ASSESSMENT OF RADIO FREQUENCY EXPOSURES IN SCHOOLS, HOMES, AND PUBLIC PLACES IN BELGIUM

Leen, Verloock*, Wout, Joseph*, Francis, Goeminne*, Luc, Martens*, Mart Verlaek, and Kim Constandt****

(email:wout.joseph@intec.UGent.be, fax:+32 9 33 14899)

***Department of Information Technology, Ghent University / iMinds, Gaston Crommenlaan 8, box 201, B-9050 Ghent, Belgium**

**** Department of Environment, Nature and Energy (LNE), Flemish government, Koning Albert II-laan 20, box 8, B-1000 Brussels, Belgium**

Abstract- **Characterization of exposure from emerging radio frequency (RF) technologies in areas where children are present is important. Exposure to RF electromagnetic fields (EMF) was assessed in three "sensitive" microenvironments namely, schools, homes, and public places located in urban environments and compared to exposure in offices. In-situ assessment was conducted by performing spatial broadband and accurate narrowband measurements, providing 6-minutes averaged electric-field strengths. A distinction between internal (transmitters that are located indoors) and external sources (outdoor sources from broadcasting and telecommunication) was made. 94% of the broadband measurements were below 1 V/m. The average and maximal total electric-field values in schools, homes, and public places, were 0.2 and 3.2 V/m (WiFi), 0.1 and 1.1 V/m (telecommunication), and 0.6 and 2.4 V/m (telecommunication), respectively, while for offices, average and maximal exposure was 0.9 and 3.3 V/m (telecommunication), satisfying the ICNIRP reference levels. In the considered schools, the highest maximal and average field values were due to internal signals (WiFi). In the considered homes, public places, and offices, the highest maximal and average field values originated from telecommunication signals. Lowest exposures were obtained in homes. Internal sources contributed on average more indoors (31.2%) than outdoors (2.3%), while the average contributions of external sources (broadcast and telecommunication sources) were higher outdoors (97.7%) than at indoor positions (68.8%). FM, GSM, and UMTS dominate the total downlink exposure in the outdoor measurements. In indoor measurements, FM, GSM, and WiFi dominate the total exposure. The average contribution of the emerging technology LTE was only 0.6%.**

***Key Words*- RF, electromagnetic exposure, school, home, exposure of general public, measurement, telecommunication, WiFi, LTE, base station, access point, indoor, outdoor.**

I. INTRODUCTION

Nowadays, wireless technologies such as smartphones and tablets are used for educational purposes and for daily use by children in schools, at home, and at public places. Also wireless local area (WLAN) networks using WiFi technology are introduced in schools and are being used at home. This rapid expansion of networks and wireless devices in schools and homes is a growing concern for parents and school boards regarding the possible adverse health effects due to radio-frequency (RF) electromagnetic fields (EMF). Consequently, international councils (WHO 2010, Council of Europe 2011) expressed the need to characterize RF electromagnetic field (RF-EMF) emissions and assess exposure levels for new and emerging RF technologies, with a particular emphasis on exposure to children and youth. Currently, little is known about RF-EMF exposure in "sensitive" environments such as schools and homes. These are denoted sensitive as often children are present in these environments. Also the recent roll-out of LTE (Long Term Evolution) networks causes concerns among people in countries like Belgium. Its exposure assessment in schools and homes is therefore valuable.

Outdoor exposure using accurate spectral equipment has already been investigated in literature (Bornkessel et al. 2007, Foster 2007, Joseph and Martens 2006, Joseph et al. 2006, 2010, 2012, Kim et al. 2008, Sirav and Seyhan 2009), while still little information is available about indoor exposure in schools or in homes. Moreover child exposure or exposure at locations where children are present is mostly not considered. Procedures for in-situ measurements of RF-EMF exposures near base stations are standardized in CENELEC 2008. Measurement campaigns of RF exposures using personal exposimeters are not considered here as exposimeters are not suitable for accurate field assessment and compliance evaluation with international guidelines (ICNIRP 1998, FCC 2001, IEEE 2005).

Only, Juhasz et al. 2011 and Khalid et al. 2011 considered personal exposure in schools and crèches. WiFi duty cycles of the access points in 7 networks in schools are determined in Khalid et al. 2011, while Peyman et al. 2011 investigated power densities of WiFi devices used in schools. Juhasz et al. 2011 reported that children's exposures are comparable to worktime exposure of adults. WLAN exposure, which is very relevant for schools nowadays, has been assessed in different studies (Foster 2007, Joseph et al. 2012, Khalid et al. 2011, Peyman et al. 2011, Schmid et al. 2007, Verloock et al. 2010) and WLAN duty cycles in various environments and for different activities and applications are determined. Tomitsch et al. 2010 measured exposures in bedrooms of residences mostly located in rural areas.

The objective of this paper is to report 6-min averaged RF exposure levels in various "sensitive" microenvironments such as schools, homes, and public places, where children are present. Also offices are considered here to enable a comparison of the exposure values with the ones measured in these microenvironments. For the first time, we distinguish clearly between external and internal sources; internal sources are transmitters that are located indoors and are installed by schools, private persons, or authorities and can be controlled (e.g., WiFi access points), while external sources are all other sources from broadcasting and telecommunication and cannot be controlled by the private persons or companies themselves (e.g., FM, PMR, TETRA, T-DAB, DVB-T, GSM, UMTS, LTE, military signals, etc.; the explanations of the abbreviations can be found below Table 4). Moreover, we compare indoor and outdoor exposures in the various microenvironments. The contributions of external and internal sources are determined and compliance of the fields of these emerging technologies with the ICNIRP guidelines (ICNIRP, 1998) for general public exposure is evaluated. This is realized by performing 119 narrowband measurements with spectrum analyzers and 713 broadband measurements. Finally, WLAN duty cycles, that determine the actual WiFi exposure are assessed for the different microenvironments.

The results of this study are not only useful for authorities, international organizations such as WHO, and epidemiologists to gain insight into the exposure levels; moreover, but also to inform prevention advisors of schools and parents about the exposure of electromagnetic sources in the vicinity of children and youth. This paper presents data for a limited amount of specifically selected microevironments and should not be generalized to all environments.

II. MATERIALS AND METHOD

A. Selection of schools, homes, public places, and offices

The considered microenvironments were schools, homes, and public places. In these environments children and youth are often present. Also offices were investigated to enable a comparison of an indoor environment where adults are present. All microenvironments were located in urban environments. Five schools (nursery, primary schools, and secondary schools) were selected based on the presence of internal RF sources and the use of WLAN devices such as laptops, tablets, and smart boards. The considered schools were located in the vicinity of several broadcast transmitters and/or telecommunication base stations. In every school WiFi was used as WLAN technology. Also five homes where children reside and WiFi was present were investigated. The homes were regular houses but no apartment buildings or flats. Finally, at five public places and in two office buildings (several floors, various offices), exposure measurements were also performed. Table 1 summarizes the number of measurement positions per microenvironment. It should be noted that the selected schools, homes, and public places are not representative for the whole country and all schools or homes in Belgium. The focus here was for schools with WLAN. Broadband and narrowband measurements were performed at in total 713 and 119 positions, respectively. The majority of the measurements were performed indoor (535 broadband measurements and 90 narrowband measurements, in class rooms, rooms in homes, etc.), while 178 broadband and 29 narrowband measurement positions were outdoor (school gate, playing grounds). The measurements were performed in the period October 2012 - April 2013.

B. Measurement equipment and procedure

In this study, exposure levels were assessed using broadband and frequency-selective narrowband measurements. A broadband probe of type Narda NBM-550 (measurement equipment) equipped with EF0391 (measurement probe with a dynamic range of 0.2-320 V/m and a frequency range of 100 kHz to 3 GHz) or EF0691 (measurement probe with a dynamic range of 0.35-650 V/m and a frequency range of 100 kHz to 6 GHz) was used to measure the total electric-field value (Narda, San Diego, USA). With broadband probes no frequency-specific information about the EMF sources can be obtained. Therefore, narrowband measurements were also performed. For these measurements, the setup consisted of tri-axial Rhode 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 a 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) (R&S, Munich, Germany). The measurement uncertainty was ± 3 dB for the considered setup (CENELEC 2008, Joseph et al. 2006, 2012). This uncertainty represents the expanded uncertainty evaluated using a confidence interval of 95%.

The measurement procedure for spatial exposure measurements was as follows. First, broadband measurements were performed at each site to determine positions of maximal exposure. These positions were identified through sweeping the area with the broadband probe at a height of 1.5 m above floor level. This is a typical height to characterize human exposure (ECC 2004). Secondly, at a position of maximal exposure, the frequency spectrum was measured from 80 MHz to 6 GHz to determine the significantly present signals. Only the downlink signals *DL* (i.e., signals originating from base stations) were considered in this study. Finally, the significant signals were then typically measured at 6 to 9 positions per measurement site.

For the settings of the spectral equipment (detector mode (RMS or root-mean-square), resolution bandwidth RBW, and sweep time SWT), we selected those proposed in Joseph et al. 2012, with the exception that for all signals except WiFi no maximum-hold measurements (i.e., narrowband measurement of a signal with the maximum-hold setting kept during a time interval until the SA reading stabilizes) were performed. Instead, RMS traces were captured during time and averaged over time periods advised in Joseph et al. 2012. This enables to obtain realistic exposures that can be compared to the ICNIRP guidelines with less overestimations, when e.g., the wireless system is using frequency hopping.

To assess WiFi exposure, the method described in Verloock et al. 2010 was applied using realistic duty cycles. Firstly, the active WiFi channels were identified using Netstumbler (http://www.netstumbler.com). Secondly, a maximum-hold measurement was performed to obtain the electric field of the different channels. Thirdly, the duty cycle (*D*) of the active dominant channels was measured using a spectrum analyzer in zero-span mode with the appropriate settings (Verloock et al. 2010). As WiFi uses the same channel, uplink UL and DL cannot be distinguished. When no power control is applied and if one is in the proximity of a transmitter (UL for WiFi card, DL for access point), this signal will dominate and one can determine the duty cycle of the transmitter under consideration by using a threshold which is high enough (above the level of signals of other transmitters or neighboring channels) (Verloock et al. 2010). In this way, one can determine the realistic exposure of the dominating link. If different significant signals are present from various transmitters in the same or neighboring channels and these cannot be distinguished, then the duty cycle of all signals is calculated. This duty cycle is then used as a worst-case value of the instantaneous exposure and is thus an overestimation. We apply in fact this formula:

$$E = \sqrt{D_1 E_1^{\,2} + D_2 E_2^{\,2} + D_3 E_3^{\,2} + ...} \quad (V/m) \tag{1}$$

With *E* the realistic worst-case calculated field. D_1, D_2, D_3, the duty cycles from channels 1, 2, 3, …. and E_1, E_2, E_3, … the dominating field levels of channels 1, 2, 3, … measured with the max-hold mode per channel and neglected if below the threshold, mentioned above.

During the measurement of the duty cycle self, the WiFi module of the laptop performing the measurements is switched off. So we do not measure the uplink traffic caused by our own measurement laptop. This approach has been validated: measuring a dominating signal with a broadband meter provided similar results as the spectral narrowband setup (CENELEC 2008, Joseph et al. 2012). This validates the protocol for spectral WiFi exposure analysis.

It has to be noted that with the presented measurement procedure, the instantaneous exposure is determined and not the exposure at maximal traffic (CENELEC, 2008). Thus, the values that will be reported are representative for 6-minutes averaged field strengths and can be compared to the ICNIRP reference levels. It is thus important to distinguish (i) field exposure measurements of downlink signals and compliance evaluation with ICNIRP reference levels (this paper), (ii) product compliance evaluation at the maximal operational state of the device using reference levels or basic restrictions, and (iii) studies using exposimeters to characterize higher and lower exposure regions but where compliance checks with ICNIRP are difficult.

C. *Data analysis*

To quantify the presence of RF signals, a factor *n* (%) was defined, which represents the percentage of occurrence of a signal with respect to the total number of measurement positions. A signal was considered to be present if its level was larger than the sensitivity of the narrowband measurement setup. The sensitivity level varies with frequency and depends on the settings of the spectrum analyzer. Furthermore, the average (*AC*) and maximal (*MC*) power density contributions (%) were calculated for each signal as the average and the maximum of the ratio of the power densities of the specific wireless signal and the total signal (Joseph et al. 2012). Finally, to enable comparison with exposure limits, the exposure ratio (*ER in %*) of a signal was defined as the maximal measured electric-field value of the considered signal over the various positions to the corresponding ICNIRP reference level for general public. Exposure ratios smaller than 100%, indicate compliance with the ICNIRP guidelines.

III. RESULTS AND DISCUSSION

A. Exposure levels in the microenvironments

Fig. 1 shows a histogram of the total electric-field values measured with the broadband probe (cumulative fields) for all field data and Table 2 summarizes the broadband measurements per microenvironment (in schools, in homes, at public places, and in offices). From the 713 measurements, 39% (277) of the values were below the sensitivity of the broadband probe, indicated in dark grey in Fig. 1. 94% of the values were below 1 V/m. The highest value was measured in offices and was 3.5 V/m (Table 2). Lowest fields were measured in homes and the highest percentage of measurements below 0.20 V/m (sensitivity of probe) occurred in homes, namely 67%. For the schools, 92% of the measurements were below 1 V/m and 56% were lower than the sensitivity level of the broadband probe (0.2 V/m). The broadband measurements give a good view on the levels of cumulative exposure in the environments. Good agreement is obtained with the cumulative value determined from the narrowband measurements (see further e.g., maximum of 3.5 V/m in offices for broadband vs. 3.3 V/m for narrowband measurements).

In this paper, we distinguish external signals (broadcast and telecommunication signals) and internal signals (WiFi and DECT). Table 3 summarizes the narrowband measurements: the maximum (E_{max}), average (E_{avg}), and standard deviation σ of the measured RMS electric-field values for external (broadcasting, telecommunication, other) and internal signals. Furthermore, for each signal category the occurrence (n), and the average (AC) and maximum (MC) contributions are listed.

All measured electric-field values of Table 3 satisfy the ICNIRP guidelines for general public (ICNIRP, 1998). The maximum cumulative field value determined with the accurate narrowband setup was 3.3 V/m in offices due to *external* sources, namely, telecommunication signals. The highest cumulative field value for *internal* sources was 3.2 V/m, in schools and originating from WiFi.

In schools, the highest maximal and average field values were thus mainly due to internal signals (WiFi, E_{max} = 3.2 V/m, E_{avg} = 0.2 V/m). In homes, public places, and offices the highest maximal and average field values originated from telecommunication signals (1.1 V/m (E_{max}) and 0.1 V/m (E_{avg}) in homes, 2.4 V/m (E_{max}) and 0.6 V/m (E_{avg}) at public places, and 3.3 V/m (E_{max}) and 0.9 V/m (E_{avg}) in offices, Table 3). Lowest total exposure values were again obtained in homes (average of 0.2 V/m). The reason for this is that in the selected homes less internal sources such as WiFi and DECT are present than in schools and in offices and less people are using wireless applications, resulting in lower WiFi duty cycles and lower exposure values (Khalid et al. 2011, Joseph et al. 2012). Measurement separations from APs in schools and homes were at similar but in schools access points providing much more capacity were present and more people use high data rate applications at the same time. This causes higher exposure values in schools applying WLAN and using wireless applications in their courses. Homes also do not have higher floors that can be line-of-sight (LOS) with base station antennas, delivering lower exposure due to external sources than in multi-floor buildings. Public places were selected outdoor, causing higher exposure values due to external sources in comparison to the values in homes (lower values due to penetration losses of outdoor sources). In indoor public places such as in shopping centers also higher exposure values can be found because of indoor pico cell telecommunication base stations.

Highest exposures were obtained in offices with multiple floors as highest exposures due to external sources occur if LOS with telecommunication base stations at higher floors. The homes in this study were single or two-storey houses and no apartments in multi-storey blocks were considered here.

Maximal power contributions (MC) of telecommunication signals were often the highest. The highest values for the average contributions AC were measured in schools for broadcasting (FM 41%), in homes, public places, and in offices for the telecommunication signals (up to 77%). In all environments, broadcasting, telecommunications, and WiFi signals were measured at at least 85% of the measured positions (n in %). In this study we focused on downlink signals (i.e., communication from base station to mobile phone).

Table 4 summarizes the electric field values per signal for all data (also minimum measured field E_{min} and exposure ratio ER). Highest maximal fields for broadcasting are due to T-DAB, for telecommunication due to GSM900, for internal sources due to WiFi. The contributions of external and internal sources to the maximal cumulative total exposure is similar (3.3 V/m for external signals and 3.2 V/m for internal signals). For average exposures E_{avg}, FM dominates broadcasting (AC = 21%, 0.1 V/m); again GSM900 dominates telecommunication signals (AC = 27%, 0.3 V/m), and WiFi dominates the internal signals (AC = 20%, 0.2 V/m). All exposure ratios ER in Table 4 are below 100%. The highest exposure ratio *ER* is measured for the GSM900 signal (7.2%) and the WiFi signal (5.3%). For the other sources, *ER* is smaller than 3.2%. The highest maximal total field value (for schools) was thus equal to 3.2 V/m and mainly due to WiFi. This value was measured at 0.8 m of a WiFi access point, located in the middle of the classroom just above the desk of the pupils. In order to minimize exposure it is recommended not to install access points near pupils. The electric field due to a WiFi access point rapidly decreases as function of distance, with field values equal to 20% of the maximum value at 2 m distance (Verloock et al. 2010). At the time of the measurement campaign, the new technology LTE was being rolled out, for which maximum field values of 0.26 V/m were measured (ER = 0.4%). Further and regular exposure assessment will be needed to evaluate the contribution of these emerging technologies.

Table 4 also shows that FM, GSM (900 MHz and 1800 MHz) and WiFi signals were present at 90% or more of the considered measurement positions (n in % in Table 4). Only at 51% of the positions in Table 4, LTE was measured because this technology is emerging and the deployment is still ongoing. The WiFi signal (2.4 GHz) was encountered at 91% of all positions whereas the DECT signal was only present at 36% of the positions. WLANs are mostly deployed over the entire school to ensure coverage in the majority of the classrooms, while DECT base stations were merely installed in a few rooms of the school such as office rooms, explaining this difference in presence.

B. *Exposure from internal versus external sources*

Fig. 2 compares the maximal and average total fields of internal and external sources in the schools, homes, public places, and offices. In the selected schools, internal sources (WiFi) dominate both average and maximal exposure, while average and maximal exposure in homes, public places, and offices are dominated by external sources. One can observe that the maximal total value for external and internal sources equals 0.6 V/m and 3.2 V/m in schools (Table 3), respectively, and is dominated by the GSM900 and WiFi signal, respectively (Table 4). On average, total external and internal exposure values in schools are 0.18 and

0.28 V/m, respectively. Exposure due to internal signals was higher than due to external sources in the considered schools as WiFi access points were omnipresent and the majority of the narrowband measurements were performed indoors. As a consequence, these measurements occurred closer to internal sources**.** For the other microenvironments, external sources dominate exposure: in homes (maximally 1.1 V/m for external versus 0.5 V/m for internal sources), public places (2.4 V/m versus 0.1 V/m), and for offices (3.3 V/m versus 0.3 V/m) (Table 3, Fig. 2).

C. Contribution of external and internal sources: indoor and outdoor

Fig. 3 shows the maximal electric-field value from external and internal sources at in- and outdoor locations for all microenvironments. For the considered locations and measurements in this papers the highest values at schools, homes, and offices were measured *indoor*. For schools this originated from internal sources, while for homes and offices this was due to external sources. For public places, highest fields were measured *outdoor*. Fig. 4 compares the average *indoor* and *outdoor* power density contribution (AC) of each signal. For outdoor locations, FM (18 %), GSM900 (38 %), GSM1800 (12 %), and UMTS (10%) had the largest contributions. For indoor measurements, the highest contributions were from FM (21 %), GSM900 signals (24 %) and WiFi signals (26 %). This is in agreement with the papers of Joseph et al. 2010b and Frei et al. 2009, where mobile phone base station dominate outdoor exposure levels. The contribution of other sources was smaller than 10% at both in- and outdoor locations.

As expected, internal sources contributed more indoors (31.2%) than outdoors (2.3%), while the contributions of external sources (broadcast and telecommunication sources) were higher outdoors (97.7%) than at indoor positions (68.8%) (Fig. 4). The average contributions for telecommunication signals were the highest for GSM900 (outdoor 38.2%, indoor 23.5%). For internal signals DECT contributed 0.5% outdoor and 4.4% indoor, while WiFi contributed outdoor to 1.8% and indoor to 26% of the total exposure values. Concerning broadcast signals, FM contributed the most, with average contributions of 21.4% indoor and 17.8% outdoor. For new emerging telecommunication signals such as WiMAX (in- and outdoor 0.2%) and LTE (indoor 0.5%, outdoor 0.6%), contributions were low.

D. *WLAN Duty cycles in schools, homes, and offices*

The duty cycle *D* for WLANs (over 6 minute periods) was assessed in two ways in situ: (i) present active WiFi channels were measured and the corresponding duty cycles were assessed using the method of Verloock et al. 2010 and (ii) three different activities were performed in situ (surfing on the Internet, video streaming, and file transfer) and the duty cycle was assessed applying the method of Verloock et al. 2010 with the zero span mode of the SA (Joseph et al. 2013). For these tests various WLAN devices were used, namely, laptops, tablets, or smartboards with WiFi connectivity (IEEE 802.11g/n).

For all microenvironments, in total at 80 positions the duty cycles of the active WiFi channels were measured, resulting in an overall median duty cycle of 2.7%, which is comparable with the median duty cycles of 1.4% and 4.8% obtained in Joseph et al. 2013 and Khalid et al. 2011, respectively.

Duty cycles (*D*) were thus also determined for three different activities, including surfing on the Internet (deredactie.be, 2012), video streaming (VRT news, 2012) and transferring a large file (Ubuntu, 2012; MiKTeX, 2012) in schools, homes, and offices. Table 5 lists the average, 50^{th} and 95^{th} percentiles and maximal duty cycle per activity for these microenvironments and all data together. Cleary, highest duty cycles occurred when transferring or downloading a file (up to 62.2 % in schools, 83.1% for all environments) followed by video streaming (18.9 %) and surfing (3.90 %). This is in agreement with Joseph et al. 2013 and Khalid et al. 2011. Higher traffic density of the WiFi connection is caused by those activities requiring more data. For all data (all microenvironments), the highest average duty cycle was 35.1% (downloading), followed by streaming video (7.3%), and surfing (2.8%) (Table 5).

In school S5, the above measurement was repeated with multiple tablet users. Table 5 lists also an overview of the determined duty cycles for the different activities and number of users (1 and class of 23 users, lowest two rows of Table 5). Increasing the number of connected tablet users (23) logically resulted in an increase of the duty cycle for each activity (e.g., from 3.1% to 14.6% for surfing). This was also found in Khalid et al. 2011 for 30 users. The duty cycles of the access points in 7 networks in Khalid et al. 2011, ranged from 1.0% to 11.7% with a mean of 4.79%.

E. Comparison of exposure levels with related research

WLAN exposure in schools was assessed in Khalid et al. 2011 and Juhasz et al. 2011. Also Peyman et al. 2011, Verloock et al. 2010, Foster 2007, and Schmid et al. 2007 investigated WiFi exposure for various scenarios. It has to be noted that in this paper exposure to APs was considered while in other studies often both exposure of APs and terminals were reported.

At 0.5 m from the access point, the maximal time-averaged exposure was 220 $\mu W/m^2$ or 0.29 V/m (including the duty cycles, Khalid et al 2011). For a classroom with 30 users 2.5 V/m (16.6 mW/m^2) was obtained. In Peyman et al. 2011, maximum electric field strengths of 2.9 and 5.7 V/m were recorded at 0.5 m from laptops and access points, respectively. In Verloock et al. 2010, average WLAN exposure was 0.12 V/m (office environment of an educational institute), with a 95th percentile of 0.90 V/m. Schmid et al. 2007 obtained values lower than 20 mW/m^2 (2.7 V/m) for a small-sized scenario (coffee shop), which is of the same order as our maximal fields in schools. Foster 2007 obtained maximum values of 1.62 V/m or 7 mW/m^2 for WLAN access points (various environments such as homes, offices, outdoor). Average WiFi exposure in schools was here 0.24 V/m, which is higher than in Khalid et al. 2011 and Verloock et al. 2010. This can be explained by the selection of the schools and the positions of the measurement locations: all considered schools have WiFi for their WLAN and a policy of using tablets and smartphones for educational purposes (Section II.A Selection of Schools), creating a worst-case scenario. A maximum value of 3.2 V/m was obtained in our study, which is between the 2.5 V/m for the 30-users' scenario in Khalid et al 2011 and the values reported by Peyman et al. 2011 (5.7 V/m at 0.5 m). The reason for this value of 3.2 V/m was the proximity from an AP type consisting of a WiFi array of 3 WiFi radios with several antennas transmitting at several channels within one housing (three 802.11g antennas at 2.4 GHz, three 802.11a antennas at 5 GHz, and one antenna for monitoring at 2.4 GHz and 5 GHz) and a high wireless activity in the class room at the moment of the measurements (duty cycles of 60% for a channel and 9% for another channel). This AP was placed above the desk of pupils but now replaced as a precautionary measure with respect to the (strict) regional legislation in Flanders, Belgium.

Juhasz et al. 2011 compared the exposure of adults who work in proximity with children to those who do not. It was stated that child exposure values were comparable to the work-time exposure of adults. This was input for future studies but no detailed exposure values were provided. Similarly as in Khalid et al. 2011, which focused on WiFi, internal sources were dominant here. In our study, DECT was less important in schools, because it was not often used in the considered schools.

The exposure values we obtained in the considered homes were lower than for public places, offices, and for schools. For homes, Tomitsch et al. 2010 measured exposures in bedrooms of residences (rural areas) and 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 $\mu W/m^2$). In our study, maximal fields of DECT dominated the internal sources in homes (maximum 0.47 V/m, not average values), while for the external sources GSM900 dominated (1.1 V/m, due to telecommunication signals). Concerning telecommunication signals, Tomitsch et al. 2010 obtained median exposure values of 0.015 V/m (0.60 $\mu W/m^2$) for UMTS and up to 0.018 V/m (0.81 $\mu W/m^2$) for GSM1800. In homes, we obtained average exposure values of 0.15 V/m (median of 0.1 V/m) due to telecommunication signals (Table 3). Our values are higher because the majority of the houses in Tomitsch et al. were in rural areas, while the houses in our study are located in urban areas. Exposures and especially downlink GSM exposure values are higher in urban areas than in rural areas (Joseph et al. 2010b). Also more wireless technologies (LTE, further deployment of HSPA) are present nowadays in comparison to the considered technologies in Tomitsch et al. 2010. We performed measurements in different rooms of houses (mostly all rooms) and also measurements outside e.g., in the garden. Finally, also Joseph et al. 2010b reported that exposure levels were in general lower in private houses than in offices and outdoors.

For public places, the studies of Bornkessel et al. 2007, 2008, and Joseph et al. 2012 are relevant. Most measurements in these studies occurred outdoor. Schmid et al. 2007 focused on WiFi exposure in public places and considered also in- and outdoor scenarios. The highest values in Bornkessel et al. 2007 were about 5 V/m (GSM and UMTS). GSM exposure values were mostly higher than the UMTS exposure values in Bornkessel et al. 2007 (85 %), as also reported here (GSM900 dominates exposure in public places here). The higher fields in Bornkessel et al. 2007 and 2008 can be explained by the fact that fields around specific base station sites (for 11 specific scenarios) were investigated, while here microevironments were considered. The field values were also extrapolated to maximal traffic of the base stations in Bornkessel et al. 2007 and 2008. Schmid et al. 2007 computed for outdoor scenarios for WiFi, values of maximally 0.34 mW/m^2 (0.36 V/m) and measured values up to 12 dB lower. The WiFi exposure values we measured at public places were also low and maximally 0.1 V/m (Table 3). WiFi is often an internal source and outdoor exposures are then limited due to wall attenuation when propagating from indoor to outdoor (Plets et al. 2009). In general, higher field values were obtained in Joseph et al. 2012. Exposure ratios were similar: these varied from 3.1 % for rural to 9.4 % for residential environments in Joseph et al. 2012, while here these were up to 7.7% for total fields (Table 4). Most measurements in Joseph et al. 2012 were outdoor and in different countries and environments. Moreover, the higher field values can also be explained by the use of maximum-hold measurements in that study, which can result in overestimations of the electric-field values (e.g., overestimation of hopping GSM signals).

Finally, for the new technology LTE (introduced in 2012 in Belgium) field values of maximally 0.26 V/m and 0.05 V/m on average (ER = 0.4%, AC = 0.6%, Table 4) were obtained. Joseph et al. 2010 and 2012b investigated in situ LTE exposure in Stockholm, Sweden and in Reading, UK, where networks were recently rolled-out at the moment of these studies and somewhat higher values were obtained than here (maximally up to 0.5 V/m and 0.8 V/m and average contributions of 0.4% to 4%, in Reading and Stockholm, respectively). The LTE roll-out in Belgium is still continuing in 2013.

F. 6-min averaged spatial field values versus temporal variations

In this paper we focused on 6-min averaged spatial field values, which can be compared to the ICNIRP guidelines. One has to distinguish these from temporal field values.

Concerning, 6-min averaged spatial field values, ICNIRP specifies a time-averaging period of 6 minutes for the squared RMS field levels (E_{rms}^2) and the power density (S) (ICNIRP, 1998). FCC specifies a 6 minutes averaging period for occupational exposure and 30 minutes (or no averaging time if this would prove impractical) for general population exposure for the squared RMS electric field or the power density (FCC, 2001). However, in practice, the averaging time is shortened to less than one minute by optimization of the settings of the measurement equipment (CENELEC 2008, Verloock et al. 2010, Joseph et al. 2012). These 6-minutes averaged spatial field values will vary during time due to different usage patterns, traffic, environmental changes, etc. Therefore, a temporal characterization, which is not part of this paper is needed.

IV. CONCLUSIONS

In this study, exposure to radio-frequency (RF) electromagnetic fields (EMF) is assessed in four environments, namely schools, homes, public places, and offices in urban environments

(Flanders, Belgium). In-situ assessment is conducted by performing spatial broadband and accurate narrowband measurements. A distinction between internal and external sources is made.

All measured (realistic-worst case) field levels satisfied the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP). From the 713 broadband measurements, 39% were below the sensitivity of the broadband probe and 94% were below 1 V/m. In total 119 narrowband measurements were performed. For the external sources, the highest cumulative field value was 3.3 V/m and 1 V/m on average, measured in offices and originated from telecommunication signals. The highest cumulative field value for internal sources was 3.2 V/m and 0.3 V/m on average, measured in schools and originating from WiFi. FM, GSM, and UMTS dominate the total downlink outdoor exposure. FM, GSM, and WiFi dominate the total indoor exposure. At the time of the measurement campaign, the new technology LTE was being rolled out, for which maximum field values of 0.26 V/m (0.05 V/m on average) were measured (exposure ratio of 0.4%). Regular exposure assessment will be needed in the future to evaluate the contribution of emerging technologies.

A limitation of this study is the limited number of different microenvironments despite the high amount of measurements in each environment. Five schools, homes, and public places are not representative for the whole country. Therefore, future research should consist of the execution of similar measurement studies in schools and homes to increase the number of microenvironments. Also a comparison among different countries would be valuable.

REFERENCES

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 22 May 2013.

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.

Council of Europe parliamentary assembly. The potential dangers of electromagnetic fields and their effect on the environment (resolution 1815). 2011. Available at http://assembly.coe.int/mainf.asp?link=/documents/adoptedtext/ta11/eres1815.htm#P1_22. Accessed 23 April 2013

Electronic Communications Committee (ECC). Electronic Communications Committee within the European Conference of Postal and Telecommunications Administrations (CEPT), 2004, ECC recommendation (02)04 (revised Bratislava 2003, Helsinki 2007) Measuring non-ionising electromagnetic radiation (9 kHz – 300 GHz); 2004 Online: http://www.ero.dk Accessed January 6, 2014.

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.

IEEE, Institute of Electrical and Electronics Engineers. IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz. New York, USA. C95.1-2005; 2005.

Joseph W and Martens L. Reconstruction of the polarization ellipse of the EM field of telecommunication and broadcast antennas by a fast and low-cost measurement method. IEEE Trans. Electromagn. Compat. 48(2): 385 – 396; 2006.

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; 2010.

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; 2010b.

Joseph W, Verloock L, Goeminne F, Vermeeren G, and Martens L. Assessment of RF exposures from emerging wireless communication technologies in different environments. Health Phys 102(2): 161-172; 2012.

Joseph W, Verloock L, Goeminne F, Vermeeren G, Martens L. In-situ LTE exposure of general public: characterization and extrapolation. Bioelectromagnetics 33(6): 466-475; 2012b.

Joseph W, Pareit D, Vermeeren G, Naudts D, Verloock L, Martens L, Moerman I. Determination of the duty cycle of WLAN for realistic radio frequency electromagntic field exposure assessment. Progress in Biophysics & Molecular Biology 111 (2013):30-36; 2013.

Juhász P, Bakos J, Nagy N, Jánossy G, Finta V, Thuróczy G. RF personal exposimetry on employees of elementary schools, kindergartens and day nurseries as a proxy for child exposures. Progress in Biophysics and Molecular Biology 107(2011): 449-455, 2011.

Khalid M, Mee T, Peyman A, Addison D, Calderon C, Maslanyj M, Man S. Exposure to radio frequency electromagnetic fields from wireless computer networks: duty factors of Wi-Fi devices operating in schools. Progress in Biophysics and Molecular Biology 107(3):412 – 420; 2011.

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.

Peyman A, Khalid M, Calderon C, Addison D, Mee T, Maslanyj M, and Mann, S. Assessment of exposure to electromagnetic fields from wireless computer networks (Wi-Fi) in schools; results of laboratory measurements. Health Physics 100(6): 594-612; 2011.

Plets D, Joseph W, Verloock L, Tanghe E, Martens L, Gauderis H, 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.

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.

WHO Radio frequency (RF) fields research agenda. Available at http://www.who.int/peh-emf/research/agenda/en/index.html Accessed 28 May 2013.

Author affiliations

Leen, Verloock *, Wout, Joseph *, Francis, Goeminne *, and Luc, Martens *

*Department of Information Technology, Ghent University / iMinds,

Gaston Crommenlaan 8, box 201, B-9050 Ghent, Belgium, fax: +32 9 33 14899

(email:wout.joseph@intec.UGent.be)

Mart, Verlaek**, and Kim, Constandt**

****** Department of Environment, Nature and Energy (LNE), Flemish government, Koning Albert II-laan 20, box 8, B-1000 Brussels, Belgium

Acknowledgement: W. Joseph is a Post-Doctoral Fellow of the FWO-V (Research Foundation–Flanders. The study was commissioned, financed, and steered by the Flemish government, Department of Environment, Nature and Energy (LNE).

.

List of captions

Table 1: Number of broadband and narrowband measurement positions and per microenvironment.

Table 2: Summary of the broadband measurements per microenvironment.

Table 3: Summary of the electric-field values of the narrowband measurements the different microenvironments for internal and external sources (maximum, average, standard deviation), the occurrence (n), and the average (AC) and maximal contribution (MC) per RF signal.

Table 4: Summary of the electric-field values per RF signal of the narrowband measurements for all data

Table 5: Measured duty cycle D (%) for different activities in schools, homes, and offices (in schools also for multiple tablet users: average, median, 95th percentile, and maximum).

Figure 1: Histogram of broadband measurements performed in all microenvironments (schools, in homes, at public places, and in offices), dark gray represents data below the sensitivity of the broadband probe.

Figure 2: Maximal and average 6-minutes averaged *electric-field exposure of external and internal sources in the different microenvironments.*

Figure 3: Comparison of indoor and outdoor maximal exposure of external and internal sources in the different microenvironments (6-minutes averaged field strenghts).

Figure 4: Average contributions AC (%) of different RF signals measured outdoor and indoor for all measurement data.