802.16-2004 (Revision of IEEE Std 802.16-2001). Piscataway New York: IEEE; 2005.

Institute of Electrical and Electronics Engineers IEEE C95.1-2005. IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz. Piscataway New York: IEEE; 2005.

International Telecommunication Union ITU-R Recommendation SM.1708. Field-strength measurements along a route with geographical coordinate registrations. Geneva, Switzerland ITU-R. 1708; 2005.

Joseph W, Verloock L, Martens L. Reconstruction of the Polarization Ellipse of the EM field of Base Station Antennas by a Fast and Low-cost Measurement Method. *IEEE Trans.* Electromag. Compat, 48(2): 385 – 396; 2006.

Joseph W, Verloock L, Martens L. Accurate determination of the electromagnetic field due to WiMAX base station antennas. IEEE Trans. Electromag. Compat. 50(3):730-735; 2008.

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

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

Joseph W, Verloock L, Goeminne F, Vermeeren G, Martens L. Assessment of general public exposure to LTE and RF sources present in an urban environment. Bioelectromagnetics 31(7):576-579; 2010b.

Joseph W., Frei P., Roösli M., Thuróczy G., Gajsek P., Trcek T., Bolte J., Vermeeren G., Mohler E., Juhasz P., Finta V., Martens L. Comparison of personal radio frequency electromagnetic field exposure in different urban areas across Europe. Environmental Research 110(2010):658 – 663; 2010c.

Kim BC, Choi H-D, Park S-O. Methods of evaluating human exposure to electromagnetic fields radiated from operating base stations in Korea. Bioelectromagnetics 29(7):579-582; 2008.

Knafl U, Lehmann H, and Riederer, M. Electromagnetic Field Measurements Using Personal Exposimeters, Bioelectromagnetics 29:160-162; 2008.

Kuhn S, Lott U, Kramer A, Kuster N. Assessment Methods for Demonstrating Compliance With Safety Limits of Wireless Devices Used in Home and Office Environments. IEEE Trans. Electromag. Compat. 49(3): 519-525; 2007.

Kutner M H, Nachtsheim C, Neter J, and Li W. Applied Linear Statistical Models 5th ed. McGraw-Hill/Irwin; 2005.

Lehmann H, Fritschi P, Eicher B. Indoor measurements of the electrical field close to mobile phone base stations. Proceedings of 27th triennial General Assembly of the International Union of Radio Science, Maastricht, The Netherlands, URSI: paper 2112; 2002.

Lönn S, Forssen U, Vecchia P, Ahlbom A, Feychting M. Output power levels from mobile phones in different geographical areas: Implications for exposure assessment. Occup Environ Med 61: 769–772; 2004.

Myhr J. Measurement method for the exposure to electromagnetic field strength from WLAN systems. Master thesis, Chalmers University of Technology, Goteborg, Sweden; 2004.

Neubauer G, Giczi W, Schmid G. An optimized method to determine exposure due to GSM base stations applied in the city of Salzburg. Proceedings *24rd* Annual Meeting of the Bioelectromagnetics Society, Quebec, Canada, BEMS: 46-47; 2002.

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

Olivier C and Martens L. Optimal settings for frequency-selective measurements used for the exposure assessment around UMTS base stations. IEEE Trans. on Instr. Meas. 56(5): 1901-1909; 2007.

Plets D, Joseph W, Verloock L, Tanghe E, Martens L, Gauderis H, and Deventer E. Extensive Penetration Loss Measurements and Models for Different Building Types for DVB-H in the UHF Band., IEEE Transactions on Broadcasting 55(3):213-222; 2009.

Röösli M, Frei P, Mohler E, Braun-Fahrländer C, Burgi A, Fröhlich J, Neubauer G, Theis G, Egger M. Statistical analysis of personal radiofrequency electromagnetic field measurements with nondetects. Bioelectromagnetics 29(6):471-478; 2008.

Schmid G., Preiner P., Lager D., Überbacher R., and Georg R. Exposure of the general public due to wireless LAN applications in public places. Radiation Protection Dosimetry 124(1): 48-52; 2007.

Sirav B and Seyhan N. Radio frequency radiation (RFR) from TV and radio transmitters at a pilot region in Turkey. Radiat Prot Dosimetry 136(2):114-117; 2009.

Tomitsch J, Dechant E, and Frank W. Survey of Electromagnetic Field Exposure in Bedrooms of Residences in Lower Austria. Bioelectromagnetics 31: 200-208; 2010.

Verloock L, Joseph W, Vermeeren G, and Martens L. Procedure for assessment of general public exposure from WLAN in offices and in wireless sensor network testbed. Health Physics 98(4): 628-638; 2010.

Viel JF, Cardis E, Moissonnier M, de Seze R, Hours M. Radiofrequency exposure in the French general population: Band, time, location and activity variability. Environ Int. 35(8): 1150-1154; 2009.

WHO World Health Organization. Available at http://www.who.int/peh-emf/research/agenda/en/index.html Accessed 17 May 2010.

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Table

Table 1: Considered environments, description, and number of measurement locations.

category	#meas. locations	#indoor	#outdoor	description
rural	41	9	32	open areas with low population density (< 400 persons/km^2), countryside and villages
residential	47	13	34	areas with houses and villas with gardens (no industry and commercial sites)
urban	77	13	64	city centre; areas with a high population density (> 700 persons/km^2), a lot of buildings and houses
suburban	50	12	38	areas outside the city centre with row houses, and small apartments, lower population density than urban areas (between 400 and 700 persons/km^2)
office	42	10	32	areas with office buildings with multiple stories
industrial	54	11	43	area with many industrial buildings
all	311	68	243	all sites together

#meas. locations: number of measurement locations
#indoor: number of indoor locations
#outdoor: number of outdoor locations

Table

Table 2: Electric-field strengths [V/m] for the different RF signals for the different locations, the exposure ratio, and the average and maximal power density contribution.

RF signal	**Frequency band [MHz]**	**Variation 311 meas. locations**		**ICNIRP ref. level [V/m]**	**E_{avg} [V/m]**	**Exposure ratio ER[1] [%]**	**ER_S[2] [%]**	**AC[3] [%]**	**MC[4] [%]**
		E_{min} [V/m]	**E_{max} [V/m]**						
FM	100	0.005	1.44	28	0.15	5.14	0.26	7.6	96.7
T-DAB	220	0.011	0.28	28	0.04	1.01	0.01	0.1	6.9
TETRA	390	0.002	0.45	28	0.04	1.59	0.03	0.5	19.0
PMR	146 – 174 406 – 470	0.002	0.29	28-29.8	0.03	0.99	0.01	0.3	39.2
Analogue TV – DVB-T	174 – 223 470 – 830	0.003	1.65	28-39.6	0.09	4.17	0.35	4.7	92.0
GSM900	900	0.013	3.85	41.3	0.49	9.33	0.87	53.2	100.0
GSM1800	1800	0.007	2.15	58.3	0.24	3.68	0.14	15.1	86.8
DECT	1880	0.008	2.67	59.6	0.15	4.48	0.20	11.3	99.9
UMTS-HSPA	2100	0.011	1.41	61	0.16	2.31	0.05	5.7	89.5
WiFi	2400	0.000	0.54	61	0.03	0.88	0.01	1.1	72.6
LTE	2600	0.024	0.76	61	0.19	1.24	0.02	0.4	23.2
WiMAX	3500	0.014	0.28	61	0.07	0.46	0.002	0.2	38.8
Total all signals	-	0.023	3.90	-	0.71	-	-	-	-

[1] Exposure ratio ER = maximal field value/ICNIRP reference level.
[2] Exposure ratio ER^S = maximal power density/ICNIRP reference level.
[3] AC = average power density contribution over 30 locations.
[4] MC = maximal power density contribution over 30 locations.
FM = frequency modulation, T-DAB = Terrestrial - Digital Audio Broadcasting, TETRA = Terrestrial Trunked Radio, PMR = Private Mobile Radio, DVB-T = Digital Video Broadcasting - Terrestrial, GSM = Global System for Mobile Communications, UMTS = Universal Mobile Telecommunications System, DECT = Digital Enhanced Cordless Telecommunications, HSPA = High Speed Packet Access**,** WiFi = Wireless Fidelity 802.11, LTE = Long Term Evolution, WiMAX = Worldwide Interoperability for Microwave Access

Table

Table 3: Settings of spectrum analyzer for exposure assessment of different RF signals using max-hold setting.

RF signal	detector mode	RBW	SWT	sensitivity [V/m]	explanation/reference
FM	rms/peak	300 kHz	2.5 ms	0.004	constant signal; rms and peak detector give similar results (ITU 2005)
T-DAB	rms	3 MHz	100 ms	0.009	RBW of 2 or 3 MHz statisfies
TETRA	rms/ peak	30 kHz	25 ms	0.002	RBW in ITU 2005, CENELEC 2008
PMR	rms/ peak	30 kHz	25 ms	0.002	RBW in ITU 2005, CENELEC 2008
Analogue TV	rms/ peak	300 kHz	2.5 ms	0.003	RBW in ITU 2005, CENELEC 2008
DVB-T	rms	5 MHz	0.8 s	0.003	ITU 2005, CENELEC 2008
GSM900	rms/ peak	200 kHz	125 ms	0.002	-RBW equal to GSM channel bandwidth of 200 kHz -broadcast control channel can be measured by rms or peak detector
GSM1800	rms	200 kHz	125 ms	0.004	similar as GSM900
DECT	rms	3 MHz	200 ms	0.005	channel BW of 1.7 MHz: RBW of 2 or 3 MHz
UMTS-HSPA	rms	5 MHz	0.8 s	0.006	settings available in (CENELEC 2008, ITU-R. 1708 in ITU 2005)
WiFi	rms	1 MHz	10 ms	0.005	determination duty cycle is required (Verloock et al. 2010) SWT [ms] = 10 if signal is not known SWT [ms] = $t_{active} \times n$ if signal is known
LTE	rms	1 MHz	20 s	0.005	appropriate selection of span (Joseph et al. 2010b).
WiMAX	rms	5 MHz	0.8 s	0.013	Joseph et al. 2008

n: the number of display points of the SA (n = 455 for the considered SA)
t_{active}: active duration (Verloock et al. 2010)
peak: positive peak (PP) detector

Table

Table 4: Summary of narrowband measurements with spectrum analyzer in different environments.

environment		FM	T-DAB	TETRA	PMR	DVB-T	GSM900	GSM1800	DECT	UMTS-HSPA	WiFi	LTE	WiMAX	tot
rural	n [%]	43.9	0	14.6	7.3	56.1	100.0	73.2	14.6	4.9	9.8	0	0	-
(41 locations)	p_{50} [V/m]	0.02	-	0.01	0.00	0.03	0.08	0.03	0.03	0.02	0.03	-	-	0.09
	p_{95} [V/m]	0.10	-	0.01	0.01	0.09	1.16	0.23	0.38	0.03	0.11	-	-	1.16
	max [V/m]	0.11	-	0.01	0.01	0.11	1.25	0.38	0.41	0.03	0.11	-	-	1.30
	σ [dB]	5.65	-	3.55	2.81	6.44	11.10	8.17	10.74	3.53	10.31	-	-	9.45
residential	n [%]	74.5	36.2	21.3	19.2	68.1	100.0	74.5	74.5	76.6	21.3	0	0	-
(47 locations)	p_{50} [V/m]	0.16	0.03	0.02	0.01	0.03	0.18	0.09	0.06	0.04	0.01	-	-	0.40
	p_{95} [V/m]	0.95	0.21	0.20	0.12	0.91	1.93	0.37	1.28	0.31	0.04	-	-	2.48
	max [V/m]	1.44	0.28	0.20	0.12	1.65	3.85	0.50	2.54	0.33	0.04	-	-	3.90
	σ [dB]	12.50	7.71	10.00	10.14	11.67	11.00	10.58	11.39	9.22	12.73	-	-	10.57
Urban	n [%]	72.7	51.9	81.8	58.4	90.9	100.0	100.0	93.5	93.5	63.6	31.2	16.9	-
(77 locations)	p_{50} [V/m]	0.06	0.02	0.02	0.01	0.04	0.32	0.19	0.08	0.12	0.02	0.06	0.05	0.74
	p_{95} [V/m]	0.57	0.13	0.12	0.07	0.81	1.90	1.39	0.27	1.09	0.12	0.73	0.27	2.44
	max [V/m]	1.17	0.28	0.37	0.29	1.65	3.56	2.15	1.18	1.41	0.54	0.76	0.28	3.61
	σ [dB]	8.19	6.60	8.01	9.47	13.09	9.86	10.66	6.99	10.39	10.32	9.52	6.06	8.52
Suburban	n [%]	70.0	4.0	36.0	26.0	80.0	100.0	100.0	96.0	86.0	48.0	2.0	10.0	-
(50 locations)	p_{50} [V/m]	0.10	0.04	0.01	0.02	0.03	0.22	0.14	0.09	0.10	0.02	0.29	0.05	0.46
	p_{95} [V/m]	0.46	0.07	0.05	0.04	0.14	2.18	0.79	0.45	0.53	0.12	0.29	0.07	2.21
	max [V/m]	0.62	0.07	0.07	0.05	0.34	2.33	1.01	1.54	1.23	0.16	0.29	0.07	2.55
	σ [dB]	8.33	8.46	6.03	7.52	7.55	10.94	9.18	7.26	9.20	10.61	0.00	5.49	7.57
office	n [%]	90.5	26.2	57.1	54.8	59.5	100.0	100.0	47.6	100.0	35.7	9.5	2.4	-
(42 locations)	p_{50} [V/m]	0.08	0.02	0.01	0.01	0.05	0.33	0.19	0.03	0.07	0.02	0.21	0.04	0.51
	p_{95} [V/m]	0.47	0.21	0.14	0.19	0.48	2.09	0.80	0.27	0.42	0.11	0.48	0.04	2.24
	max [V/m]	0.70	0.22	0.16	0.22	1.26	2.21	1.64	0.39	0.68	0.11	0.48	0.04	3.13
	σ [dB]	11.27	7.37	10.04	13.06	10.55	8.63	9.80	8.38	9.10	15.28	6.76	0.00	6.96
Industrial	n [%]	50.0	16.7	37.0	14.8	63.0	100.0	98.2	55.6	96.3	33.3	0	1.85	-
(54 locations)	p_{50} [V/m]	0.05	0.02	0.02	0.02	0.02	0.31	0.11	0.05	0.07	0.01	-	0.03	0.49
	p_{95} [V/m]	0.52	0.04	0.38	0.09	0.22	1.78	0.55	0.51	0.51	0.08	-	0.03	2.04
	max [V/m]	1.16	0.04	0.45	0.09	0.25	3.10	0.81	2.67	0.67	0.08	-	0.03	3.12
	σ [dB]	8.75	4.45	11.61	11.98	9.49	8.67	8.57	10.61	8.54	10.49	-	0.00	7.70

Table 5: Average value and standard deviation for lognormal fits (all data and per environment).

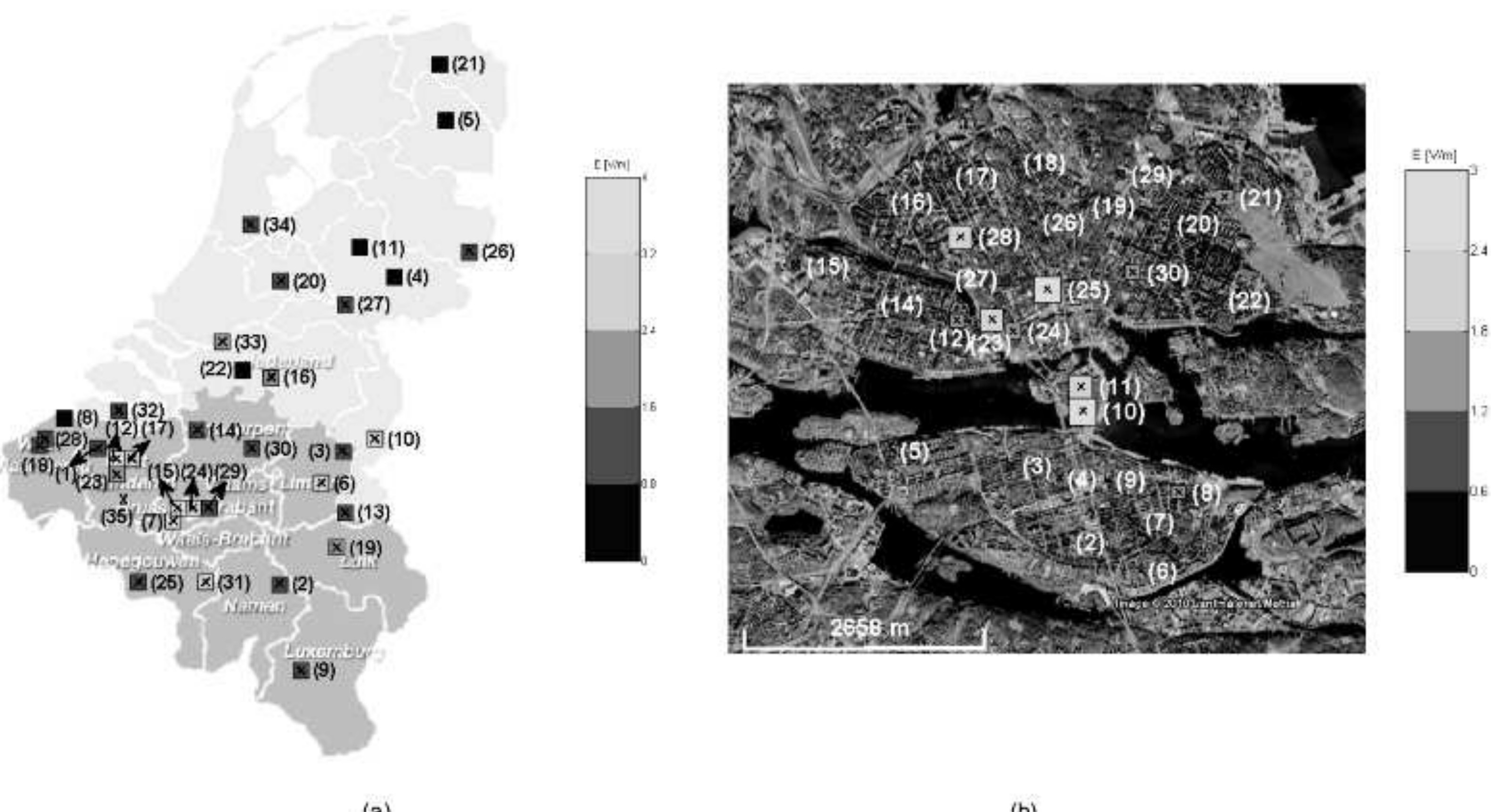
environment	μ_{est} [dBV/m]	σ_{est} [dB]
rural	-17.33	9.45
residential	-8.79	10.57
urban	-4.12	8.52
suburban	-6.62	7.57
office	-5.43	6.96
industrial	-5.71	7.70
all data	-7.42	9.41

Table

Table 6: Comparison of indoor and outdoor exposures.

	indoor		outdoor		all	
frequency band	p_{50} [V/m]	p_{95} [V/m]	p_{50} [V/m]	p_{95} [V/m]	p_{50} [V/m]	p_{95} [V/m]
FM	0.06	0.71	0.07	0.59	0.07	0.59
T-DAB	0.02	0.11	0.02	0.16	0.02	0.13
TETRA	0.01	0.17	0.01	0.17	0.01	0.17
PMR	0.01	0.19	0.01	0.13	0.01	0.13
Analogue TV – DVB-T	0.02	0.47	0.03	0.32	0.03	0.33
GSM900	0.10	0.91	0.29	1.90	0.24	1.85
GSM1800	0.04	0.49	0.15	0.81	0.13	0.79
DECT	0.12	1.50	0.06	0.22	0.07	0.49
UMTS-HSPA	0.03	0.44	0.10	0.61	0.08	0.54
WiFi	0.04	0.16	0.01	0.10	0.02	0.11
LTE	0.10	0.12	0.07	0.73	0.08	0.72
WiMAX	0.18	0.28	0.05	0.15	0.05	0.24
Total GSM/UMTS-HSPA/LTE/WiMAX	0.11	1.31	0.40	2.20	0.32	2.14
Total all signals	0.28	2.18	0.51	2.22	0.45	2.22

Figure



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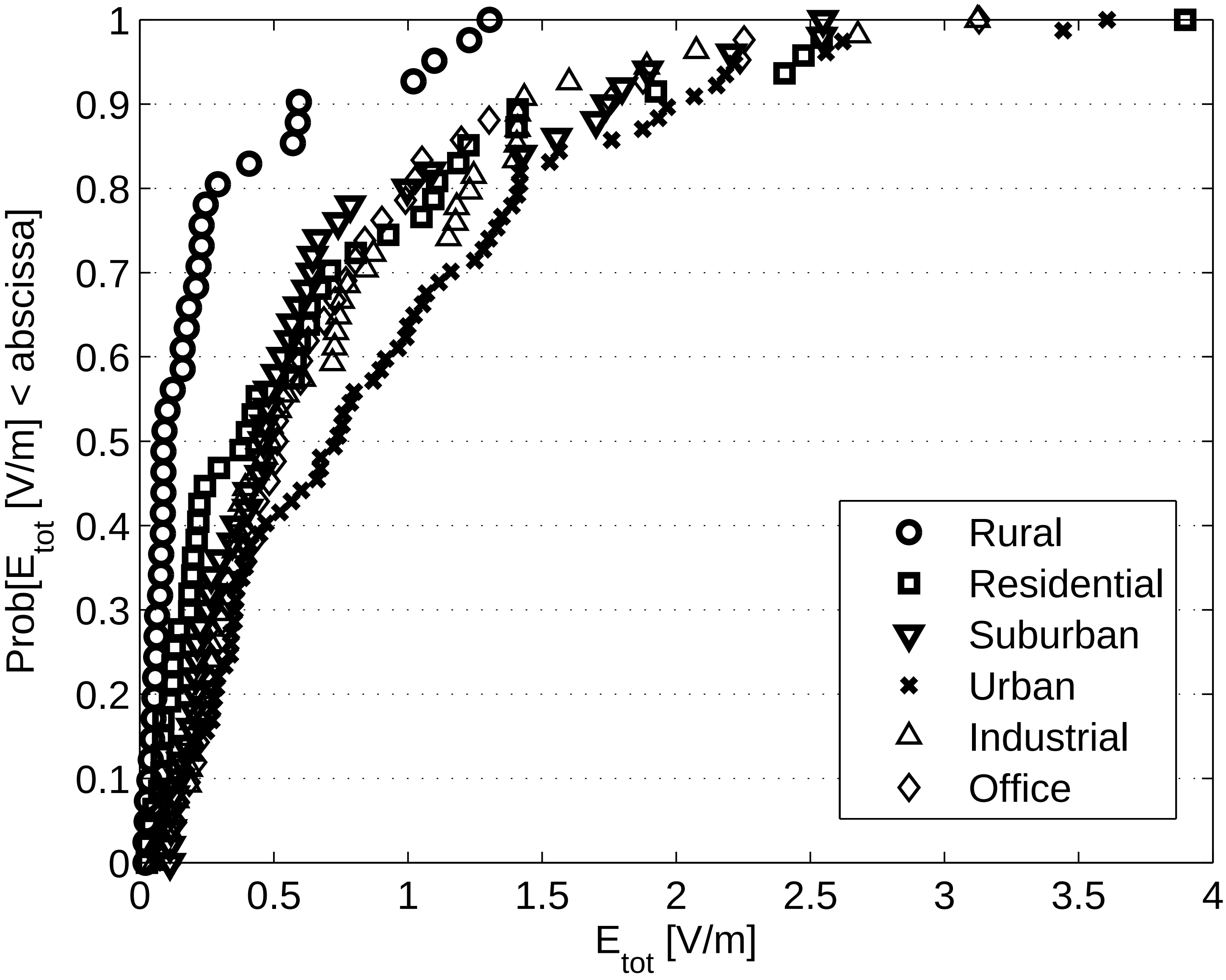

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3
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4
Rural
Residential
Suburban
Urban
Industrial
Office

Figure

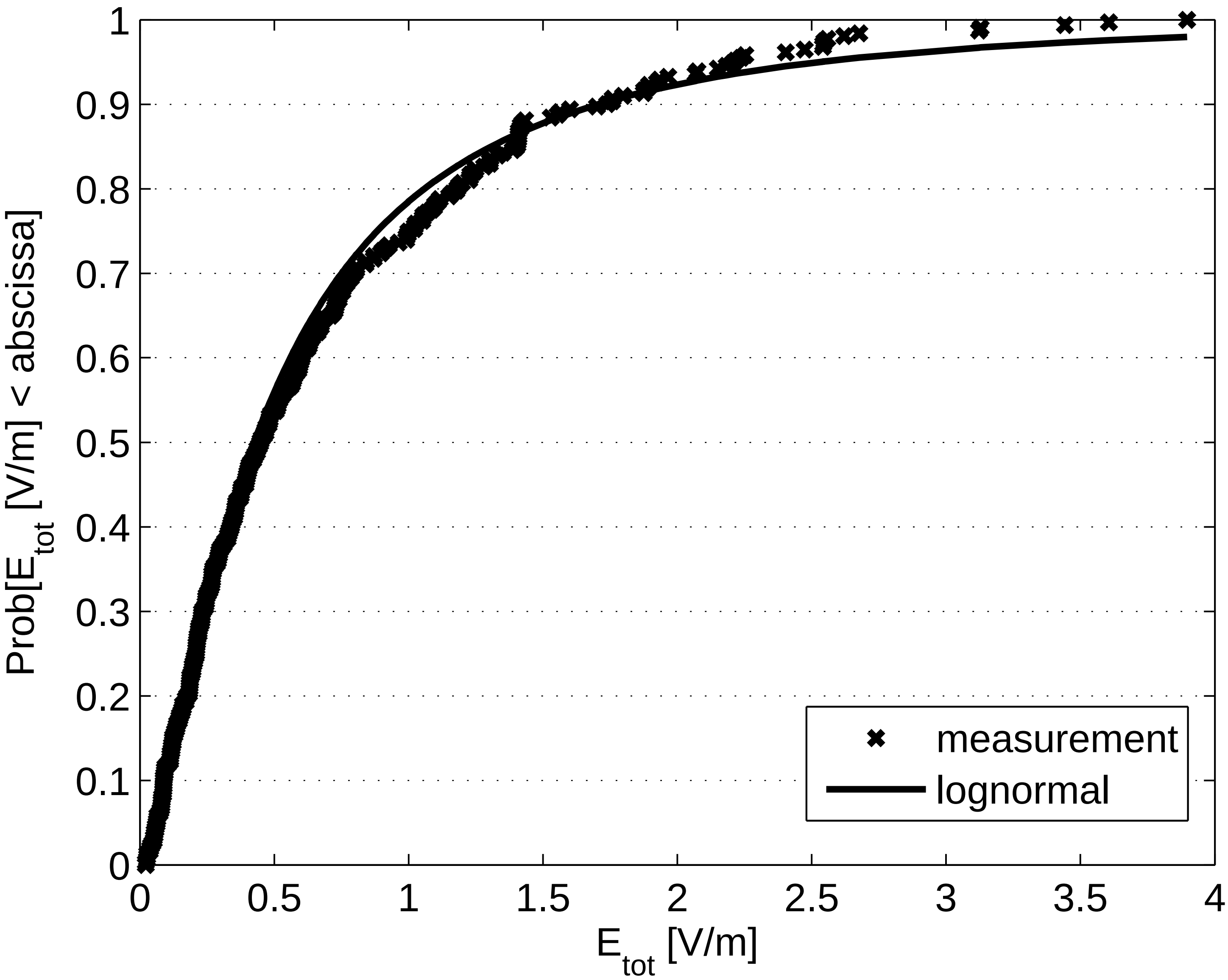

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Figure

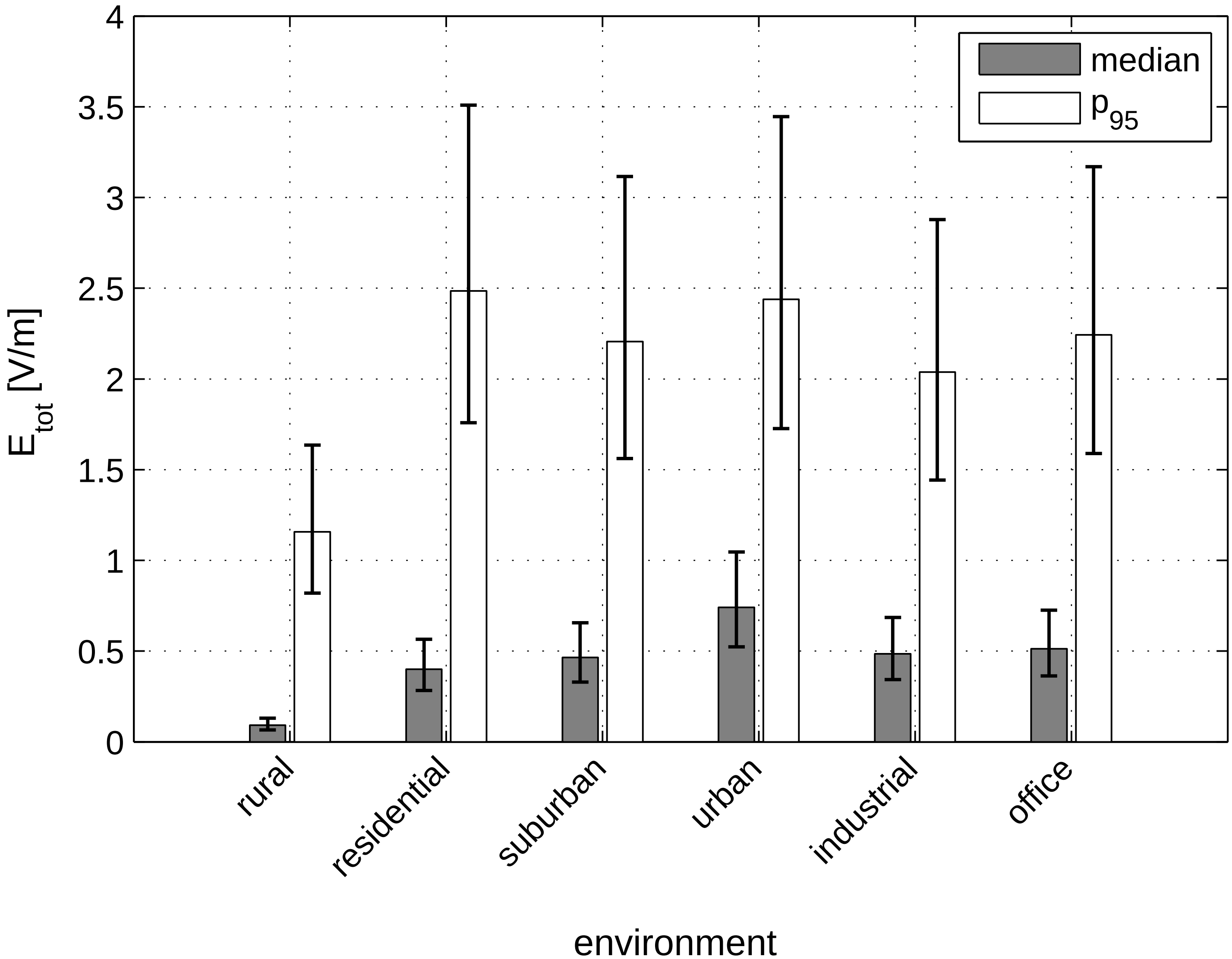

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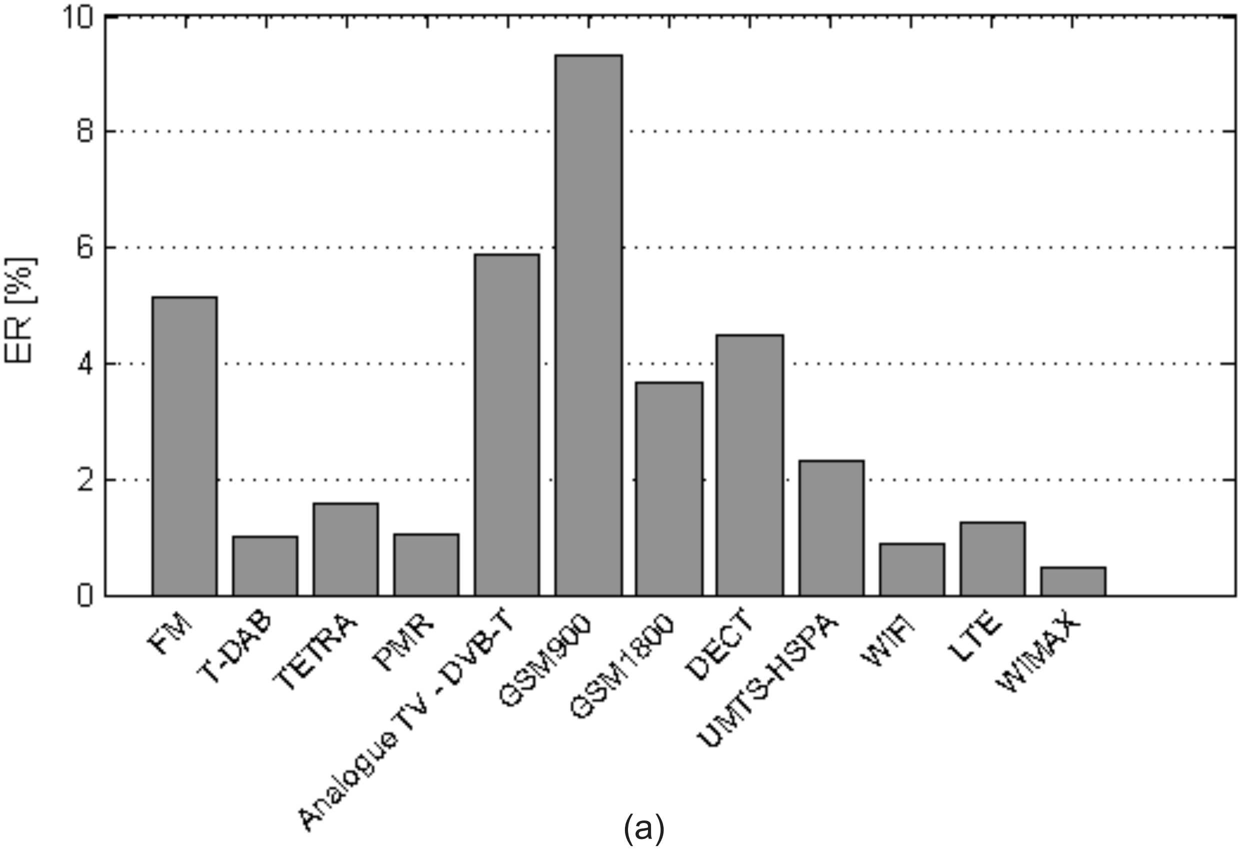
Figure



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UMTS-HSPA
WIFI
LTE
WIMAX

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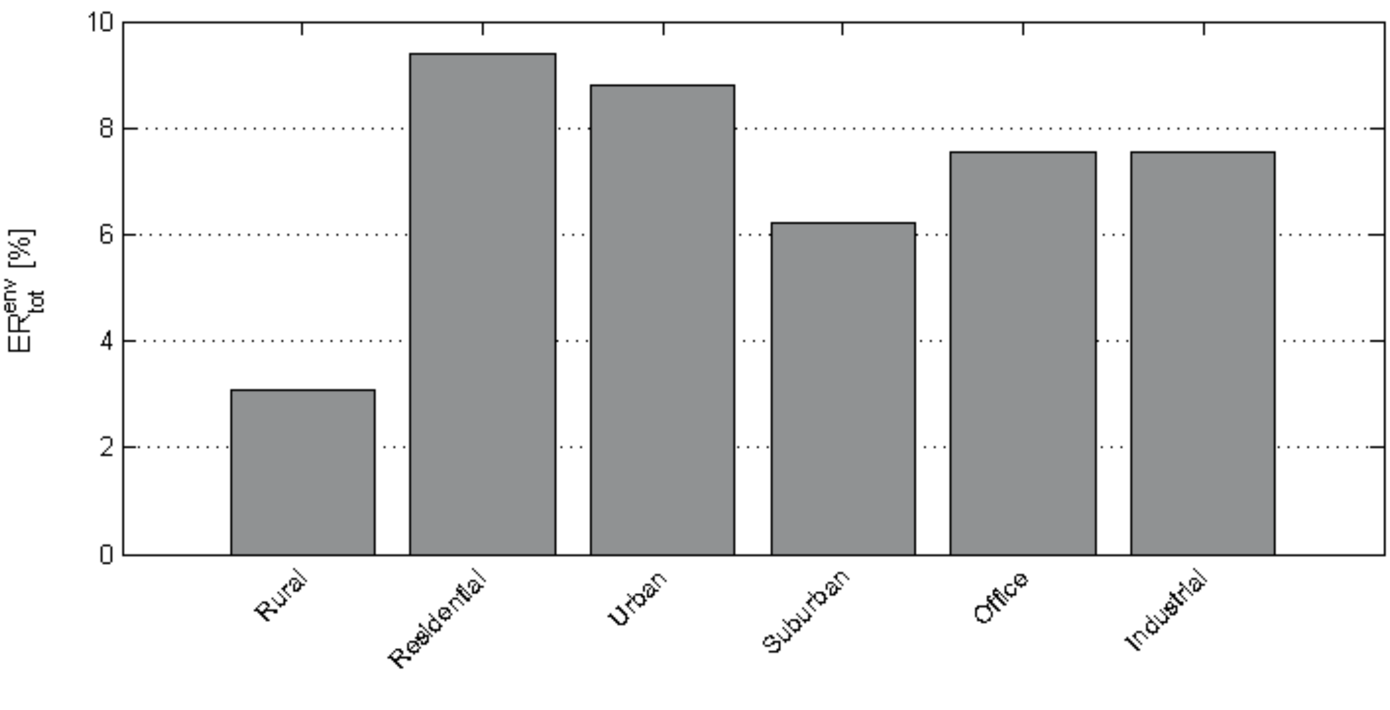

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Residential
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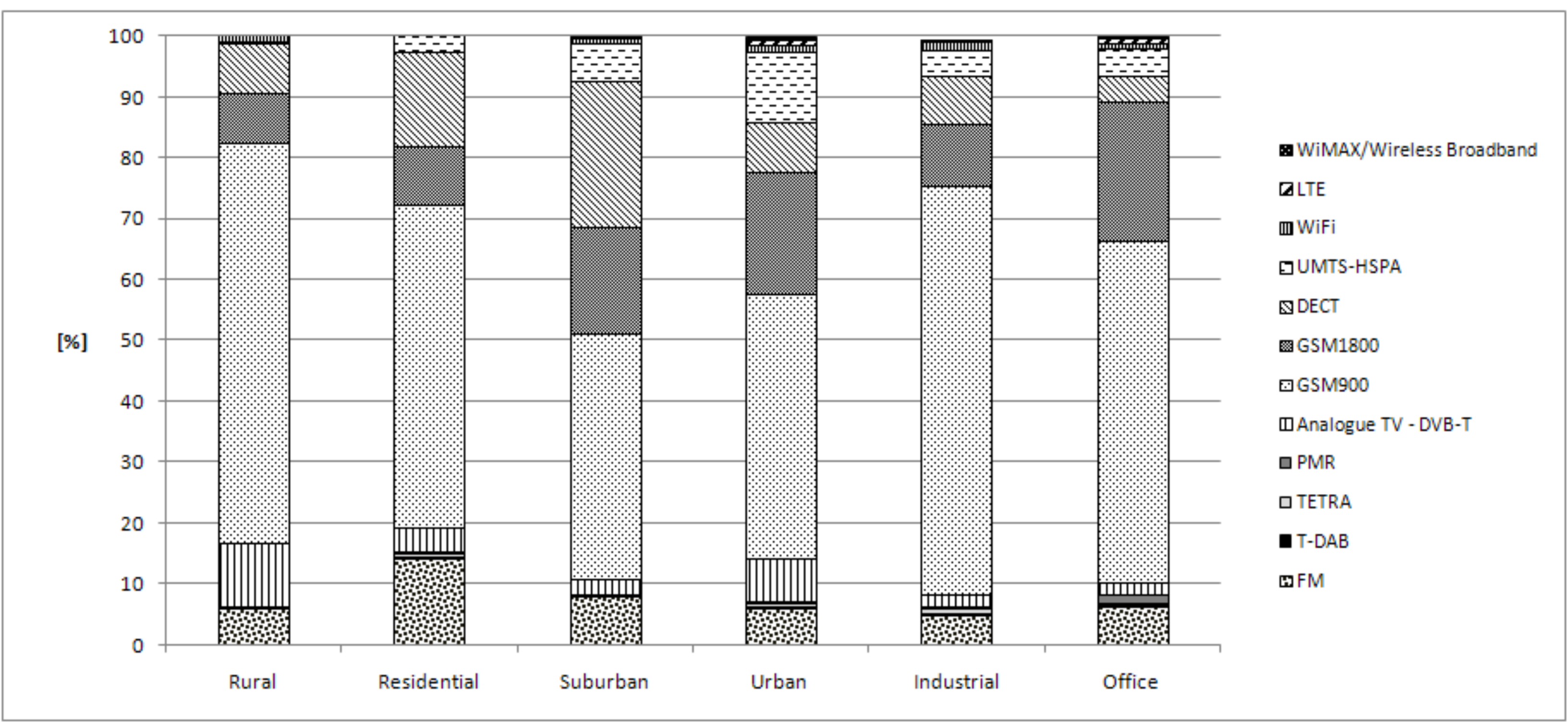
Suburban
Office
Industrial

(b)

Figure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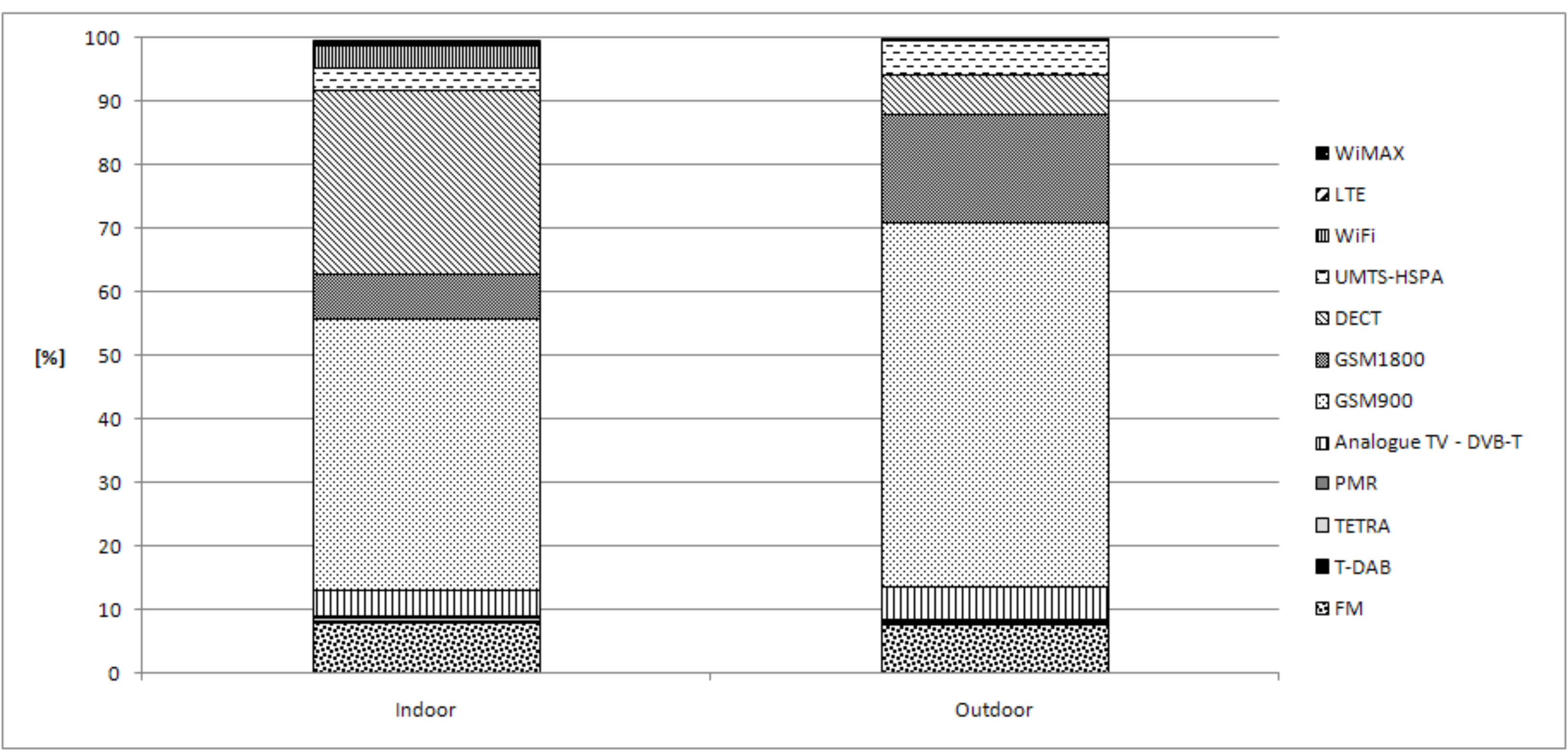
TETRA
T-DAB
FM

Figure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