










Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Environmental Research

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

Temporal change of outdoor RF-EMF levels in four European countries: a microenvironmental measurement study

Lea Belácková^{a,*}, Adriana Fernandes Veludo^{b,c} , Reza Aminzadeh^d , Han Van Bladel^d, Vincent Griffon^f, Elisabeth Cardis^{h,i,j}, Stefan Dongus^{b,c}, Marloes Eeftens^{b,c} , Mònica Guxens^{g,h,i,j,k}, Wout Joseph^d , Patricia de Llobet^{h,i,j} , Paul Mazet^l, Patrick Van Torre^d , Arno Thielens^{d,e} , Roel Vermeulen^a, Joe Wiart^m, Martin Rössli^{b,c} , Anke Huss^a 

^a IRAS, Utrecht University, Yalelaan 1, 3584, Utrecht, Netherlands^b Swiss Tropical and Public Health Institute, Allschwil, Switzerland^c University of Basel, Basel, Switzerland^d Department of Information Technology Ghent University / IMEC, Technologiepark-Zwijnaarde 126, 9052, Ghent, Belgium^e The Graduate Center of the City University of New York, 85 St Nicholas Terrace, 10031, New York, NY, USA^f Ineris, Parc Technologique Alata, BP 2, Verneuil-en-Halatte, 60550, France^g ICREA, Barcelona, Spain^h ISGlobal, Barcelona, Spainⁱ Universitat Pompeu Fabra, Barcelona, Spain^j Spanish Consortium for Research on Epidemiology and Public Health (CIBERESP), Instituto de Salud Carlos III, Madrid, Spain^k Department of Child and Adolescent Psychiatry/Psychology, Erasmus MC, University Medical Centre, Rotterdam, Netherlands^l CETIM, 52 Av. Félix Louat, Senlis, 60300, France^m Telecom Paris, 19 place marguerite perey, Palaiseau, 91120, France

ARTICLE INFO

Keywords:

RF-EMF exposure

Time trends

Microenvironmental study

Non-ionizing radiation

Temporal exposure assessment

ABSTRACT

Introduction: Over the past two decades, the amount of transmitted mobile data has increased rapidly. It is unknown whether the implementation of the new technologies enabling this has resulted in changes of outdoor radio-frequency electromagnetic fields (RF-EMF) exposure. Therefore, microenvironmental measurements were used to investigate temporal trends in RF-EMF exposure between 2016 and 2023, in the Netherlands, Switzerland, Belgium and Spain, following a similar protocol across campaigns. Microenvironmental measurements refer to exposure measurements performed at predefined small areas that have been differentiated with a specific function in that particular area. This allowed us to compare exposure trends between countries and years.

Methods: The data was collected as part of the ACCEDERA (2016–2018), ETAIN (2023), and GOLIAT (2023) projects, walking repeatedly the same routes with RF-EMF exposimeters. Identical microenvironments were identified in each country and measurements of the exposure from mobile base stations, mobile phones and the total exposure were compared across years.

Results: Comparing measurements between 6 and 14 unique microenvironments in each country, our data did not suggest significant changes in the exposure from the mobile base station origin (total downlink exposure) between baseline measurements in 2016 to follow up and 2023 for the four countries. Across all countries and years the median values of the mobile base station exposure ranged from 0.11 mW/m² (Switzerland, 2023) to 0.62 mW/m² (Netherlands, 2018). There was no consistent trend in the individual microenvironments across the countries.

Conclusions: Our measurements of RF-EMF outdoor exposure levels across included microenvironment groups do not indicate change in exposure levels between 2016 and 2023 despite an increase in mobile data traffic by a factor of 8 in Western Europe¹.

* Corresponding author.

E-mail address: l.belackova@uu.nl (L. Belácková).<https://doi.org/10.1016/j.envres.2025.122315>

Received 18 February 2025; Received in revised form 2 July 2025; Accepted 6 July 2025

Available online 11 July 2025

0013-9351/© 2025 The Author(s). Published by Elsevier Inc. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Over the past two decades, mobile communication technologies have advanced rapidly. Currently, new generations of communications technology, like 5G, co-exist with legacy generations, in particular 3G and 4G/long term evolution (LTE), which have not yet been phased out. Additionally, rapid advancements have been achieved in coverage: For example, 4G network coverage doubled between 2015 and 2022, reaching 88 % of coverage area worldwide (ITU, 2022). Mobile data traffic increase requires the implementation of a dense network of base stations as part of the transition to 5G mobile telecommunications (Aerts et al., 2023). The most notable technological advances in 5G network base stations are the use of beamforming and beam steering, allowing dynamic adjustment of the signal energy in specific directions (Aerts et al., 2023). It is unclear whether these technological developments have introduced changes in exposure patterns of radiofrequency electromagnetic fields (RF-EMFs) in public spaces.

To fully deploy 5G, countries have allocated new frequency bands, specifically the 700 MHz band and the 3.6 GHz band (Khwandah et al., 2021; European Commission). In 2016, the EU adopted a plan to start rolling out 5G services in all member countries in 2020; with the aim to achieve coverage of all populated areas by 2030 (European Science-Media Hub). The 5G rollout and implementation process differs between European countries: Spain was one of the first EU countries to start rolling out 5G, and local mobile operators launched the first 5G services in autumn 2020 (European Commission). At the same time, Belgium delayed its 5G rollout and auction of new frequency bands to be used for 5G services (European Science-Media Hub). Nonetheless, by 2024, implementation was underway in all EU countries, and most of the pioneer 700 MHz and the 3.6 GHz bands had been allocated to operators (CEPT ECC Report 303).

To date, only a few studies have examined whether and to what extent these changes affect RF-EMF exposure levels, and available reports have either been performed in single countries e.g. Greece (Manassas et al., 2023), Switzerland (Loizeau et al., 2023), Norway (Markussen et al., 2022), Australia (Bhatt et al., 2024), or using localized measurements with stationary broadband sensors (Iakovidis et al., 2022), or a combination of the above that might not be representative for other locations and times. To the best of our knowledge, insight into general changes of RF-EMF exposure patterns over time is still scarce.

Microenvironmental studies have been applied to characterize outdoor RF-EMF levels and have proven useful in representing exposure levels in defined microenvironments (Sagar et al., 2016). Microenvironments are defined as small areas with distinct local characteristics e.g. city centre, residential area or industrial area. A validated method for such measurements has been developed previously (Sagar et al., 2016; Thielens et al., 2018). To achieve replicability and a representative measurement sample for each outdoor microenvironment, a trained researcher walks a predefined path taking measurements for at least 15 min in each microenvironment. In this study, we used repeated microenvironmental measurement campaigns to investigate temporal trends in RF-EMF exposure during the introduction of a new generation of mobile communications, 5G.

We compared RF-EMF measurements in identical microenvironments to identify changes in exposure in public outdoor environments between baseline in 2016 to follow up in 2023. Four countries were included: The Netherlands, Switzerland, Belgium and Spain. This allowed us to compare exposure trends over time and identify differences in exposure between countries.

2. Methods

2.1. Data collection

The data was collected as part of the ACCEDERA (2016–2018), ETAIN (2023) (ETAIN Project) and GOLIAT (2023) (GOLIAT project)

projects, investigating RF-EMF exposure levels in different public microenvironments. More information on the measurement protocol of ACCEDERA is provided in Huss et al. (2021) and more details about the protocol and measurement campaign in 2023 can be found in Veludo et al. (2024). In brief, the microenvironments were selected based on city size and main activity performed by the public in that type of environment (e.g. residential area, park, shopping area). Data collection was conducted in Utrecht in the Netherlands, Basel and Zurich in Switzerland, Ghent and Brussels in Belgium, and Barcelona and Mataro in Spain, in addition to several smaller villages in each country. The list of microenvironments included in the measurement campaigns in the different countries is provided in Supplementary Table A1 in Appendix. Each microenvironmental measurement was done with an exposimeter for approximately 15 min, during which the mobile phones of the trained researchers were switched off or set to airplane mode. Only repeated measurements along the same routes were included in this manuscript, and the routes that were taken in different streets were excluded. The paths were walked during the week days and during the working hours mainly between 08:00–18:00. In the Netherlands, 6 matching microenvironments were walked in 2017, 2018 and 2023. In Belgium, repeated measurements were taken in 2016, 2017 and 2023 in 6 microenvironments. For Switzerland, we included 13 microenvironments measured in 2016, 2017, 2018 and 2023. In Spain, the measurement campaign was repeated in 2017, 2018 and 2023 and had 14 matching microenvironments. The number of individual measurements per microenvironment ranged from 131 to 1569. The average number of measurements per microenvironment for included countries is shown in Appendix Tables A2-A5.

2.2. Measurement set-up and devices

Measurements were performed with personal exposimeters ExpoM-RF, developed by Fields at work (Fields at Work GmbH, 2023). During the ACCEDERA study between 2016 and 2018, measurements were taken using the ExpoM-RF 3 (frequency range 87.5 MHz to 5.875 GHz). While in 2023, measurements were conducted with the ExpoM-RF 4 (frequency range 50 MHz to 6 GHz). During the two measurement campaigns two different methods were used for carrying the exposimeters. The ExpoM-RF 3 was worn on the body using a textile vest with pockets on each side of the body (Huss et al., 2021). The ExpoM-RF 4 was placed in a case to avoid movement and placed in a backpack that was worn during the measurements. Picture of the set up for the 2023 measurement campaign is included in Appendix Figure A1. The ExpoM-RF devices measure root-mean-square (RMS) electric field strengths (V/m) with the values for each frequency band, at a sampling interval of 4 s for ExpoM-RF3 and 6.1 s for ExpoM-RF4. The trained researchers used a smartphone application to record the time and type of each microenvironment where they were measuring. Table 1 shows the frequency bands measured by ExpoM-RF3 and RF4. Lower detection limits of both devices are listed in Appendix TableA2.

2.3. Data processing

The data were recorded in electric field strength and subsequently converted to power flux density (mW/m^2) for the purpose of all calculations. The time stamp of the diary logs was used to align the ExpoM measurements with the respective microenvironment. First, mean values were calculated per microenvironment, country and year. Then, unique IDs for each microenvironment were used to match microenvironments across different years. Downlink exposure is considered environmental exposure from base stations and uplink exposure originates from other phone users. The total of the downlink bands, the total of uplink bands and the total of all bands were considered for the analysis. The total downlink includes the following frequency bands: 700, 800, 900, 1800, 2100, and 2600 MHz downlink band (Table 1). The total uplink includes the following frequency bands: 700, 800, 900,

1800, 2100, and 2600 MHz uplink band. The total of all bands is measured by the ExpoM devices.

2.4. Statistical analysis

We calculated medians and interquartile ranges (25th and 75th percentile) of downlink and uplink power density totals for each country, based on the arithmetic means of the matched microenvironments across the years. Downlink and uplink frequency bands were then plotted with boxplots for each year to visualize the exposure levels. Additionally, we plotted downlink total for included individual microenvironments for all countries and grouped based on population density estimation into low, medium and large. Due to unavailable GPS data for many measurement locations, microenvironments were grouped by estimation of population according to general city characteristics. As population density changes only very slowly in cities, we did not base the characterization on the corresponding years. For highly populated areas we considered areas in city centers e.g. residential area city center, train station in cities. For medium areas, e.g. suburban residential areas, parks and low populated areas were considered industrial areas, village center, train/bus station in villages.

Kruskal-Wallis test were applied to determine whether statistically significant differences existed between years. Linear regression was used to test if significant trend is observed in the downlink total levels measured between the included years. All analyses were done in R version 4.2.3 (R Core Team, 2021).

3. Results

3.1. Downlink and uplink exposure

Fig. 1 shows box-plots of the distribution of total measured downlink

ambient RF-EMF power density (mW/m²) exposure measured by year for all included microenvironments for all four countries. The median and IQR of total downlink exposure for each year can be found in Table 2. The mean downlink exposure levels per individual microenvironment per country can be found in the Appendix (Table A4-7).

Overall, we did not observe clear changes of total downlink exposure in Switzerland and in Spain over time. In the Netherlands, mean total downlink exposure was similar the baseline and follow up measurement campaigns of 2017 and 2023, but higher in 2018. A similar pattern was seen in Belgium with higher values in 2017 compared to baseline 2016 and follow up in 2023. However, these differences were not statistically significant as presented in Table 1. Linear regression confirmed no significant time trends ($p \geq 0.05$) in all included countries. At the level of individual microenvironments, we mostly observed no consistent trend in downlink exposure among the countries (see Appendix FigureA1-A4). For individual microenvironments, we found slight increase in total downlink exposure level from baseline measurement campaign compared to follow up 2023 in the Downtown city area of both Belgium and Spain. Otherwise, we found there were no consistent temporal trends among the matching microenvironments in the included countries that would indicate similar increase or decrease.

Additionally, all microenvironments were grouped based on estimated population density of the microenvironments into Low, Medium and Large population density (Fig. 2). We observed a decrease in total downlink exposure for low and medium population density microenvironments from 2017 to 2023. For large population density microenvironments we observe an increase from 2016 to 2018 and a slight decrease from 2018 to 2023.

3.2. Uplink and individual bands RF-EMF exposure

Additionally, we compared uplink RF-EMF levels among the years

Table 1

Frequency bands measured by the ExpoM-RF3 and ExpoM-RF4 and blue highlights exact correspondence in frequency bands measured by both devices).

Band	ExpoM-RF3 frequency bands	ExpoM-RF4 frequency bands	Bands added to downlink/uplink totals
FM Radio	87.5 - 108 MHz	80.25 - 115.25 MHz	
DAB/DAB+	-	164.5 - 239.5 MHz	
Polycom / TETRAPOL	-	367.5 - 402.5 MHz	
TETRAPOL, amateur, ISM 433	-	405 - 440 MHz	
PMR/PAMR	-	435 - 470 MHz	
DVB-T/broadcasting	470 - 790 MHz	470 - 697 MHz	
Mobile 700 uplink	-	700.5 - 735.5 MHz	Uplink
Mobile 700 TDD	-	730.5 - 765.5 MHz	
Mobile 700 downlink	-	753 - 788 MHz	Downlink
Mobile 800 downlink	791 - 821 MHz	791 - 826 MHz	Downlink
Mobile 800 uplink	832 - 862 MHz	829.5 - 864.5 MHz	Uplink
Mobile 900 uplink	880 - 915 MHz	880 - 915 MHz	Uplink
Mobile 900 downlink	925 - 960 MHz	925 - 960 MHz	Downlink
Mobile 1400 Supplementary down link	-	1442 - 1517 MHz	
Mobile 1800 uplink	1710 - 1785 MHz	1710 - 1785 MHz	Uplink
Mobile 1800 downlink	1805 - 1880 MHz	1805 - 1880 MHz	Downlink
DECT	1880 - 1900 MHz	1880 - 1915 MHz	
Mobile 2100 uplink	1920 - 1980 MHz	1919.5 - 1994.5 MHz	Uplink
Mobile 2100 downlink	2110 - 2170 MHz	2107.5 - 2182.5 MHz	Downlink
ISM 2.4 GHz	2400 - 2485 MHz	2388 - 2488 MHz	
Mobile 2600 uplink	2500 - 2570 MHz	2497.5 - 2572.5 MHz	Uplink
Mobile 2600 TDD	-	2575 - 2610 MHz	
Mobile 2600 downlink	2620 - 2690 MHz	2619.5 - 2694.5 MHz	Downlink
WiMAX 3.5 GHz	3400 - 3600 MHz	-	
Mobile 3500	-	3425-3785 MHz	
ISM 5.8 GHz /WiFi 5 GHz	5150 - 5875 MHz	5150 - 6000 MHz	

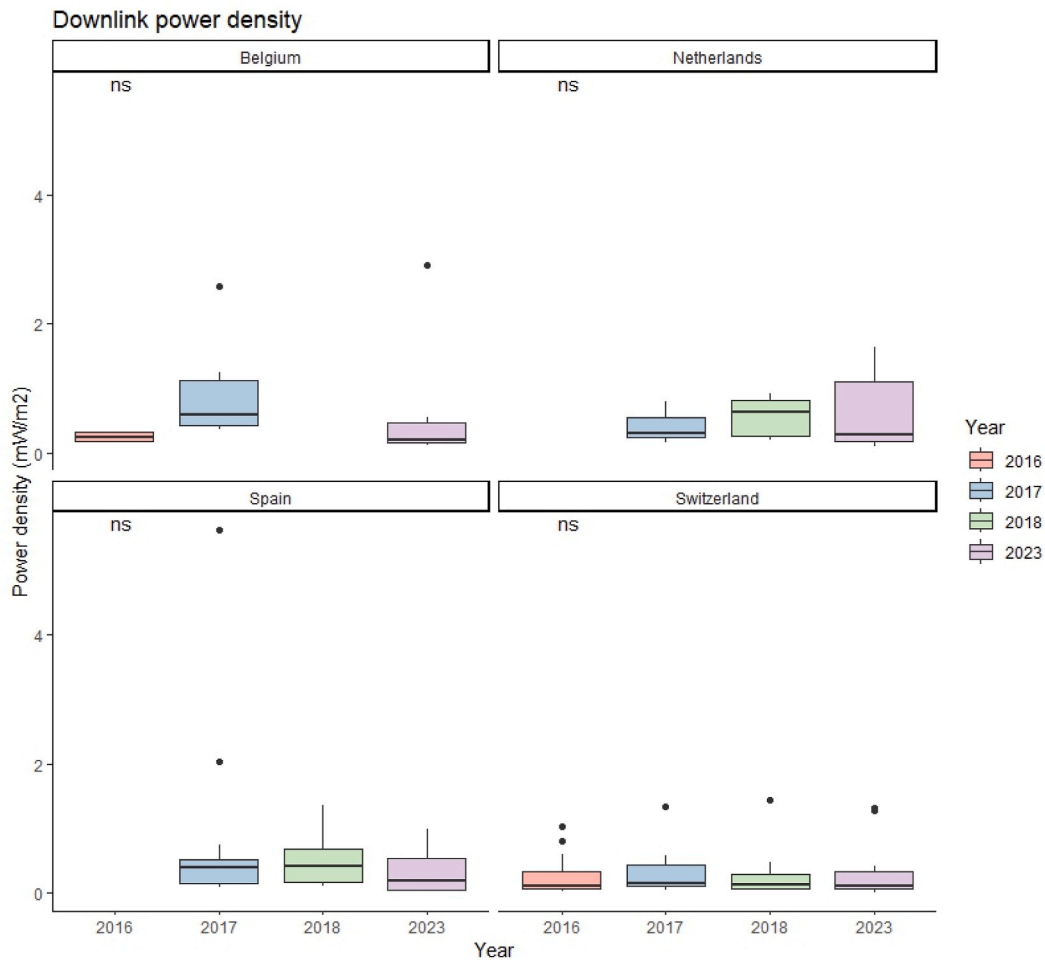


Fig. 1. Total downlink power density (mW/m^2) on a log scale each year per country; ns means not statistically significant after Kruskal-Wallis tests across the years. The central line of the boxplot show median, box the interquartile range and variability by the whiskers. Points represent outliers.

Table 2
Median (Interquartile Range, IQR) of power density of total downlink exposure per country.

Year	Median (IQR) total downlink power density				N	p-value
	2016	2017	2018	2023		
Power Density (mW/m^2)						
Netherlands	-	0.31 (0.23–0.55)	0.62 (0.27–0.81)	0.28 (0.18–1.09)	6	0.73
Belgium	0.24 (0.18–0.31)	0.60 (0.42–1.12)	-	0.20 (0.16–0.46)	6	0.07
Switzerland	0.12 (0.07–0.33)	0.14 (0.11–0.42)	0.12 (0.07–0.28)	0.11 (0.07–0.33)	13	0.9
Spain	-	0.38 (0.13–0.51)	0.41 (0.17–0.67)	0.19 (0.049–0.53)	14	0.21

Values in of total downlink exposure per country, N = number of measured microenvironments of same type matched for included years. P-values of Kruskal-Wallis rank sum test.

per country. As seen in Fig. 3, the total uplink exposure levels decreased in all countries after initial increase between baseline and follow up measurement campaigns (p-values: 0.004 Belgium, p-value 0.0035 Netherlands, 0.0001 Spain, 0.00002 Switzerland). Uplink exposure is originating from other users of nearby mobile communication devices and therefore, contributes little to the total. The total of measured all bands was also not significantly different (Appendix Figs. 2–5).

Regarding individual frequency bands, for the 800 MHz band we observed a statistically significant increase in all countries. We also observed a statistically significant increase in the 2600 MHz band in Spain. In other bands we observed significant decreases in exposure levels, in particular in the 900 MHz (Belgium, Spain) and 2100 MHz (Belgium) bands in the measurement from 2017 to 2023 (Belgium) and 2018 to 2023 (Spain). For all other frequency bands, no clear increase or

decrease was observed. Individual box plots for each frequency band with significance test can be found in the Appendix (Fig. A6–A25).

4. Discussion

We compared average downlink RF-EMF exposure levels in outdoor environments between baseline measurements in 2016/2017 and follow up 2023 in four European countries. We found no clear change in exposure levels for total downlink exposure between 2016/2017 and 2023 for the included countries. We found increases in total downlink exposure in Belgium between 2016 and 2017, and in the Netherlands between 2017 and 2018, respectively, but levels were then decreased again in 2023. There were no trends identified in the total downlink trend when looking at individual microenvironments per country. We

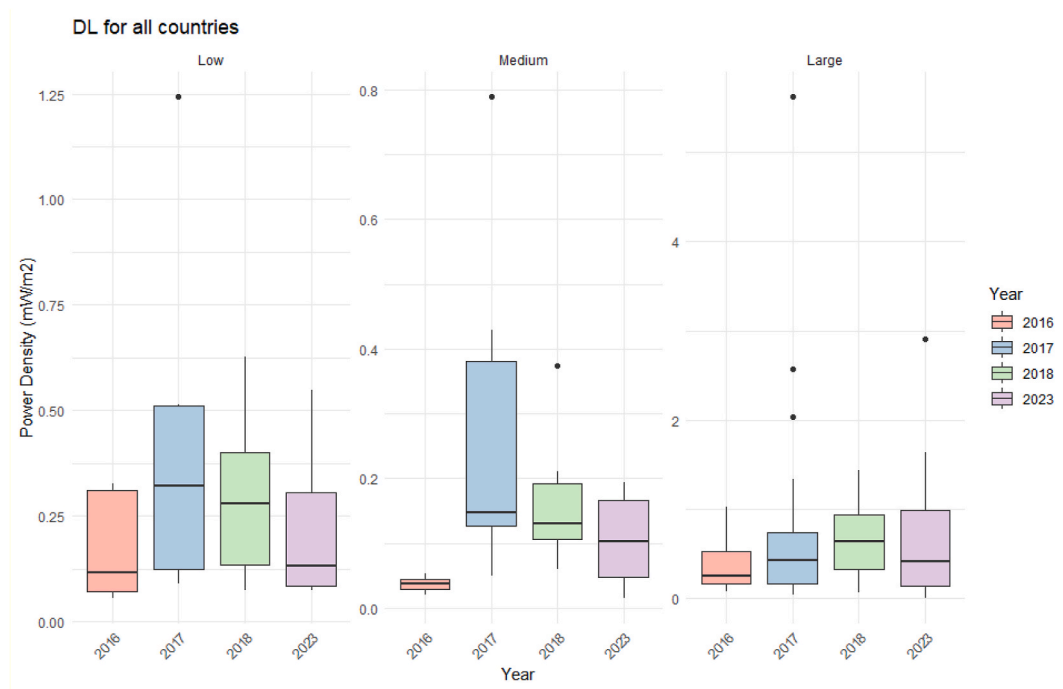


Fig. 2. Boxplots of total Downlink measurements for all included measurements divided by population density of the microenvironments. Low population density includes microenvironments: Park, Residential area outskirts Medium city, Village centre. Medium population density includes microenvironments: Residential central area Medium city, Residential subcentral Large city. Large population density includes: Business area Large city, Downtown area Large city, Residential Central area Large city, Train station, Shopping centre, University, Downtown area Large city. Microenvironments from all countries were included.

observe decreases in exposure levels for the total uplink, but not for the total of all frequency bands. This likely reflects technological adaptation over time with a shift in bands towards those used more often in 4G or 5G, with more efficient technology (5G Observatory; Radio Spectrum Policy Group, 2023). The median values ranged between 0.11 mW/m² to 0.62 mW/m² across the countries and years and all values in our study were well below the ICNIRP reference exposure limits (International Commission on Non-Ionizing Radiation Protection, 2020).

4.1. Literature comparison

Several studies have investigated long-term changes in exposure to RF-EMF. Rowley et al. (2012) collected RF-EMF exposure data from 23 countries and investigated exposure trends by country. The data collected between 2000 and 2010 showed no significant increase in the RF-EMF exposure in public areas, during the introduction of 3G services (Rowley and Joyner, 2012).

Urbiniello et al. (2014) showed an increase in total outdoor exposure to RF-EMF between April 2011 and March 2012 in cities in Belgium and Switzerland (Urbiniello et al., 2014). This study was conducted by walking in predefined microenvironments, and the methodology was similar to ours. Since 2012, a couple of other studies have examined temporal trends: The Manassas study monitored total exposure between 2003 and 2022 using a network of fixed sensors across Greece (Manassas et al., 2023). This study showed no clear upward or downward trend, but some sensors indicated an increase in levels of RF-EMF after 2014, when 4G was introduced. They also showed high variability over time, with no clear trend in exposure pattern until 2023. However, the study used a network of sensors placed on rooftops or balconies, which means that their results are more limited in terms of evaluating changes in particular microenvironments at an individual level. Bhatt et al. (2024) measured RF-EMF in 2015 and 2022 in Melbourne, Australia, with the trained researcher walking with ExpoM-RF 3 and ExpoM-RF 4 in matching microenvironments, similarly to our study. For total downlink exposure they showed an increase of median downlink exposure from

0.15 V/m to 0.19 V/m for all pooled data (Bhatt et al., 2024). In addition, Loizeau et al. (2023) compared RF-EMF exposure levels in the same Swiss microenvironments between 2014 and 2021, also using the ExpoM-RF3 and ExpoM-RF4 devices. Here, a slight decrease in downlink exposure levels in 2021 compared to 2014 was reported. Overall, these previous studies are consistent with our findings, where we do not observe statistically significant changes in the trends of RF-EMF exposure levels in recent years (Loizeau et al., 2023). A systematic review by Ramirez-Vazquez et al. (2024) review articles between 1998 and 2023 that measured RF-EMF environment exposure. They report highest average to be 0.20 W/m² in Norway in study published in 2022 and lowest in Spain of 0.0663 μW/m² for study published in 2020 for the included European countries. In this review we do not observe high exposure values in more recent studies, rather different exposure among the countries and their measurement locations.

This suggests between the period 2016/2017 to 2023 we do not observe significant changes in exposure across European countries even if data traffic increased (Statista). Further studies are necessary to observe how complete roll out of 5G alters the exposure to RF-EMF.

4.2. Strengths and limitations

A strength of our study is that it provides an overview of temporal trends in RF-EMF exposure between 2016/2017 and 2023 in four different countries. Similar measurement protocols were used, and data collection was standardized across all included countries and years. We only included data collected by collecting measurements at the same paths to ensure data comparability. Another strength is the inclusion of different types of microenvironments that represent common outdoor areas in all included countries, which provides some reassurance that the measurements represent pertinent exposure levels (Eftens et al., 2019).

Limitations of our study include that we were able to link the location of the ExpoM-RF measurements for Switzerland, Belgium and Spain only on the level of the identical microenvironment and not to their

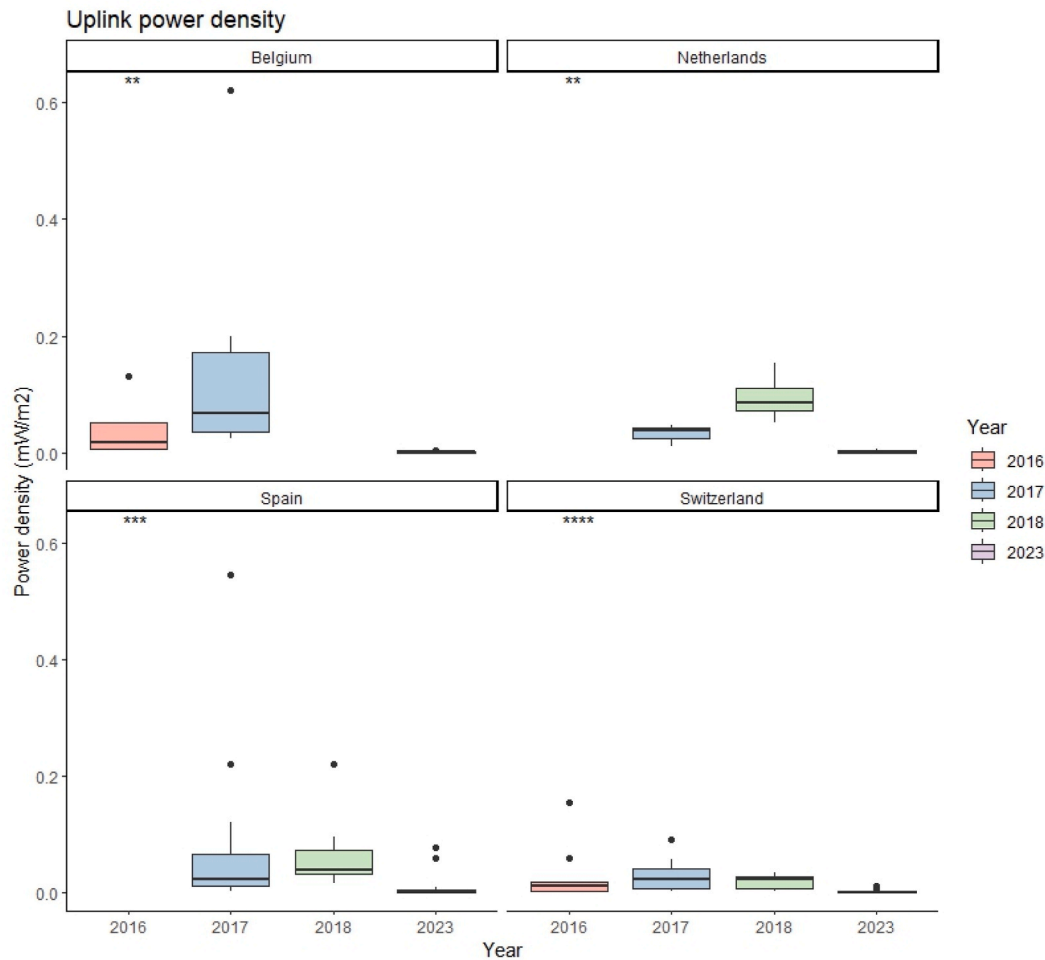


Fig. 3. Boxplots of Uplink total measurements for all included measurements.

specific spatial coordinates. Although measurement paths were pre-defined and followed as closely as possible, small differences may have occurred by trained researchers walking on different sides of the road, or by walking around obstructions, construction sites, or newly constructed buildings. In addition, we did not follow the time schedule of the first protocols, which means that timing during the day, and day of the week of the measurement differed across the years. However, most measurements were conducted during the week at working hours throughout the studies. These differences are not systematic and add noise to the data. It is thus unlikely that they affect temporal trends, but they may reduce the statistical power to detect differences.

A different number of microenvironments per country was included (e.g 6 in Belgium and 13 in Switzerland), which meant that not all public environments are equally represented. For this reason, one cannot draw firm conclusions about exposure differences between countries. This should, however, not impact the possibility to observe a trend over time, should one exist.

There was a change between the way the measurement devices were set up during the campaigns. Between 2016 and 2018 the ExpoM were inside of a vest worn by a trained researcher and during the 2023 measurements the ExpoM was in a case inside of a top part of a backpack to avoid body shielding. All ExpoM devices were calibrated but there might be a systematic bias in measurement accuracy for the temporal analysis considering different measurement campaigns and calibration sessions. A previous real-world quality assessment study showed that the microenvironment characteristic determines most of the exposure level and systematic differences between devices are negligible (GSMA, 2022). Additionally, wearing measurement devices in a vest or in a

backpack can lead to underestimating of exposure values as a result of body shielding. This was tested in real-life conditions, where a body-worn distributed meter was compared with exposimeters including the ExpoM. The results showed the exposimeters measured lower uplink, DECT and Wi-Fi exposure compared to body-worn distributed meter, however, measured values were highly correlated for total and downlink RF-EMF exposure levels (Huss et al., 2021).

A further limitation is the use of two different ExpoM device models. These devices differ in terms of some of the captured frequency bands that are being measured. To best estimate the differences in temporal trends, we included only the downlink bands measured by the device in each year and created totals of downlink for each year, as the use of the uplink and downlink frequency bands could have been switched between bands by the operators. The 800 MHz band was assigned to operators for the 5G implementation and Time Division Duplex (TDD) bands were also adopted for the use of 5G²⁶. Our presented metric should therefore still capture if there was a clear change of the general exposure pattern. Another difference between ExpoM devices is their sampling rate (4 vs 6 s), which resulted in more collection points for collection during the years 2016–2018. However, it was shown that shorter sampling interval does not over- or underestimate the exposure levels (Huss et al., 2021). In the analysis we consider medians for the included microenvironments with at least 100 measurements per microenvironment and we believe this still represents the exposure levels.

5. Conclusions

Overall, the analysis of temporal trends of RF-EMF outdoor exposure levels did not indicate changes in the total downlink exposure levels between baseline measurements in 2016 or 2017 and follow up in 2023. This was observed for all included countries: the Netherlands, Spain, Switzerland and Belgium. We also observed a decrease in the total up-link exposure levels. Medians of mobile total downlink exposure across the included microenvironments showed no changes in trend of total downlink mobile exposure even with increased data usage over this period.

CRedit authorship contribution statement

Lea Belácková: Writing – original draft, Visualization, Methodology, Formal analysis. **Adriana Fernandes Veludo:** Writing – review & editing, Data curation. **Reza Aminzadeh:** Writing – review & editing. **Han Van Bladel:** Writing – review & editing. **Vincent Griffon:** Writing – review & editing. **Elisabeth Cardis:** Writing – review & editing. **Stefan Dongus:** Writing – review & editing. **Marloes Eeftens:** Writing – review & editing, Data curation. **Mónica Guxens:** Writing – review & editing. **Wout Joseph:** Writing – review & editing. **Patricia de Llobet:** Writing – review & editing. **Paul Mazet:** Writing – review & editing. **Patrick Van Torre:** Writing – review & editing. **Arno Thielens:** Writing – review & editing. **Roel Vermeulen:** Writing – review & editing. **Joe Wiart:** Writing – review & editing. **Martin Rööslí:** Writing – review & editing. **Anke Huss:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Funding

This project has received funding from the ETAIN project that is funded by the European Union's Horizon Europe research and innovation program under grant agreement No. 101057216.

This project has received funding from the GOLIAT project that is funded by from the European Union's Horizon Europe research and innovation programme under grant agreement No 101057262. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the Health and Digital Executive Agency. 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 Accedera project was funded by the National Research Program of the French Agency for Food, Environmental and Occupational Health and Safety (ANSES), grant No 2015-2-RF-07.

The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2025.122315>.

Data availability

Raw data and codes will be shared

References

- 5G Observatory. "National 5G Spectrum Assignment." European 5G Observatory. <https://5gobservatory.eu/national-5g-spectrum-assignment/#1533313191850-e4c4e41d-ac05>. (Accessed 2 October 2024).
- Aerts, S., Deprez, K., Verloock, L., Olsen, R.G., Martens, L., Tran, P., Joseph, W., 2023. RF-EMF exposure near 5G NR small cells. *Sensors* 23 (6), 3145. <https://doi.org/10.3390/s23063145>.
- Bhatt, C.R., Henderson, S., Sanagou, M., Brzozek, C., Thielens, A., Benke, G., Loughran, S., 2024. Micro-environmental personal radio-frequency electromagnetic field exposures in Melbourne: a longitudinal trend analysis. *Environ. Res.* 251, 118629.
- CEPT ECC report 303. 4403 (cept.org). https://5gobservatory.eu/wp-content/uploads/2023/10/BR-19_October-2023_Final-clean.pdf. (Accessed 23 August 2024).
- Eeftens, M., Dongus, S., Bürgler, A., Rööslí, M., et al., 2019. A real-world quality assessment study in six ExpoM-RF measurement devices. *Environ. Res.* 182, 22142. <https://doi.org/10.1002/bem.2214>.
- ETAIN Project. ETAIN Project (n.d.). <https://www.etaainproject.eu/>. (Accessed 22 January 2025).
- European Commission. 5G for Europe: action plan. <https://digital-strategy.ec.europa.eu/en/policies/5g#:~:text=The%20objective%20of%20the%20action,main%20transport%20paths%20by%202025>. (Accessed 23 August 2024).
- European Science-Media Hub. 5G and health concerns. <https://map.sciencemediahub.eu/5g#p=38>. (Accessed 23 August 2024).
- Fields at Work GmbH, 2023. ExpoM-RF4 - configurable exposure meter. Fields at Work GmbH. <https://fieldsatwork.ch/products/expom-rf/expom-rf4/>. (Accessed 10 August 2024).
- GSMA, 2022. 5G spectrum positions. <https://www.gsma.com/connectivity-for-good/spectrum/wp-content/uploads/2022/06/5G-Spectrum-Positions.pdf>. (Accessed 26 November 2024).
- Huss, A., Dongus, S., Aminzadeh, R., Thielens, A., van den Bossche, M., Van Torre, P., de Seze, R., Cardis, E., Eeftens, M., Joseph, W., Vermeulen, R., Rööslí, M., 2021. Exposure to radiofrequency electromagnetic fields: comparison of exposimeters with a novel body-worn distributed meter. *Environ. Int.* 156, 106711. <https://doi.org/10.1016/j.envint.2021.106711>. Epub 2021 Jun 19. PMID: 34153890.
- Iakovidis, S., Apostolidis, C., Manassas, A., Samaras, T., 2022. Electromagnetic fields exposure assessment in Europe utilizing publicly available data. *Sensors* 22, 8481. <https://doi.org/10.3390/s22218481>.
- International Commission on Non-Ionizing Radiation Protection, 2020. Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). <https://www.icnirp.org/cms/upload/publications/ICNIRPrfgdl2020.pdf>.
- ITU, 2022. Mobile network coverage. <https://www.itu.int/itu-d/reports/statistics/2022/11/24/ff22-mobile-network-coverage/>. (Accessed 23 August 2024).
- Khwandah, S.A., Cosmas, J.P., Lazaridis, P.I., et al., 2021. Massive MIMO systems for 5G communications. *Wirel. Pers. Commun.* 120, 2101–2115. <https://doi.org/10.1007/s11277-021-08550-9>.
- Loizeau, N., Zahner, M., Schindler, J., Stephan, C., Fröhlich, J., Gugler, M., et al., 2023. Comparison of ambient radiofrequency electromagnetic field (RF-EMF) levels in outdoor areas and public transport in Switzerland in 2014 and 2021. *Environ. Res.* 116921. <https://doi.org/10.1016/j.envres.2023.116921>.
- Manassas, A., Apostolidis, C., Iakovidis, S., et al., 2023. A study of the long term changes in the electromagnetic environment using data from continuous monitoring sensors in Greece. *Sci. Rep.* 13, 13784. <https://doi.org/10.1038/s41598-023-41034-3>.
- Markussen, A.C., Sjoemoen, T.M., Unander, E.H., Klæboe, L., 2022. Regular measurements of EMF in a representative Norwegian city—constant exposure over time despite introduction of new technologies. *Environ. Monit. Assess.* 194, 694. <https://doi.org/10.1007/s10661-022-10231-4>.
- Project GOLIAT. Project GOLIAT (n.d.). <https://projectgoliat.eu/>. (Accessed 22 January 2025).
- R Core Team, 2021. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.
- Radio Spectrum Policy Group, 2023. RSPG Report on Mobile Technology Evolution (With Annexes). European Commission. https://radio-spectrum-policy-group.ec.europa.eu/system/files/2023-03/RSPG23-010final-RSPG_Report_on_Mobile_technology_evolution_%28with%20annexes%29.pdf. (Accessed 2 October 2024).
- Rowley, J.T., Joyner, K.H., 2012. Comparative international analysis of radiofrequency exposure surveys of mobile communication radio base stations. *J. Expo. Sci. Environ. Epidemiol.* 22 (3), 304–315. <https://doi.org/10.1038/jes.2012.13>. Jun.
- Sagar, S., Struchen, B., Finta, V., Eeftens, M., Rööslí, M., 2016. Use of portable exposimeters to monitor radiofrequency electromagnetic field exposure in the everyday environment. *Environ. Res.* 150, 289–298.
- Statista. (n.d.). Worldwide monthly mobile data traffic per smartphone from 2016 to 2027. Statista. Retrieved [Accessed 2024 August 23], from <https://www.statista.com/statistics/738977/worldwide-monthly-data-traffic-per-smartphone/>.

- Thielens, A., Van den Bossche, M., Brzozek, C., Bhatt, C.R., Abramson, M.J., Benke, G., et al., 2018. Representativeness and repeatability of microenvironmental personal and head exposures to radio-frequency electromagnetic fields. *Environ. Res.* <https://doi.org/10.1016/j.envres.2017.12.017>.
- Urbiniello, D., Joseph, W., Verloock, L., Martens, L., Rösli, M., 2014. Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities. *Environ. Res.* 134, 134–142. <https://doi.org/10.1016/j.envres.2014.07.003>.
- Veludo, A.F., Stroobandt, B., Van Bladel, H., Sandoval-Diez, N., Guxens, M., Joseph, W., Rösli, M., 2024. Exploring RF-EMF levels in Swiss microenvironments: an evaluation of environmental and auto-induced downlink and uplink exposure in the era of 5G. *Environ. Res.* 266, 120550. <https://doi.org/10.1016/j.envres.2024.120550>.