Environment International 197 (2025) 109368

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Full length article

RF-EMF exposure assessment with add-on uplink exposure sensor in different microenvironments in seven European countries

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ARTICLE INFO

Keywords:
5G
Radiofrequency electromagnetic fields (RF-EMF)
Mobile telecommunications
Non-ionizing radiation
Personal exposure measurements

ABSTRACT

Introduction: Several devices have been developed to assess exposure to radiofrequency electromagnetic field (RF-EMF). Since the existing solutions to measure the personal exposure induced by emerging 5G New Radio (NR) are expensive, complex, and bulky, a new cost efficient and low-complexity sensor is developed, that aims to measure RF-EMF exposure in different scenarios of data transmission within different areas.

Methods: With this novel sensor, activity-based microenvironmental surveys were conducted across seven European countries: Belgium, Hungary, Italy, Poland, Switzerland, the Netherlands, and the United Kingdom. The device is attached to a smartphone to quantify the auto-induced uplink (a-UL) transmission component of the total exposure for a broadband frequency range from 100 MHz to 6000 MHz and is thus denoted as add-on sensor. In-situ measurements were performed for three usage scenarios, namely non-user (i.e., environmental exposure), maximum downlink (max DL), and maximum uplink (max UL) scenarios, in a large city, a secondary city, and three rural villages a priori selected within each country.

Results: Power levels were lowest in non-user scenarios (median: −2.64 dBm or 0.54 mW), increasing by a factor of 5.00 dB in maximum downlink scenarios and by a factor of 14.15 dB in maximum uplink scenarios. In the maximum uplink scenarios, the highest median a-UL power of 18.68 dBm (= 73.79 mW) was recorded in The Netherlands, while the lowest median a-UL power of 4.77 dBm (= 3 mW) was observed in the UK. The analysis of the measured data showed a prominent trend of a 2.72 dB lower power in the cities compared to the villages. Further comparisons were made based on microenvironment groups, where the lowest a-UL power levels (median: 12.35 dBm) were measured in outdoor areas, with an increase of 1.78 dB and 1.91 dB in power was measured compared to public transport and public places, respectively.

Conclusion: This study compares RF-EMF power levels between different countries, urbanization settings, and usage scenarios, which is important for future epidemiological studies.

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https://doi.org/10.1016/j.envint.2025.109368
Received 7 November 2024; Received in revised form 27 February 2025; Accepted 4 March 2025
Available online 10 March 2025
0160-4120/

1. Introduction

The evaluation of exposure to radiofrequency electromagnetic fields (RF-EMF) has gained significant attention with the ongoing deployment of the fifth generation New Radio (5G NR) base stations (3GPP, 2024). This emerging technology raised concerns among the public and governments regarding general health implications related to exposure to RF-EMF emitted from base stations and devices (Elzanaty et al., 2021). In recent years, efforts were made to develop new measurement equipment and methodologies (Adda et al., 2020; Deprez et al., 2023; Diez et al., 2017; Shalaby et al., 2019; Lee and do Choi, 2023; Aerts et al., 2021; Kwon et al., 2023; van Wyk et al., 2019; Minucci et al., 2022; Zeleke et al., 2018; Jalilian et al., 2019; bin Khuzairi et al., 2019; Bonato et al., 2020; Aerts et al., 2022) to accurately assess the spatio-temporal exposure to 5G NR. Currently, this technology is primarily commercially available for sub-6 GHz frequencies, but research and development into the millimeter-wave (mmWave) frequency range is ongoing. (Wali et al., 2022; Wu et al., Mar. 2015; Brandao, 2023). Coexisting alongside legacy telecommunications technologies (2G-4G), it is critical to measure 5G RF-EMF to evaluate exposure levels and ensure compliance with the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines (Matthes et al., 1999) and potentially stricter local regulations (WHO, 2010). In related studies, exposure levels to RF-EMF have been measured with different methodologies and equipment (Gati et al.; Joseph et al., 2010; Joshi et al., 2020; Velghe et al., 2021; Joshi et al., 2024). Assessing exposure to RF-EMF involves distinct challenges, such as varying signal strengths, environmental interference, and differences in distance between devices and base stations, when measuring exposure from downlink (signals transmitted from base stations (BS) to smartphones) or uplink (signals transmitted from smartphones to BS), respectively. In 2020, Joshi et al. collected and analyzed output power data from 5G user equipment (UE) in commercial networks over a 15-day period to assess time-averaged power levels relevant to electromagnetic field (EMF) uplink exposure. (Joshi et al., 2020). Another study, performed by Joseph et al., measures in-situ RF downlink exposure to base stations of emerging wireless technologies across six environmental categories in three European countries, finding that exposures are generally well below ICNIRP reference levels (Joseph et al., Feb. 2012). Gati et al., have assessed the exposure to RF-EMF from mobile networks by analyzing the power exchanged between handsets and base stations across 2G and 3G networks, focusing on the duality between downlink and uplink signals for these telecommunication technologies (Gati et al., Nov. 2010). However, quantifying auto-induced transmission uplink (a-UL), i.e., the RF-EMF exposure generated by the user's own devices, presents challenges (Velghe et al., 2021). Existing devices like the ExpoM RF-4 exposimeter (Fields at Work, Switzerland (Fields at Work, 2023) are relatively bulky and large compared to smartphones and are costly, rendering them unusable for individuals to assess their auto-induced RF-EMF exposure. The ExpoM RF4 is also designed for measuring environmental RF-EMF instead of a-UL, and the ExpoM RF4 should thus be kept on a distance from the source. There is a demand for a smaller device with an efficient form factor, a broad frequency and power range, and the ability to attach to a smartphone, to accurately and efficiently assess RF-EMF exposure. An existing device with smaller dimensions is the Devin, introduced in (Mazloum et al., 2023), this device is more low-cost and is battery powered. The Devin provides specific frequency information for 4 frequency bands. It was used in related studies, where auto-induced uplink powers are measured. A second alternative exposimeter is proposed in (Rivera González et al., 2021) functions similarly to a signal analyzer, providing detailed measurements over a range of 78 MHz to 6 GHz, though it comes with high cost and complexity. Mobile device software solutions like QualiPoc, developed by Rohde & Schwarz, (RohdeSchwarz, 2023) and Nemo, developed by Keysight, (Keysight, 2024) provide very detailed insights in many different network parameters related to auto-induced exposure. However these are expensive and complex, limiting their practicality for non-experts and large-scale campaigns. To fill these gaps, a low-cost and user-friendly personal RF-EMF exposure sensor was developed (Velghe et al., 2021). The proposed device, referred to as the 'add-on sensor,' is primarily designed to measure a-UL. Additionally, it captures downlink signals and environmental exposure in close proximity to the phone under test, allowing for a comprehensive assessment of the total exposure experienced by the user. The add-on sensor is designed, calibrated, and validated in-lab and in-situ in Belgium. The resulting add-on sensor of this work can be attached to a mobile phone, enabling its use in activity-based micro-environmental surveys as part of the GOLIAT EU project across seven European countries, and can furthermore be used by individuals. The device aims to assess RF-EMF exposure for three usage scenarios (i.e. non-user, maximum downlink and maximum uplink) with the focus on the uplink exposure from legacy, current, and emerging wireless technologies in a practical and accessible manner.

The key innovations of this study include (i) the design and calibration of an add-on RF-EMF sensor for smartphone and (ii) its application in cities and villages for seven European countries for three usage scenarios. This was the first measurement campaign of this scale that includes the current coexistence of 4G and 5G in Europe. Additionally, (iii) personal exposure is evaluated across various microenvironments (MEs), first introduced by Röösli et al. (Röösli et al., 2010), classified based on the main activity performed by the public (e.g., residential, commercial, schools, industrial, public transport) (Velghe et al., 2021) generally divided in outdoor areas, public places, and public transport (Röösli et al., 2010). (iv) This study presents the results of large scale measurements in Europe for three usage scenarios and aims to investigate the occurrence of general trends regarding the measured power. Measurement results with the add-on sensor are discussed for seven countries, namely Belgium, Hungary, Italy, Poland, Switzerland, The Netherlands and The United Kingdom. The resulting datasets, i.e. the power values, will provide the possibility to be used in real power simulations for dose absorption assessment in real environments.

2. Methods

2.1. Sensor design

Fig. 1 illustrates the add-on device (Fig. 1.a), its housing and position when attached to a mobile phone (Fig. 1.b-c). It is intended to be low-cost, and thus designed with off-the-shelf components and a custom Printed Circuit Board (PCB). The size and formfactor are chosen to keep the sensor sufficiently small (115x65x55 mm^3) and furthermore, easily attachable and removable from a smartphone to ensure flexible usage.

The core component of the RF-EMF add-on is the RF Meter Click by MikroElektronika, which incorporates an AD8318 logarithmic RF detector and an MCP3201 12-bit Analog-To-Digital Converter (ADC). This component operates over a frequency range from 100 to 8000 MHz, which covers the current frequencies used for telecommunication (2G-5G, Wi-Fi but also FM radio etc.). However, the actual output data will cover a frequency range of 600–6000 MHz, because of the selected antenna, a wideband monopole antenna. The relevant, current telecommunication technologies (2G to sub-6 GHz 5G) all use frequencies (i.e., the frequencies of interest) within this range. Thanks to the use of a broadband antenna, the add-on captures the summation of all frequencies in the range simultaneously, though it is not designed for frequency-selective analysis. As a result, the data obtained represents a summation of all frequencies within the range, providing an inclusive view of the signals received at that time. The RF detector has a suitable dynamic power range of 60 dB. The output of the ADC is read by an Adalogger Feather M0 manufactured by Adafruit. During 0.5 s, 500 samples are taken with a sampling frequency of 1 kHz. In the following 0.5 s, statistical calculations (including the average, median, minimum, and maximum power values in dBm) are performed, producing one output for these statistics every second. With a micro SD-card slot, this

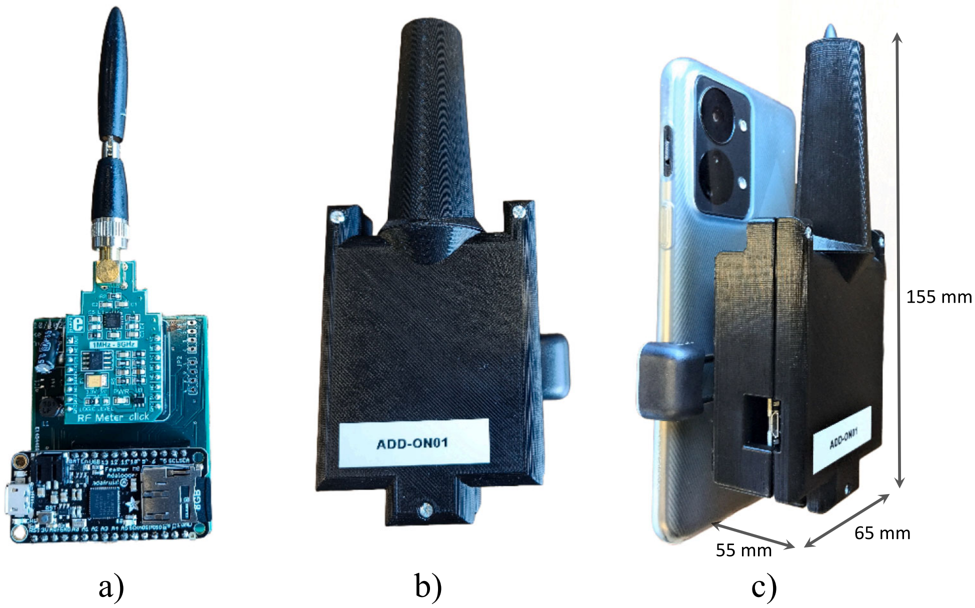

Fig. 1. A) add-on device. b) 3d-printed protection case. c) add-on attached to smartphone.

microcontroller board can directly store the measurement data to a removable data card. Table 1 provides an overview of the above-mentioned specifications.

The RF-EMF sensor is housed inside a protective case, 3D-printed with polylactide (PLA) filament (Fig. 1.b). A cut-out is incorporated into the side to make the micro-USB port accessible. This is necessary for powering the sensor: either powered by a portable battery, power bank, or by the smartphone. The sensor can be attached to the mobile device through a spring-based phone holder (Fig. 1.c). To access or remove the micro SD card, the case must be opened.

2.2. Calibration and validation

In order to ensure accurate exposure assessment, both an on-board and an in-situ calibration (denoted as free-space calibration from now on) were performed. The purpose of the on-board calibration was to quantify power loss due to the electronic circuit and to verify the hardware's power response. The add-on was connected to a calibrated signal generator by Rohde & Schwarz (type: SMB100A) via an RF cable to determine the output voltage of the RF detector as a function of the incident power (Deprez et al., 2021). This was done for frequencies going from 500 MHz to 8000 MHz, in steps of 50 MHz, and input powers from −70 to 0 dBm in steps of 1 dB. The output response was stored into a look-up table. The cable loss and antenna factor were also taken into account to ensure an accurate calibration. These were acquired by measuring the cable and the monopole antenna with a Vector Network Analyzer (VNA). This large dataset was reduced to 1 single calibration factor, since the add-on does not have any frequency information while performing measurements. This calibration factor is obtained by taking the median of the errors compared to the power of the signal generator for the most common frequencies (800 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2400 MHz and 3600 MHz) (Deprez et al., 2021) used for wireless telecommunication in Belgium and then taking the average for those frequencies. With this average error value being approximately 1.43 dBm, this is a good calibration factor which leads to a fully calibrated add-on sensor.

A free-space calibration was performed besides the on-board calibration to quantify the response of the add-on sensor with the broadband antenna. This step was performed by making a comparison between the add-on sensor and QualiPoc, a multifunctional smartphone based tool for monitoring voice and data service quality and RF optimization by Rhode & Schwarz, during in-situ measurements (RohdeSchwarz, 2023). QualiPoc tracks the incident and transmitted power from the smartphone under test. When the add-on and QualiPoc software are used simultaneously, a comparison in power measured by the add-on and reported by Qualipoc is made, which leads to a free-space calibration factor of the add-on. In addition, QualiPoc measurements are able to provide further detailed parameters. For example, the add-on has no frequency information and can thus not determine which wireless technology is used. Since QualiPoc and the add-on are used simultaneously, this information can be found afterwards in the QualiPoc data.

The add-on device was validated in-situ in Ghent, Belgium. A trained researcher followed a predetermined route on foot through a defined residential microenvironment with a smartphone equipped with an add-on exposure sensor and QualiPoc software. This process is illustrated in Fig. 2.

2.3. Measurement methodology

2.3.1. European campaign

The measurement campaign was performed in 2023 in seven European countries, namely Belgium, Hungary, Italy, Poland, Switzerland, The Netherlands and The United Kingdom. A measurement protocol was developed and is briefly summarized in the following sections (Veludo et al., 2025). In each country two cities and three villages were selected (Röösli et al., 2010). Within each study area, different microenvironments were identified. For each microenvironment, three usage scenarios were performed. The campaign is presented visually in Fig. 3. These different steps are clarified in more detail in following sections.

With this campaign, the present 5G exposure will be measured, as well as the coexistence with other, legacy, telecommunication

Table 1
Specifications of the add-on sensor.

Frequency range	600 – 6000 MHz
Case dimensions	115 x 65 x 55 mm^3
Dynamic range	60 dB
Supply voltage	3.3 V
Reported accuracy	1.0 dB over 55 dB range
Output sampling time	1 s

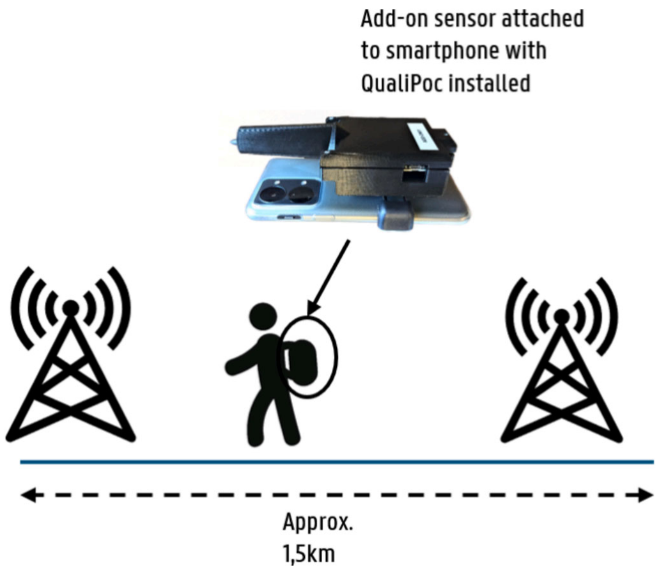

Fig. 2. Visual presentation of the free-space in-situ calibration and validation.

technologies; 2G, 3G and 4G. This allows to get a global view of the total RF-EMF exposure in these microenvironments for the present situation.

2.3.2. Urbanization and microenvironments

In the preparation phase of the measurement campaign, each country defined different areas based the urbanization (Fig. 3.). One large city (LC), one secondary city (SC) and three villages (V) are selected. The LC (i.e., > 500.000 inhabitants), often but not necessary, the capital city and SC (i.e., 100.000 – 500.000 inhabitants) being a slightly smaller city. The villages represent the rural areas as defined in (Veludo et al., 2025).

The two cities were subdivided in a central (C), non-central (NC) and outskirt (OUT) areas. This introduces a distinction in urbanization within the city, which varies from the densely populated and visited city centers to the suburbs. This classification was only done for the parks and the residential areas.

The defined cities and villages were divided into microenvironments (Fig. 3.). i.e. a geographical area categorized based on the main activity that is performed there by the public (Röösli et al., 2010; Veludo et al., 2025). The three main groups of microenvironments include public transportation, public places and outdoor areas.

The public transport includes bus, tram, train and metro rides. The respective transport was taken when traveling in between the areas, so for a varying amount of time. The public places were visited during 15 min (Röösli et al., 2010). This group entails schools and universities (grouped as education), shopping centers, stations and public parks. The third group, the outdoor areas are predefined routs of approximately 1 km. These were walked by trained researchers in residential, business, industrial and downtown areas. An overview of the microenvironments is shown in Fig. 3.

Fig. 4 gives an example of the microenvironments, annotated by a blue line, defined for Ghent, Belgium. The green lines represent the public transport lines, the public places are located at the yellow pins and the routes in the outdoor areas are shown in red.

2.3.3. Usage scenarios

For each microenvironment, the measurement was repeated for three different scenarios, namely non-user (NU), maximum downlink (max DL) and maximum uplink (max UL). For the non-user scenario, the user equipment (UE) was switched to flight mode. Here, the exposure induced by the bystanders and base stations in the vicinity of the sensor was measured without influencing the network traffic itself. This provides an indication of the ambient environmental exposure. For the max DL and max UL, a large file of 1 GB and 500 MB was repeatedly downloaded or uploaded, respectively. For these scenarios, the auto-induced downlink and uplink powers were measured, combined with ambient power. Because the UE is much closer to the sensor, it is presumed dominant in the measured power. The personal devices of the researcher are set to flight mode during the complete measurement time.

Since measuring auto-induced uplink is a key objective of this study, the ambient exposure power must be removed. This can be achieved by first transforming the power to milliwatts, then subtracting the power measured with the NU scenario from the power measured from the max

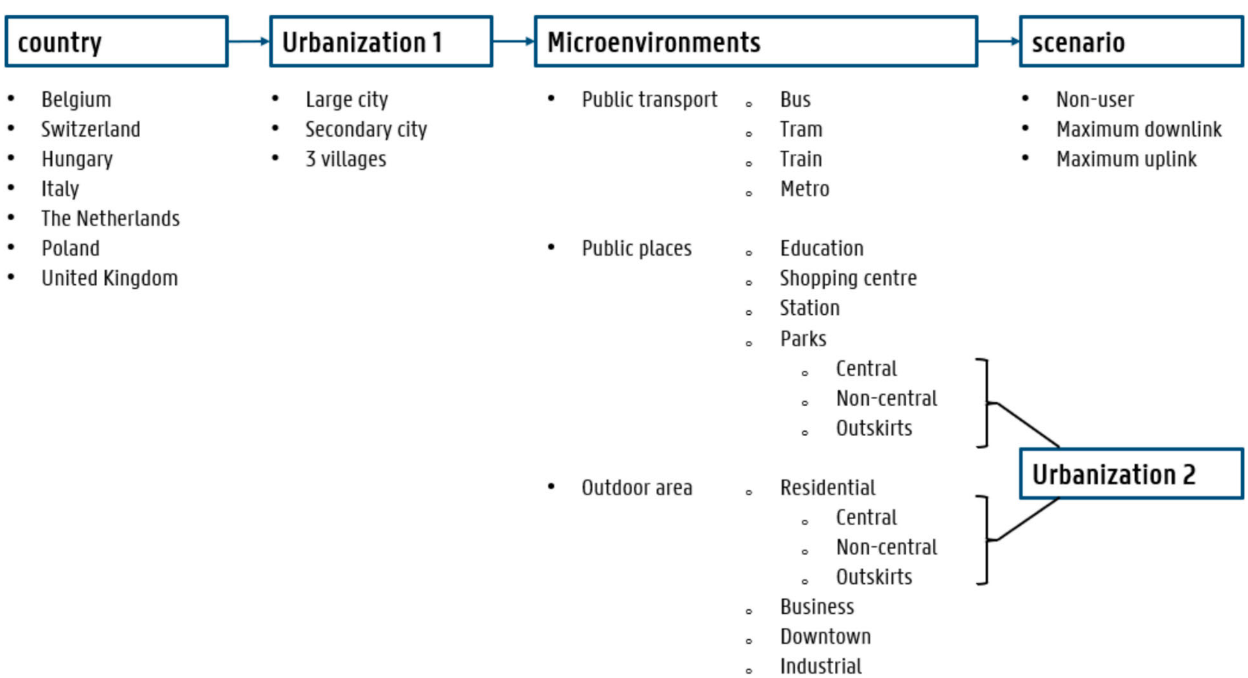

Fig. 3. Overview of the measurement campaign in Europe. Cities and villages are selected within each of the seven countries. These areas are subdivided in microenvironments. For every microenvironment, measurements for three scenarios were performed.

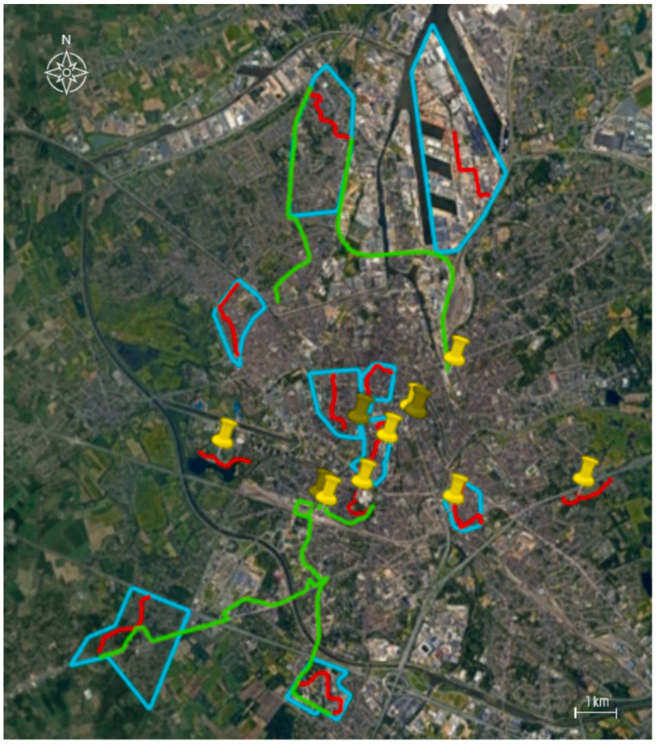

Fig. 4. Example of the microenvironments, defined in Ghent, Belgium. The microenvironments (ME) are indicated by light blue lines. The outdoor areas (i.e., the routes walked in the ME's – red lines), the public places (the yellow stamps) and the public transport routes (green lines) are presented on the map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

UL scenario, presented in Equation (1):

$$\Delta P_{UL} = P_{maxUL} - P_{NU} \tag{1}$$

With: ΔP_{UL} = [mW], P_{maxUL} = [mW], P_{NU} = [mW]

The power, ΔP_{UL}, is then converted back to dBm. The design of a sensor device that can be used to give an indication of the auto-induced uplink with or without the influence of the environment, is one of the novelties of this work.

2.3.4. Measurement set-up

At the start of the measurement day, the add-on was powered on. It keeps measuring continuously until power is disconnected. The start and stop times of the measurements, as well as the connection time of the add-on sensor, were registered in a form-based diary application, which was installed on the personal phone of the researcher performing the measurement. From then on, per microenvironment the start and stop times were recorded. A possible description of the present crowd (e.g. crowded, empty), additional information of the microenvironment (e.g. the city, the place, etc.) and the applied scenarios were also added in this form. This way, each microenvironment was repeated for three scenarios: non-user (NU), maximum downlink (max DL) and maximum uplink (max UL) (Veludo et al., 2025). Each measurement takes fifteen minutes on average (Röösli et al., 2010). A block diagram of the measurement method is presented in Fig. 5.a).

2.3.5. Data processing

The data collected in these measurements were intensively cleaned to ensure the quality of the results. The first step was to match the measurement data to the corresponding ME, as recorded in the diary app and noted by the executing researcher. With the insights obtained by QualiPoc, periods of low network throughput (i.e., throughput levels below 350 kbps and the absence of 2G and 3G signals) were traced. These periods are left out of the measurement results, because the respective scenario is not working properly. This was done in line with the methodology of previous research about RF-EMF exposure in Europe (Veludo et al., 2025; Stroobandt et al., 2024). Not discarding these

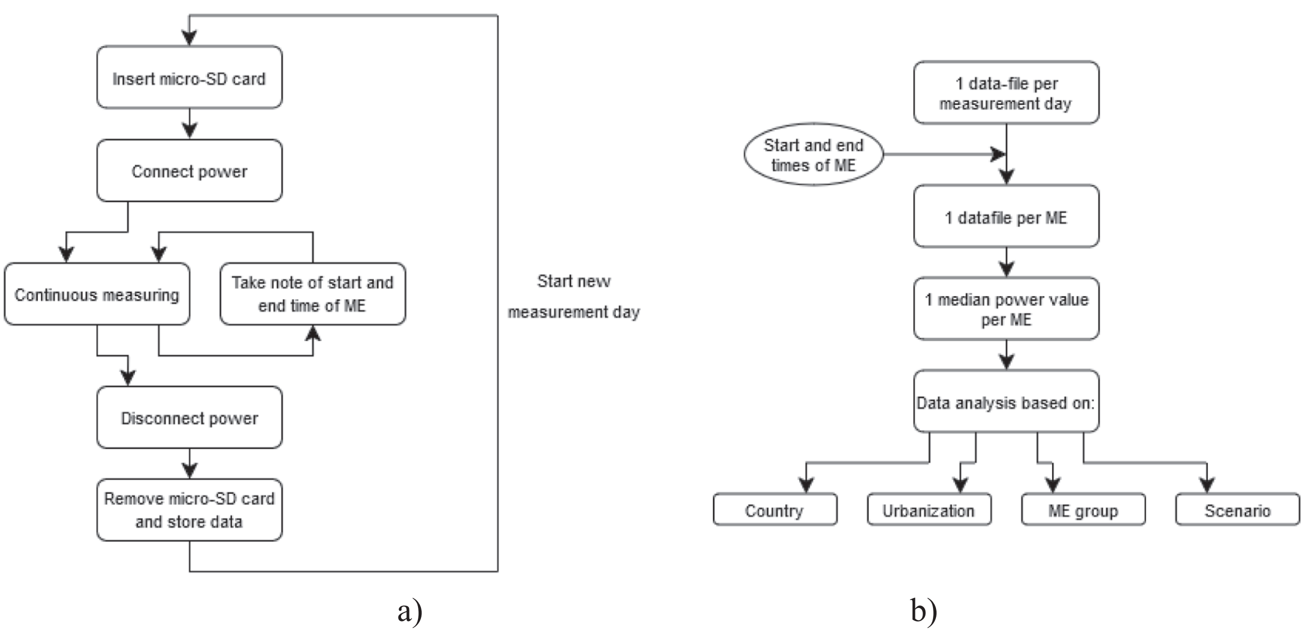

Fig. 5. Visual summary of the measurement methodology (a) and the data processing steps (b). a) At the start of the measurement day, the micro-SD cards is inserted into the sensor. Once the sensor is powered, it will measure the RF-EMF power continuously as long as power is connected. For every walked microenvironment (ME) the start and end time will be noted to synchronize the data afterwards. At the end of the measurement day, the power is disconnected and the data file is stored on the micro-SD card. b) This measurement file will be split into multiple.txt files, 1 per ME, after synchronization with the noted start and end times. For every ME, one median power will be calculated for further data analysis based on Country, urbanization, ME group and scenario.

samples would lead to different conclusions when comparing the scenarios.

The entire measurement in a given microenvironment was reduced to a single median value. The results will be compared over the seven countries, based on the scenarios, urbanization and microenvironments. Other, different, median values will be taken into account for these comparisons based on the country, urbanization type, microenvironment and scenario.

The data processing steps are illustrated in Fig. 5.b).

3. Results and discussion

3.1. Measurements campaign results

Table 2 provides an overview of the number of measurements performed in the seven European countries. For a total of 1194 microenvironments, power levels were measured in the seven countries during this campaign.

As noted above the add-on sensor outputs a value every second. This means that about 900 exposure power samples are collected per microenvironment and thus 1,074,600 samples for the whole campaign. To investigate the occurring trends a median value was taken per measurement. Leading to a total of 1194 median values. Another, second, median is taken per respective parameter group that is being compared.

Table 3 presents a comparison of median power levels across the three scenarios stratified by country (first part), by urbanization (2nd and 3rd part), and by type of microenvironment (4th part). The table shows the absolute power values for the three scenarios and the ΔPUL as defined in Equation (1).

3.1.1. Comparison usage scenarios

The following general trend was found for all measurements, with an increase in power level from the NU to max DL to max UL scenarios, as expected. Based on the median values of the measurement campaign the NU power is 5.00 dB lower than max DL and 14.15 dB lower than max UL across the countries. This is explained because the max DL and max UL scenarios also include environmental exposure, thus the non-user values. Subsequently the maximum uplink power is higher because the sensor is attached to the UE.

3.1.2. Comparison countries

Table 3 and Fig. 6 present the comparison of the seven countries. In Fig. 6, the median of the boxplot is corresponding with the value in Table 3. This median was taken for all the measurement results in all areas in every country per usage scenario. With a ΔP_{UL} of 4.77 dBm in the UK and 7.60 dBm in Poland, the measured power in the UK and Poland are significantly lower than for the other countries. Namely, the uplink power without the influence of the environment, measured in Poland, is 7.24 dB lower than in Hungary. The uplink power in Hungary not significantly different in power value compared to Italy, Switzerland and Belgium.

The highest ΔP_{UL} was measured in the Netherlands (median 18.68 dBm). The $P_{max\ UL}$ measured value in the Netherlands is within the same range as Belgium, Switzerland and Italy and is 2.80 dB higher than the second highest power value, Belgium. However, because P_{NU} (i.e., the environmental power) is with an average of 3.17 dB significantly higher

Table 3
Measurement results: (i) comparison of median powers in seven European countries based on country Belgium (BE), Switzerland (CH), Hungary (HU), The United kingdom (UK), Poland (PL), Italy (IT) and The Netherlands (NL). (ii) Comparison based on urbanization 1: a large city (LC), a secondary city (SC) and three villages per country. (iii) Comparison based on urbanization 2: a central area (C), non-central area (NC) and outskirts (OUT) for every Large City and Secondary City. (iv) Comparison based on microenvironment (ME) group. P_{NU}: power measured for the non-user (NU) scenario, $P_{max\ DL}$: power measured for the maximum downlink (max DL) scenario, $P_{max\ UL}$: power measured for the maximum uplink (max UL) scenario, ΔP_{UL}: power calculated with Equation (1). The raw data was measured with the add-on RF-EMF sensor.

		P_{NU} [dBm]	$P_{max\ DL}$ [dBm]	$P_{max\ UL}$ [dBm]	ΔP_{UL} [dBm]
Country	BE	1.48	6.48	16.04	15.88
	CH	0.58	3.88	15.05	14.89
	HU	2.25	6.68	15.07	14.84
	UK	0.18	5.46	6.06	4.77
	PL	1.53	6.60	8.56	7.60
	IT	0.15	3.99	14.30	14.13
	NL	4.20	10.84	18.83	18.68
Urbanization1	LC	2.37	6.59	12.68	12.26
	SC	1.53	6.48	15.07	14.87
	Villages	−2.64	5.61	15.05	14.98
Urbanization2	C	1.37	5.15	14.72	14.51
	NC	1.11	5.78	13.35	13.08
	OUT	−2.80	7.09	16.26	16.21
ME group	OA	2.72	6.02	12.80	12.35
	PP	0.58	5.65	14.32	14.13
	PT	0.81	5.19	14.45	14.26

Table 2
Number of measurements (15 min measurement per microenvironment per user scenario) performed in the seven countries, Belgium (BE), Switzerland (CH), Hungary (HU), The United kingdom (UK), Poland (PL), Italy (IT) and The Netherlands (NL), for large cities (LC), secondary cities (SC) and villages (V).

		BE			CH			HU			IT			NL			PL			UK		
		LC	SC	V	LC	SC	V	LC	SC	V	LC	SC	V	LC	SC	V	LC	SC	V	LC	SC	V
Public transport	Bus	1	12	4	3	14	4	8	3	10	4	3	3	4	2	2	3	0	0	14	21	18
	Metro	5	5	0	0	0	0	2	0	0	1	1	0	2	0	0	0	0	0	15	0	0
	Train	18	2	12	8	19	5	7	8	7	0	2	0	0	1	0	4	3	0	4	7	3
	Tram	8	0	0	4	9	0	4	0	0	2	0	0	2	2	0	1	1	0	3	0	0
Public place	Education	9	9	9	9	6	0	10	3	9	3	3	3	3	4	0	0	0	6	6	9	3
	Parcs	9	10	9	9	12	9	9	6	9	8	9	9	9	8	9	9	9	3	11	18	10
	Shopping centre	1	3	1	0	0	0	1	1	0	1	1	5	3	2	0	2	1	2	1	1	0
	Station	6	4	6	0	1	3	5	3	5	5	4	2	15	2	3	7	3	2	6	5	5
Outdoor area	Residential	15	12	9	9	9	9	17	11	9	17	12	11	15	15	9	7	12	7	12	21	9
	Business	3	3	0	3	3	0	3	3	0	3	3	0	3	3	0	3	3	0	3	3	0
	Downtown	4	4	9	3	3	9	4	3	9	4	3	9	4	4	10	5	3	10	4	6	9
	Industrial	4	3	5	3	3	6	3	3	3	3	3	4	3	3	0	0	3	0	3	7	0
Total		83	67	64	51	79	45	73	44	61	51	44	46	63	46	33	41	38	30	82	96	57
		214			175			178			141			142			109			235		

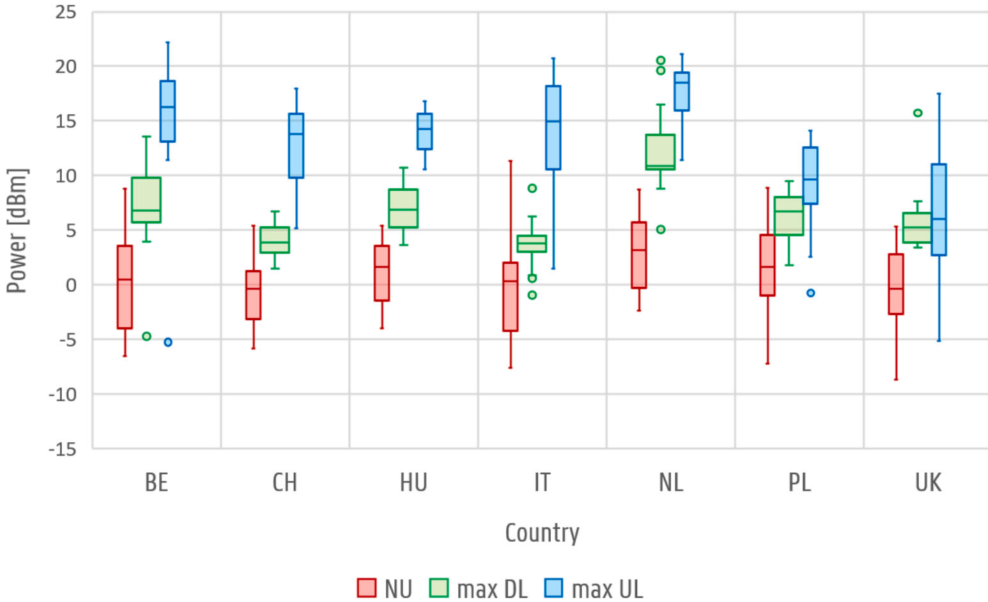

Fig. 6. Measurement results: comparison of exposure powers in seven European countries, i.e. Belgium (BE), Switzerland (CH), Hungary (HU), The United kingdom (UK), Poland (PL), Italy (IT) and The Netherlands (NL), for 3 user scenarios, i.e. non– user (NU) where the smartphone is in flight mode, maximum downlink (max DL) and maximum uplink (max UL) where the smartphone performs a continuous download and upload, respectively. The boxplots represent power value in dBm per user scenario in every city and village in every microenvironment per country. The raw data was measured with the add-on RF-EMF sensor.

in the Netherlands, the ΔP_{UL} is similar as Belgium, Switzerland, Hungary and Italy. Table 2 shows that less measurements (33 MEs compared to an average of 51 MEs in the other countries) were performed in the villages in the Netherlands, compared to the other countries where higher uplink powers were measured. This means that the values of the cities are dominant. When comparing countries it is important to take into account that every country has different specific regulations regarding the exposure levels. For some countries there are even local changes in maximum allowed exposure levels. E.g., in Belgium the regulation is more strict in the capital, Brussels, compared to the other regions. Another aspect to consider is that the deployment of 5G stations is not equal over the European countries. E.g., Italy has better 5G coverage compared to Belgium.

Fig. 7 presents boxplots for a second comparison of the seven countries, but only for the large cities. Hence, all power levels obtained by the add-on in the large cities are combined to one single median value, as presented in Table 3. Here the P_{UL} in Poland is 8.56 dBm (= 7.18 mW), which is with a difference of 4.39 dB significantly higher than the uplink power measured for the UK. This can be explained because less measurements were performed in the villages, which is why the measured power in the large city of Poland dominates. For the other countries the same trend occurs as for the combination of the two cities and three villages. i.e. the highest ΔP_{UL} of 13.07 dBm in the Netherlands and the lowest ΔP_{UL} of 4.00 dBm in the UK.

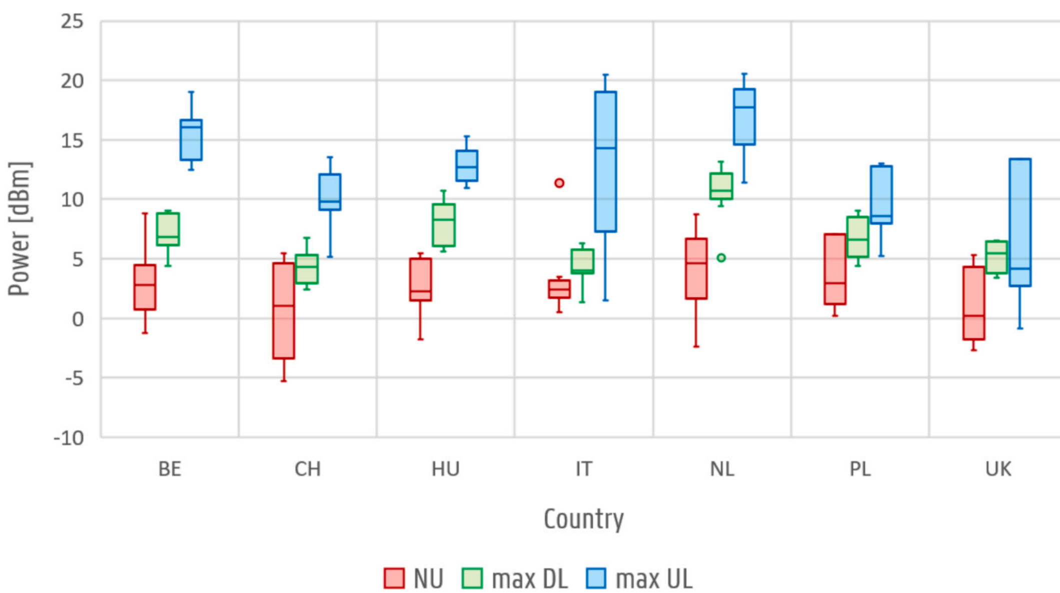

Fig. 7. Measurement results: comparison of powers in seven European countries, i.e. Belgium (BE), Switzerland (CH), Hungary (HU), The United kingdom (UK), Poland (PL), Italy (IT) and The Netherlands (NL), for 3 user scenarios, i.e. non– user (NU) where the smartphone is in flight mode, maximum downlink (max DL) and maximum uplink (max UL) where the smartphone performs a continuous download and upload, respectively. The boxplots represent the power value in dBm per user scenario in the large city for every microenvironment per country. The raw data was measured with the add-on RF-EMF sensor.

Joseph et al. (Joseph et al., Feb. 2012) has assessed RF-EMF exposure in over 35 areas in three European countries in 2010, but the differences between the countries were not analyzed. Their study focused on measuring downlink EM field values for 2G-4G instead of uplink powers in the current study, with 5G included. A maximum of 3.9 V/m downlink field strength was measured. In France, Gati et al. measured in two cities including their rural areas. Since there objective was to investigate the instantaneous relationship between the power transmitted by handsets (UL) and that received from the base stations (DL) for 2G and 3G, no comparisons based on location were made. 90 % uplink power values of 33 dBm, 30 dBm and 0 dBm were measured for Global System for Mobile communications (GSM900), GSM 1800 and Universal Mobile Telecommunications Service (UMTS), respectively (Gati et al., Nov. 2010). Mazloum et al. have developed a small low cost sensor. DEVIN (Mazloum et al., 2023), focusses on miniaturizing the device and support 5G and frequency selectivity for different sampling frequencies. With DEVIN, maximum power values of 21 dBm were recorded during (Voice over Long Term Evolution) VoLTE calls (Mazloum et al., 2023).

3.1.3. Comparison urbanization density

The median values of the measurements in the seven countries are compared based on the urbanization in Table 3 (urbanization 1) and Fig. 8. The highest ΔP_{UL} of 14.98 dBm was measured in the villages and the lowest ΔP_{UL} of 12.26 dBm in the large city. This is due to the better network coverage in the crowded cities compared to the villages. Network operators deploy more dense base stations in cities than villages, due to the higher number of users. More power is required to upload the same files when the coverage is less dense.

This same result and trend occur for the comparison of the central, non-central and outskirt city areas, measured in the parks and residential areas and presented in Table 3 (urbanization 2) and Fig. 9. The lowest ΔP_{UL} of 13.08 dBm was measured in the non-central area of the cities. In the outskirts and the central city area, the auto-induced uplink powers are higher, respectively 16.21 dBm and 14.51 dBm. With a factor of 3.13 dB, the exposure in the outskirts is significantly lower compared to the non-central and central city areas. While the power is expected to be lower in the central city area compared to non-central, the difference of 1.43 dB is not significant. The explanation for this trend is equal to the comparison of the cities and the villages. The same trend was found by Joseph et al. where field strengths of 0.51 V/m, 0.49 V/m and 0.09 V/m were measured for urban, sub-urban and rural areas, respectively (Joseph et al., Feb. 2012). However, only 2G-3G were measured. Gati et al., measured the uplink and downlink powers in two French cities, but did not specifically compare the difference based on urbanization (Gati et al., Nov. 2010). The DEVIN, introduced in (Mazloum et al., 2023), was also not used to compare different urbanization types.

3.1.4. Comparison microenvironments

Fig. 10 shows a comparison of the median telecommunication power levels in the microenvironments for Brussels, i.e. the large city (LC) in Belgium. Fig. 10 serves only as an indication that deeper analyses can be performed on the specific subdivision of microenvironment per country and per city/village, but due to the large dataset and the variability of the results the comparison of the microenvironments was done with the grouped microenvironments. These are defined as public transport, public places and outdoor areas, presented in Table 3 (ME groups) and Fig. 11. This final comparison is based on median values of all the cities and villages in the seven countries.

A ΔP_{UL} of 14.13 dBm was measured in the public places. Multiple bystanders are in the close vicinity in public places (like parks, shopping centers, stations) of the UE equipped with the add-on sensor, using their personal device. This leads to a lot of environmental uplink exposure generated in nearby area as well as a higher power required to provide every user with transmission power. In public transport, the highest ΔP_{UL} of 14.26 dBm was measured, which is with a difference of 0.13 dB not statistically significant compared to the public places. The explanation of the high uplink power lies in the public transport changing telecommunication cells, i.e., handover and with some being underground, more uplink power is required to upload the same files compared to public places and outdoor areas. Besides the cell handover, trains, trams and metros are built of metallic walls and roofs blocking outgoing and incoming signals, causing the mobile devices to radiate higher power levels. This phenomenon was also observed for 2G-3G and 4G (Joseph et al., Feb. 2012).

The lowest ΔP_{UL} of 12.35 dBm is measured in the outdoor areas, 1.8 dB lower compared to the public places and public transport. This can be explained because these places are generally more densely crowded, resulting in a better network coverage by the operators (Ofcom, 2021) to meet the high demand for a stable reliable and fast network connection. Therefore mobile phones use less power to communicate with a base station. Joseph et al. measured a maximal total field of 3.9 V/m in a residential area, since no public transport was measured (Joseph et al.,

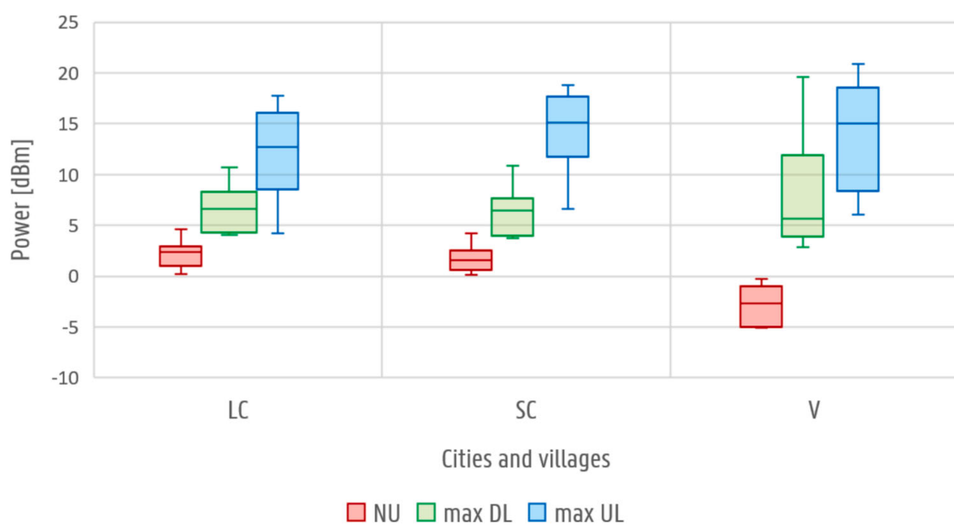

Fig. 8. Measurement results: comparison of powers in seven European countries based on urbanisation density. A distinction is made between large cities (LC), secondary cities (SC) and villages. The boxplots represent the power value in dBm for 3 different user scenarios in the different city areas over seven countries. The scenarios include non– user (NU) where the smartphone is in flight mode, maximum downlink (max DL) and maximum uplink (max UL) where the smartphone performs a continuous download and upload, respectively. The raw data was measured with the add-on RF-EMF sensor.

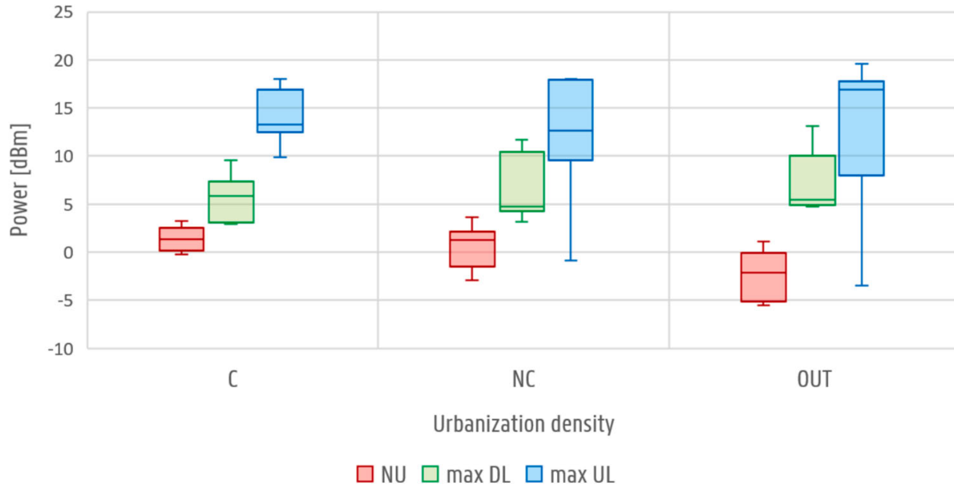

Fig. 9. Measurement results: comparison of powers in city section subdivided based on urbanisation density, i.e. central areas (C), non-central areas (NC) and outskirts (OUT), for 3 user scenarios, i.e. non– user (NU) where the smartphone is in flight mode, maximum downlink (max DL) and maximum uplink (max UL) where the smartphone performs a continuous download and upload, respectively. The boxplots represent the power value in dBm per user scenario for the different city areas over seven countries. The raw data was measured with the add-on RF-EMF sensor.

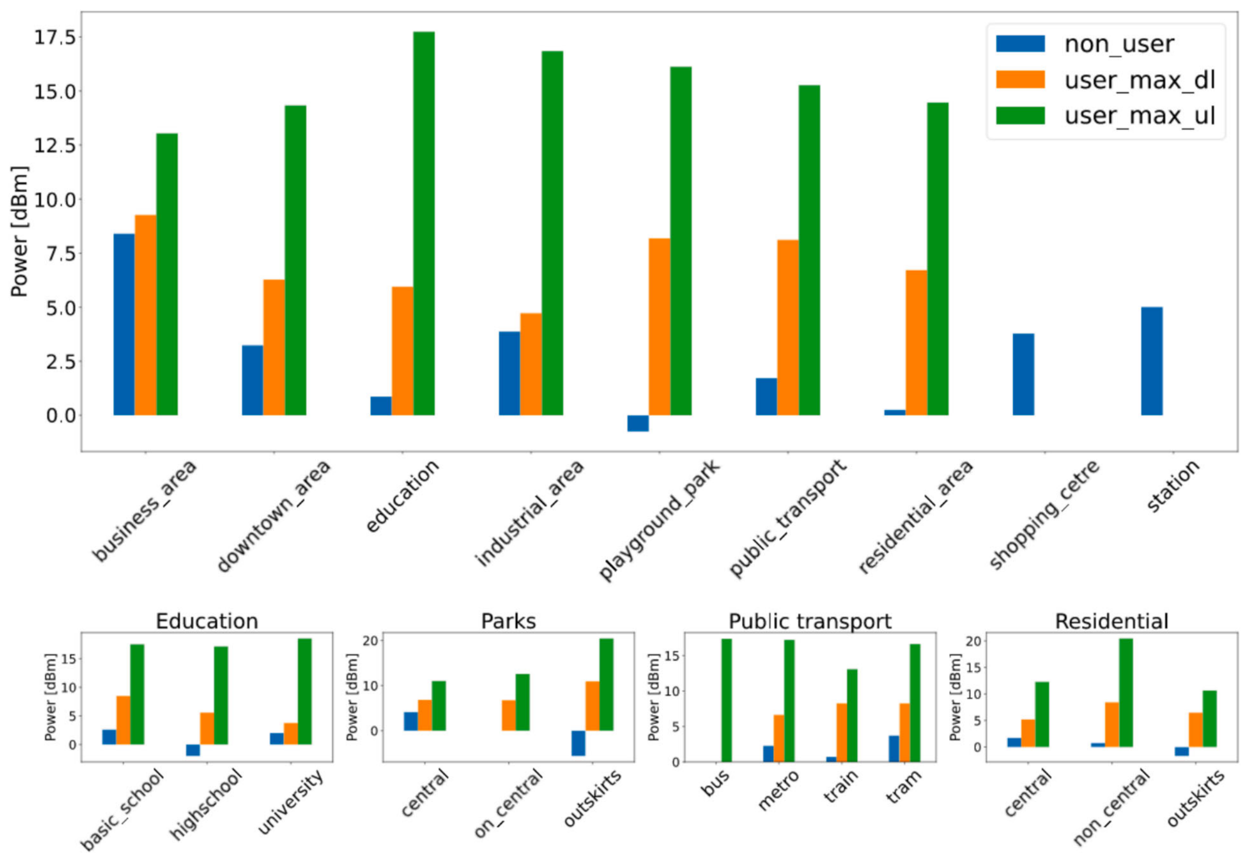

Fig. 10. Measurement results: example data presentation for the different microenvironments in large city (LC) in Belgium. The barplots represent the median power value in dBm per user scenario for the microenvironment (ME) types over seven countries. 3 scenarios are performed, i.e. non– user (NU) where the smartphone is in flight mode, maximum downlink (max DL) and maximum uplink (max UL) where the smartphone performs a continuous download and upload, respectively. For some microenvironments not all scenarios were performed or succeeded, hence the missing bars. The raw data was measured with the add-on RF-EMF sensor.

Feb. 2012). In this study, residential areas are considered in the outdoor areas and more different microenvironments were taken into account. Gati et al., Johsi et al. and Mazloum et al. did not make comparisons based on microenvironments (Joshi et al., 2020; Gati et al., Nov. 2010; Mazloum et al., 2023).

3.2. Strengths and limitations

Strengths of this study entail the design of a low-cost and low-complexity sensor for smartphones that measures the auto-induced uplink over all the telecom frequencies, including the newly introduced frequency band (5G n77), with and without the influence of the

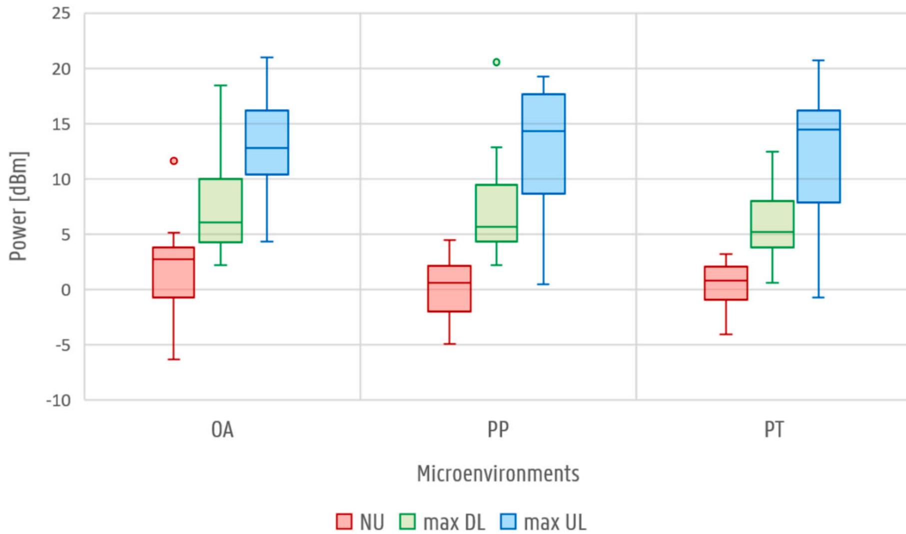

Fig. 11. Measurement results: comparison of powers in 3 microenvironment groups, i.e. outdoor areas (OA), public places (PP) and public transport (PT), for 3 user scenarios, i.e. non– user (NU) where the smartphone is in flight mode, maximum downlink (max DL) and maximum uplink (max UL) where the smartphone performs a continuous download and upload, respectively. The boxplots represent the power value in dBm per user scenario for the microenvironment (ME) groups over seven countries. The raw data was measured with the add-on RF-EMF sensor.

environment. Other available measuring solutions are very expensive and complex to use, making the add-on sensor suitable for large scale measurements performed by non-experts. It is attached and measuring very close to the smartphone, allowing for relevant data for personal exposure assessment, filling a gap where only little data is available. The sensor was used in seven European countries in multiple microenvironments, leading to a very large dataset of 1194 measurements. For the first time uplink powers were measured and compared for seven European countries for non-user, user max DL and user max UL scenarios with a newly developed and calibrated add-on sensor for smartphones. Comparisons are made per urbanization type and microenvironment in every country and in between the countries. This data, i.e. the power values, also provides the possibility to be used for dose absorption assessment in real environments.

A limitation of the sensor is that, no frequency selective information can be obtained. Hence, only one global power value can be obtained. Despite the small form factor, the add-on sensor is currently too large to be used with smartphones by the general public since it will not fit in pockets and is thus only usable in a scientific measurement campaign. Another limitation is the directional antenna, since these type of antennas underestimate environmental measurements as measured electric field strength depends on signal polarization and add-on antenna relative position. A final shortcoming is that the device is powered by an external power source. There is no integrated rechargeable battery or energy harvesting option. In the measurement campaign the sensor, was powered by the smartphone under test and so draining its battery. This will be solved in a future version.

4. Conclusions

An add-on RF-EMF sensor was used in an activity-based microenvironmental surveys. The low-cost broadband add-on sensor was used to map RF-EMF exposure in Belgium, Hungary, Italy, Poland, Switzerland, The Netherlands and The UK in different microenvironments for three network usage scenarios, i.e., non-user, maximum downlink and maximum uplink. Median powers were used to determine any underlying general trends. When examining the measured data, the most prominent trend is found with the difference of 2.27 dB between the cities and villages and the different city areas. Lowest powers are obtained during the non-user scenarios and increase 5.00 dB and 14.15 dB for the maximum downlink and maximum uplink scenarios, respectively.

Future work entails the comparison of the measurement results obtained by this add-on sensor with the results of other measurement devices and phone applications, namely QualiPoc and the ExpoM – RF4, that were used simultaneously to verify the discussed trends. Including the GPS data creates the possibility of investigating present base stations on the different routes and locations. Furthermore, the temporal behavior will be investigated as this activity-based measurement campaign will be repeated after two years, to investigate the influence of the 5G deployment.

CRediT authorship contribution statement

Han Van Bladel: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bram Stroobandt:** Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adriana Fernandes Veludo:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kenneth Deprez:** Writing – review & editing, Supervision, Conceptualization. **Martin Röösli:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Gabriella Tognola:** Writing – review & editing, Investigation. **Marta Parazzini:** Writing – review & editing, Investigation. **György Thuróczy:** Investigation. **Kinga Polańska:** Writing – review & editing. **Piotr Politański:** Writing – review & editing, Investigation, Conceptualization. **Joe Wiart:** Conceptualization. **Monica Guxens:** Writing – review & editing, Resources, Project administration. **Wout Joseph:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work is part of the European Union's Horizon Europe research and innovation program under grant agreement No 101057262

(GOLIAT) funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. We acknowledge support from the grant CEX2023-0001290-S funded by MCIN/AEI/10.13039/501100011033, and support from the Generalitat de Catalunya through the CERCA Program.

The authors greatly acknowledge all people involved in the data collection process, apart from themselves, namely: Dr Marta Bonato, Dr. Silvia Gallucci, and Dr. Martina Benini from CNR (Italy), Zsuzsanna Vecsei from NCPHP (Hungary), Magda Mariańska and Paweł Mamrot from NIOM (Poland), Lea Beláccková from Utrecht University (The Netherlands), Patricia de Llobet from ISGlobal (Spain).

Data availability

The data that has been used is confidential.

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