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5G RF EMF Spectral Exposure Assessment in Four European Countries

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ABSTRACT

This study assesses the exposure to 5G radio frequency electromagnetic fields (RF EMF) across four European countries. Spot measurements were conducted indoor and outdoor in both public spaces and educational institutions, encompassing urban and rural environments. In total, 146 measurements were performed in 2023, divided over Belgium (47), Switzerland (38), Hungary (30) and Poland (31). At 34.9% of all measurement locations a 5G connection to 3.6 GHz was established. The average cumulative incident power density (S_{avg}) and maximum cumulative incident power density (S_{max}) were determined, for both "background" exposure (no 5G user equipment; No UE) and worst-case exposure (maximum downlink with 5G user equipment; Max DL). Furthermore, 3.6 GHz 5G-specific average $S_{avg,5G}$ and maximum $S_{max,5G}$ incident power density are considered as well. For the No UE scenario, the highest S_{max} is 17.6 mW/m^2, while for the Max DL, the highest S_{max} is 23.3 mW/m^2. Both values are well within the ICNIRP guidelines. The highest $S_{max,5G}$ measured over all countries and scenarios was 10.4 mW/m^2, which is 3.2% of the frequency-specific ICNIRP guidelines. Additionally, a comparison was made between big cities, secondary cities, and villages for all four countries. The ratio of power density measured in rural areas was significantly lower than in urban areas (−4.8 to −10.4 dB). Under LOS conditions, the average incident power density was 2.3 mW/m^2, whereas under NLOS conditions, the average incident power density decreases to 0.9 mW/m^2. Furthermore, the relative variation increases under NLOS scenarios. Lastly, an analysis was performed regarding the power density in educational institutions compared to all other measurement locations, both indoors and outdoors for the different city types. The measured incident power density is not extensively lower in or around schools compared to public places, neither in the big cities, secondary cities, or the villages.

1 | Introduction

The proliferation of wireless communication technologies has led to an increased concern regarding radio frequency electromagnetic field (RF EMF) exposure and its potential health effects (Chiaraviglio et al. 2021; Russell 2018; Di Ciaula 2018). As mobile networks innovate (e.g., 5G) and new technologies such as Massive Multiple Input Multiple Output (MaMIMO) and beam steering capabilities are deployed (3GPP 2025), assessing the levels of RF EMF exposure correctly in all environments becomes crucial for both public health policy and scientific research. Hence, measurement methodologies must be adapted to ensure these are applicable for 5G NR exposure assessment (IEC 2022; Aerts et al. 2019, 2021; Deprez et al. 2022).

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Summary

- Radio frequency electromagnetic fields exposure assessment measurements across four European countries are conducted using a standardized measurement method.
- All measurements were well within the ICNIRP guidelines.
- The incident power density measured in rural areas was significantly lower than in urban areas.

International guidelines to limit RF EMF exposure are constructed such as those by the International Commission on Non-ionising Radiation Protection (ICNIRP 2020) and the Institute of Electrical and Electronics Engineers (IEEE 2019). Despite the establishment of international guidelines, variations in local regulatory standards, environmental factors, usage, and technological infrastructure could result in different exposure levels across diverse countries.

Several techniques can be used to assess the exposure from RF EMF originating from base stations. First, simulations can be performed (Shikhantsov et al. 2020; Wydaeghe et al. 2022; Wiame et al. 2024; Xu et al. 2021; Hirata et al. 2021). However, these are often limited by computational power, abstractions to mimic reality, and storagse. In addition to simulations, three types of measurements can be used: spot measurements, personal exposure measurements, and measurements from a monitoring network. Spot measurements are short-term measurements (typically 6 or 30 min, according to ICNIRP 2020) on a predefined location (Aerts et al. 2019, 2021; Deprez et al. 2022; Bieńkowski et al. 2024). These spot measurements entail using dedicated measurement setups, resulting in the most accurate in situ measurements but they are time-consuming. Personal exposure measurements are measurements performed with an exposimeter to measure the exposure to RF EMF of a single person individually, often related to the profession of that worker (e.g., welders) or specific groups within the population (e.g., children) (Loizeau et al. 2023; Sagar et al. 2016; Ramirez-Vazquez et al. 2023; Bhatt et al. 2022). Monitoring networks encompass long-term measurements with (semi) fixed low-cost sensors that capture the temporal behavior of the RF EMF exposure (Deprez et al. 2023; Aerts et al. 2022; Ulversoy 2010). These sensors are not suitable for compliance assessment due to design limitations. However, the temporal behavior is crucial to provide a full overview of the total RF EMF exposure and rescaling of the spot measurements can be performed to obtain the worst case exposure. Korkmaz et al. made a comprehensive overview regarding 5G RF EMF exposure assessment technologies (Korkmaz et al. 2024).

In previous studies, RF EMF exposure has been measured across multiple countries using personal exposure meters. In 2010, RF EMF exposure was measured in five European countries (Joseph et al. 2010). All exposure values were found well below international exposure limits, local regulatory limits were not considered. Urbinello et al. performed measurements in 2014 in four different European cities by means of another personal exposimeter (Urbinello et al. 2014). Sagar et al. measured 94 microenvironments between 2015 and 2017 in six countries with two types of personal exposimeters (Sagar, Adem, et al. 2018). Exposure levels tended to increase with increasing urbanicity. In most microenvironments, downlink from mobile phone base stations is the most relevant contributor to the environmental "background" exposure. While these studies have provided valuable insights, they all relied on personal exposimeters, which entail less precise measurements. In contrast, this study uses more accurate spot measurements to assess RF EMF exposure. Joseph et al. performed a similar study in 2012 over three European countries (Belgium, The Netherlands, and Sweden) (Joseph et al. 2012a). Here, the exposure levels also increased with increasing urbanicity. At that moment in time, the highest contribution to the downlink exposure was due to GSM. Gajšek et al. presented an overview of the scientific literature on RF EMF exposure in Europe in 2013 (Gajšek et al. 2015). No exposure levels were found above the current recommendations (ICNIRP 2020). One of the limitations raised by the authors was that there was no uniform or comparable measurement protocol.

The contributions of this paper are as follows: first, RF EMF spectral exposure spot measurements across four European countries using a standardized measurement method are presented: Belgium, Switzerland, Poland, and Hungary. Second, the RF EMF levels are compared between different types of urbanization (big cities, secondary cities and villages), urban versus rural environments for each separate country, and for two user scenarios. Next, a comparison is made between measurement locations that have a line of sight (LOS) with a base station and measurement locations which have no line of sight (NLOS). Last, as a multitude of the measurements were performed in educational institutions (primary schools, high schools and universities) and these environments are considered "sensitive places" in regulations of some countries, a comparison is made between the exposure measured in these environments versus all other environments.

2 | Materials and Methods

2.1 | Measurement Locations

In total, 146 spot spectral measurements were performed between February and September 2023 at various locations in four European countries; Belgium (47), Switzerland (38), Hungary (30) and Poland (31). The measurement positions were selected to correspond to a location on the paths defined in microenvironmental studies performed within the European project "5G expOsure, causaL effects, and rIsk perception through citizen engAgemenT (GOLIAT)" (Veludo et al. 2025). The selection aimed to cover as many of the GOLIAT-defined microenvironments as possible, with a focus on those frequented by young people and a balanced representation of urban and rural settings. Where feasible, measurements were conducted on the same weekday and time of day as in the aforementioned studies to ensure temporal comparability. This approach facilitates integration with the broader GOLIAT measurement framework.

Measurements were performed at public places (97) and educational institutions (49). Educational institutions include primary schools, high schools, and universities. Public places encompass all other measurement locations, such as (but not limited to), public transport stations, parks, and residential areas. Both indoor (42) and outdoor (104) measurements were performed. Measurements were performed in big cities (usually the capital city) and its suburbs (i.e., > 500.000 inhabitants), secondary cities (smaller city and its suburbs (i.e., 100–500.000 inhabitants) and villages (rural areas).

The trained researcher indicated if the measurement equipment was in Line Of Sight (LOS) of a base station. In Belgium, 40.4% of the measurement locations were in LOS, in Switzerland it was 31.6%, and in Hungary it was 10%. Lastly, 35.5% of the measurements performed in Poland were in LOS. These percentages were dependent on the environmental conditions at the time of the measurements. It should also be noted that the specific azimuth or elevation orientation of the base station antenna was not taken into account when determining LOS. Furthermore, no verification was performed to ensure the UE was connected to the LOS base station. The device connected automatically to the strongest available signal from the selected operator, which may or may not necessarily have corresponded to the nearby LOS base station.

2.2 | Measurement Equipment

Spot measurements are executed to characterize downlink RF exposure originating from base stations. The measurement setup for the spot measurements in Belgium, Switzerland, and Hungary consisted of a spectrum analyzer type SRM-3006 from Narda Safety Test Solutions. The SRM-3006 has a frequency range from 9 kHz to 6 GHz. The spectrum analyzer was connected to a tri-axial E-field antenna (3502/01 from Narda Safety Test Solutions) with a frequency range from 420 MHz to 6 GHz and a dynamic range of 0.14 to 160 V/m. In Poland, a SRM-3000 from Narda Safety Test Solutions was used, which has a frequency range from 100 kHz to 3 GHz. This spectrum analyzer was connected to a tri-axial E-field antenna (3AX 75M-3G from Narda Safety Test Solutions) with a frequency range from 27 MHz to 3 GHz and a dynamic range of 0.2 mV/m to 200 V/m. The antenna for both spectrum analyzers was connected to a wooden tripod at a fixed height of 1.5 m. The measurement uncertainty for the incident power density is ±3 dB for the considered measurement equipment (IEC 2022). This uncertainty represents the expanded uncertainty evaluated using a confidence interval of 95% (Joseph et al. 2012b). Figure 1 shows this setup. The spectrum analyzer and antenna are indicated, as well as the user equipment (UE), and the base station.

The power density generated by the base stations (downlink) for the present signals in a frequency range from 700 MHz to 4 GHz are assessed. For this study, five downlink telecommunication frequency bands (Frequency Division Duplex; FDD) and two Time Division Duplex (TDD) frequency bands were selected: 791–821, 920–960, 1805–1880, 2110–2170, 2620–2690, 703–788, and 3400–3800 MHz.

In three countries (Belgium, Switzerland, Hungary), the newly introduced 5G frequency band (TDD 3400–3800 MHz) is licensed and used in commercial telecommunication networks.

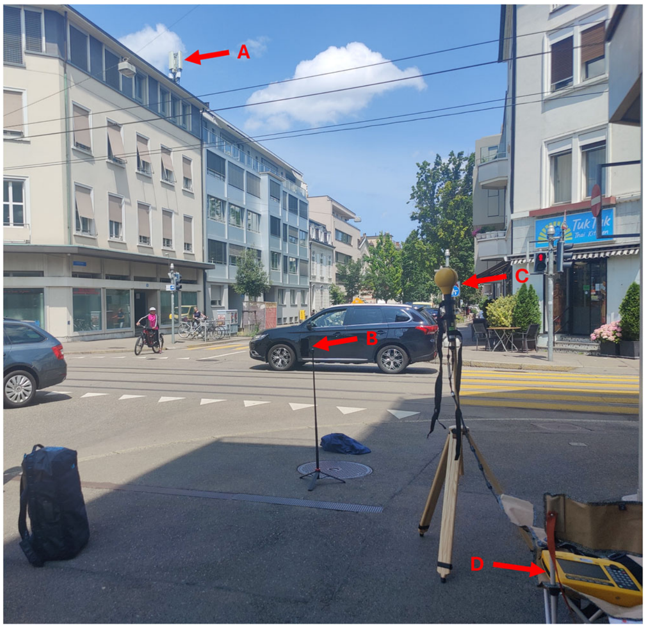

FIGURE 1 | Example of the measurement setup in Switzerland. The spectrum analyzer (D) was connected to the antenna (C) which was placed in line of sight of the base station (A). The UE (B) was placed in line with both the base station and the antenna of the spectrum analyzer, so that in the case of 5G technology (if present), the beam was directed towards the measurement setup.

Additionally, 5G can transmit at lower frequencies (over 20 different bands are defined for FR1 5G usage (IEC 2022; TSGR 2018), where it coexists with legacy technologies (2–4G). However, the usage depends on regional allocations. For that reason, for 5G, a main frequency range is considered (3400–3800 MHz), which has a center frequency of 3.6 GHz and is defined as 3.6 GHz 5G within this paper. In Poland, this frequency range was not yet licensed when the measurements were performed. As a result, the discussed spectrum analyzer (SRM-3000) can be used in Poland without loss of information.

To be able to compare measurements performed by different researchers in various countries, a uniform measurement procedure was adopted and training was foreseen for the researchers. The settings of the spectrum analyzer were agreed upon beforehand. The range of the frequency sweep (span) performed by the spectrum analyzer was set to 3300 MHz (700–4000 MHz) in Belgium, Switzerland, and Hungary, with a resolution bandwidth (RBW) of 300 kHz. In Poland, the span was set to 2600 MHz (400–3000 MHz) with a RBW of 1 MHz. While the RBW settings differ, this has minimal impact on the results since exposure levels were assessed by integrating power across entire frequency bands.

The cumulative incident power density is analyzed, which is the summation of the power density across all investigated (downlink) frequency bands to derive a single exposure value on a measurement location. Within an environment, the highest maximum cumulative incident power density ($S_{\max}$) and the average cumulative incident power density (S_{avg}) (i.e., the maximum and mean power density of all measurement locations within the environment) are considered. Furthermore, maximum and mean 3.6 GHz 5G-specific incident power density ($S_{\max,5G}$ and $S_{\text{avg},5G}$) is regarded as well.

2.3 | Measurement Procedure

For 5G, the measured power density is dependent on the user and their activity (Velghe et al. 2021). Hence, two measurement scenarios were considered. First, a "background" exposure measurement was performed with a 6 min duration, where no additional traffic is generated (No UE). Thus, the researcher measures the environmental exposure as present in the environment. Second, a UE was used to perform a "maximum downlink scenario," where a large file (1GB) was continuously downloaded over a 6-min period (Max DL), to stimulate sustained downlink activity and, where applicable, steer the 5G beam toward the measurement setup (Aerts et al. 2019). The UE was held at least 1 m from the measurement setup to limit unwanted exposure originating from the UE (Deprez et al. 2022). Furthermore, it is guaranteed that bystanders did not pass the measurement setup within 1 m. The UE was not forced on any frequency band or any telecommunication technology, to mimic a realistic scenario. For the Max DL scenario, measurements were conducted using a single telecommunication operator. However, the analysis accounts for exposure across the entire (downlink) frequency ranges. The measurement procedure follows the current standardized procedure (IEC62232) to measure 5G downlink exposure, except for two deliberate deviations. Measurements were performed directly at 1.5 m above ground without sweeping the probe horizontally and vertically, to minimize operator influence and simplify the procedure. Only the non specific (No UE) and high load (Max DL) base station profiles were used, rather than the typical load profile, to focus on maximum (worst case) exposure conditions (IEC 2022).

2.4 | RF EMF Exposure Regulations

The EMF power density regulations in the four countries are summarized in Table 1. Switzerland, Hungary, and Poland follow the ICNIRP guidelines (ICNIRP 1998), which states the maximum power density for frequencies between 2 GHz and 300 GHz can be maximally 61 V/m or 10 W/m^2. For lower frequencies between 0.4 and 2 GHz, the maximum power density recommendation is dependent on the frequency, given by the following formula: $f/200$, with f being the frequency expressed in MHz. However, in Switzerland, two different types of limits are defined in the Ordinance relating to Protection from Non-Ionizing radiation (ONIR 1999). First, everywhere the frequency-dependent ICNIRP 1998 limits have to be adhered to. Second, in line with the Swiss environmental law, precautionary levels were defined that apply to the emission from one single mobile phone antenna site and are only relevant for sensitive areas where persons spend most of their time, such as residences, schools, kindergartens, hospitals, nursing homes, workplaces, children's and school playgrounds. The precautionary limits of electric field strengths are between 4 and 6 V/m (0.04–0.10 W/m^2) for mobile RF frequency bands.

In Belgium, measurements have been performed in Flanders and Brussels. The regions are responsible to set the recommendation regarding maximum EMF power density (Belgisch Staatsblad 2022; Brussels Capital Region 2023). In Flanders, the recommendation includes an additional safety limit so that the maximum allowed power density is half that of the ICNIRP guidelines. Additionally, there is a limitation that regulates the maximum incident power density per operator at 0.22 W/m^2 (at 900 MHz) (Belgisch Staatsblad 2022). For Brussels, a distinction is made between publicly accessible outdoor areas (e.g., parks, playgrounds, and terraces) and publicly accessible indoor areas (e.g., hotels, schools, and hospitals). At 900 MHz, the indoor reference level is 0.22 W/m^2, while the outdoor reference level is 0.57 W/m^2. At 3600 MHz, the reference levels are 0.50 and 1.25 W/m^2, for indoor and outdoor incident power density, respectively (Brussels Capital Region 2023).

As simultaneous exposure to multiple frequencies will be discussed, the cumulative exposure needs to be checked with the according ICNIRP guidelines. For power density, the formula is as follows:

$$\sum_i \frac{S_i}{S_{\lim,i}} \leq 1, \tag{1}$$

where S_i is the power density at frequency i, with the frequency being the center frequency of the considered frequency range, $S_{\lim,i}$ is the reference limit for power density at frequency i. The sum must be less than or equal to 1 to ensure compliance with the ICNIRP guidelines (ICNIRP 1998).

3 | Results

3.1 | Overview of Four Countries

An overview is given for the cumulative incident power density in all four countries for both measurement scenarios. Table 2

TABLE 1 | National regulatory RF EMF exposure limits for the four countries at 900 MHz and 3600 MHz frequencies.

Country	900 MHz (W/m^2)	3600 MHz (W/m^2)	Source
Belgium[a,b]	0.22	0.5	Belgisch Staatsblad (2022), Brussels Capital Region (2023)
Hungary	4.5	10	ICNIRP (1998)
Switzerland[c]	0.04	0.10	ICNIRP (1998), ONIR (1999)
Poland	4.5	10	ICNIRP (1998)

[a] Only one value for Belgium is retained, even though the measurements were conducted in two separate regions (Flanders and Brussels).
[b] Regulatory exposure limit for indoor publicly available places (exceptions for various technologies).
[c] Regulatory exposure limit per base station for sensitive areas.

TABLE 2 | Overview of measurements conducted across Belgium, Hungary, Switzerland, and Poland.

	Belgium		**Hungary**		**Switzerland**		**Poland**	
# Measurement locations	47		30		38		31	
Sites with 3.6 GHz 5G	13 (28%)		18 (60%)		24 (63%)		0 (0%)	
	No UE	**Max DL**	**No UE**	**Max DL**	**No UE**	**Max DL**	**No UE**	**Max DL**
S_{avg} (SD) (mW/m^2)	1.1 (2.4)	1.7 (3.9)	0.9 (1.8)	1.2 (2.5)	0.4 (0.5)	0.5 (0.6)	1.6 (3.7)	1.6 (3.8)
S_{max} (mW/m^2)	15.1	23.2	6.9	11.0	2.5	2.7	17.6	19.9

Note: The table includes the number of (#) measurements, the percentage of sites with 3.6 GHz 5G present, and average (S_{avg}), standard deviation (SD) of S_{avg} and maximum (S_{max}) cumulative incident power density (in mW/m^2) for both No UE and Max DL conditions.

lists S_{avg}, which is the average cumulative incident power density calculated across all measurements performed in the respective environment (i.e. average over all measurements performed within the country, over both measurement scenarios). Furthermore, the standard deviation (SD) is given, which is an indication for the variation within the measured power density within the country. S_{max}, which represents the highest observed cumulative incident power density within the environment, is also included. Additionally, the table includes the percentage of sites where 3.6 GHz 5G was detected.

A sample size of at least 30 measurement locations per country is generally considered sufficient to provide reliable comparative insights, particularly when the objective is to assess broad trends and regional variations in exposure (Sagar, Adem, et al. 2018; Gajšek et al. 2015; Veludo et al. 2025). This approach aligns with previous spot measurement campaigns using spectrum analyzers across Europe. Sagar et al. reviewed scientific literature published between January 2000 and April 2015 and included 10 spot measurement studies, with the number of measurement locations ranging from a single site up to 1348 (Sagar, Dongus, et al. 2018). It is important to note, however, that not all these studies employed spectrum analyzers.

In all countries, low S_{avg} values (0.4–1.7 mW/m^2) were obtained, for both measurement scenarios. However, the standard deviation was higher than the average for all measurements, in some cases exceeding twice the mean value. This can be attributed to the high heterogeneity of the data. Measurements were performed in LOS and NLOS, indoors and outdoors and in different grades of urbanization. The standard deviation was lowest in Switzerland (e.g., 0.4 mW/m^2 mean with 0.5 mW/m^2 standard deviation under No UE), indicating relatively stable power density levels across measurement locations, which could be a consequence of stricter local regulatory RF EMF exposure limits.

For the No UE scenario, the highest S_{max} was 17.6 mW/m^2, while for the Max DL scenario, the highest S_{max} was 23.2 mW/m^2. For Belgium, Hungary, and Switzerland, S_{avg} and S_{max} increased during the Max DL scenario, as expected due to the active role users pertain during this scenario for 5G technology. The number of sites with a dedicated 3.6 GHz 5G base station differed for all countries, from 0% in Poland to 27.6% in Belgium and more than 50% in Hungary and Switzerland. In the coming years, it is expected that 5G technology will be the dominant telecommunication standard, fully utilizing all frequency bands defined for 5G technology.

To compare the two scenarios (No UE vs. max DL), the ratio (Δ) between the power density values in these scenarios is expressed in decibels (dB). This ratio was calculated as the difference in power density levels ($10 \log_{10}(S_1/S_2)$) between the two scenarios. The values of Δ for S_{avg} were +1.9 dB for Belgium, +1.2 dB for Hungary, and +1.0 dB for Switzerland. In Poland, no Δ in S_{avg} was observed. In the 3.6 GHz 5G band, an active user lead to higher downlink exposure. The Δ between S_{max} for both measurement scenarios, from No UE to Max DL, were +1.9, +2.0, +0.3, and +0.5 dB for Belgium, Hungary, Switzerland, and Poland, respectively. Both S_{avg} and S_{max} were almost always higher comparing Max DL to No UE, indicating that performing a Max DL scenario is crucial to obtain worst-case incident power density values and thus assess the realistic worst-case exposure.

Switzerland and Belgium have stricter local regulatory RF EMF exposure limits compared to Poland and Hungary, as outlined in Table 1. In the case of Switzerland, the observed maximum cumulative incident power density, S_{max}, was notably lower than those measured in the other countries, which is consistent with the stricter local regulatory standards. However, the relationship between stricter regulatory limits and lower measured exposure levels warrants further investigation to establish underlying causality. In Belgium, Poland, and Hungary, S_{max} was of comparable magnitude, despite Belgium's more strict exposure limits. The average incident power densities, S_{avg}, were found to be similar across all four countries, regardless of the differences in regulatory limits.

3.2 | Comparison Between Big Cities, Secondary Cities, and Villages

A comparison was made between the big cities, secondary cities, and villages of the four European countries.

Big cities: Table 3 presents the RF EMF incident power density measurements conducted in the big cities of Belgium, Hungary, Switzerland, and Poland. Table 3 includes the number of measurement locations and the presence of 3.6 GHz 5G. Furthermore, the maximum cumulative power density (S_{max}) and 5G-specific maximum power density ($S_{max,5G}$) within the observed city (i.e., absolute maximum cumulative power density over both measurement scenarios) is given. Last, average 5G incident power density $S_{avg,5G}$ during both measurement scenarios is listed.

TABLE 3 | Overview of incident power density measurements across different environments (big city, secondary city, and village) in Belgium, Hungary, Switzerland, and Poland.

Environment	Metric	Belgium	Hungary	Switzerland	Poland
Big city	# Measurement locations	12	12	13	12
	Measurement locations with 3.6 GHz 5G	0	9	9	0
	S_{max} (mW/m^2)	5.0	7.7	2.7	19.9
	$S_{max,5G}$ (mW/m^2)	—	4.4	0.4	—
	$S_{avg,5G}$ (No UE) (mW/m^2)	—	0.4	2.0×10^{-2}	—
	$S_{avg,5G}$ (Max DL) (mW/m^2)	—	0.5	0.2	—
Secondary city	# Measurement locations	13	12	13	11
	Measurement locations with 3.6 GHz 5G	13	7	9	0
	S_{max} (mW/m^2)	23.2	11.0	1.8	3.3
	$S_{max,5G}$ (mW/m^2)	10.4	0.6	0.4	—
	$S_{avg,5G}$ (No UE) (mW/m^2)	9.4×10^{-2}	1.6×10^{-2}	8.9×10^{-2}	—
	$S_{avg,5G}$ (Max DL) (mW/m^2)	1.1	0.1	0.1	—
Village	# Measurement locations	22	6	12	8
	Measurement locations with 3.6 GHz 5G	0	2	6	0
	S_{max} (mW/m^2)	5.3	1.0	0.9	3.4
	$S_{max,5G}$ (mW/m^2)	—	3.4×10^{-3}	4.2×10^{-2}	—
	$S_{avg,5G}$ (No UE) (mW/m^2)	—	1.7×10^{-3}	7.3×10^{-4}	—
	$S_{avg,5G}$ (Max DL) (mW/m^2)	—	2.4×10^{-4}	7.4×10^{-3}	—

Note: The table provides the number of measurement locations, presence of 5G, maximum cumulative incident power density (S_{max}) over all measurements at that location, maximum 5G power density ($S_{max,5G}$) over all measurements at that location, and the average 5G power density for both measurement scenarios at 5G-specific sites ($S_{avg,5G}$).

In each city, 12 to 13 spot measurements were conducted. Notably, 5G at 3.6 GHz was not rolled out yet in the big city of Belgium, which is unusual since big cities typically lead in adopting new technologies, given their prominent role in the country. However, this can be explained due to the strict regulations of the Brussels government with regard to 5G (Brussels Capital Region 2023).

$S_{avg,5G}$ during the No UE scenario was the lowest in Switzerland, only 2.0×10^{-2} mW/m^2. The increase during the Max DL scenario to 0.2 mW/m^2, confirmed that the exposure originating from the 5G base station was higher while performing the download. In Hungary, the increase in $S_{avg,5G}$ was less distinct ($S_{avg,5G}$ increased from 0.4 to 0.5 mW/m^2), likely due to the UE not fully utilizing 5G for the download throughout the measurement period. The highest $S_{max,5G}$ was measured in Hungary and was 4.4 mW/m^2, which is 0.04% of the ICNIRP incident power density reference level at this frequency.

Regarding S_{max} levels in the big cities, these were far below the ICNIRP cumulative S_{max} levels. The maximum S_{max} measured was in Poland (19.9 mW/m^2), which corresponds to a cumulative power density of 0.05, well below 1 (Equation 1) (ICNIRP 2020, 1998).

Secondary cities: Table 3 presents the RF-EMF incident power density measurements conducted in secondary cities of Belgium, Hungary, Switzerland, and Poland. 11 to 13 measurements were performed over all four countries. 3.6 GHz 5G networks were detected in Belgium, Hungary, and Switzerland. In Belgium, 3.6 GHz 5G was measured at all measurement locations in the secondary city, whereas for Hungary and Switzerland, 3.6 GHz 5G was observed at 7 of 12 and at 9 of 13 measurement locations, respectively.

In Belgium, a substantial average increase in $S_{avg,5G}$ was observed comparing the No UE and Max DL scenario from 9.4×10^{-2} to 1.1 mW/m^2, indicating that the UE effectively utilized 5G technology during the download scenario. Furthermore, the average contribution of 5G to the cumulative incident power density increased from 22.7% to 48.4%. The highest $S_{max,5G}$ (10.4 mW/m^2) is 0.1% of the ICNIRP power density reference level, remaining well below the established guidelines. The highest S_{max} was measured in Belgium as well, with 23.2 mW/m^2, which is below the cumulative ICNIRP guideline ($0.004 < 1$), calculated using Equation (1) (ICNIRP 2020, 1998). This single maximum value reflected specific local conditions at the time of measurement, rather than a general trend. As such, we focussed primarily on the overall distribution and patterns of exposure. All other measurements were well below the cumulative guideline as well.

In Hungary, $S_{avg,5G}$ increased from 1.6×10^{-2} to 0.1 mW/m^2 comparing No UE versus Max DL, indicating that during the Max DL scenario, the 5G-specific power density increased. In Switzerland, a similar response is obtained, although less pronounced (increase from 8.9×10^{-2} to 0.1 mW/m^2). In both countries, $S_{\max,5G}$ was a fraction ($< 0.1\%$) of the frequency-specific ICNIRP guidelines at 3.6 GHz.

$S_{\max}$ in Hungary and Switzerland is comparable for both secondary cities to the big cities (11.0 mW/m^2 compared to 7.7 and 1.8 mW/m^2 compared to 2.7 mW/m^2, respectively). For both cities, the $S_{\max}$ remained well below the cumulative ICNIRP guidelines. In Poland, $S_{\max}$ measured in the secondary city was 3.3 mW/m^2.

Villages: Table 3 lists $S_{\max}$, $S_{\max,5G}$, and $S_{\mathrm{avg},5G}$, from the measurements conducted in villages across the four European countries, with the number of measurements varying from 6 to 22. The high variation in # of measurement locations is explained by the number of villages where measurements are performed. For Belgium and Switzerland, measurements were performed in three villages, in Hungary in one village and in Poland, measurements were conducted in two villages. As anticipated, the number of measurement locations with 5G coverage at 3.6 GHz was low (16.6%), reflecting the early stage of 5G deployment in rural areas. In Belgium and Poland, no 3.6 GHz 5G sites were identified in villages. In Hungary, only 2 of 6 measurement locations were equipped with a 3.6 GHz 5G base station, while Switzerland had 6 of 12 measurement locations featuring active 5G base stations. $S_{\max,5G}$ at 3.6 GHz was 4.2×10^{-2} mW/m^2, which is $< 0.01\%$ of the ICNIRP guidelines.

In Hungary, for the first time $S_{\mathrm{avg},5G}$ decreased from No UE to Max DL (from 1.7×10^{-3} to 2.4×10^{-4}). This indicates that the UE did not utilize 3.6 GHz 5G to perform the download, and consequently, the measured power density may originate from a different telecommunication operator than the one used for the testing. $S_{\mathrm{avg},5G}$ was very low in both scenarios. Furthermore, there is only a limited subset of 2 measurement locations included in this analysis.

For 3.6 GHz 5G-specific exposure, $S_{\max,5G}$ was substantially lower in the villages of Hungary and Switzerland in comparison with cities. In Hungary, $S_{\max,5G}$ decreases from 0.6 to 3.4×10^{-3} mW/m^2. For both No UE and Max DL, $S_{\mathrm{avg},5G}$ also decreased drastically from cities to the villages. In Switzerland, this decrease was also established within the 3.6 GHz 5G measurement results. In Belgium and Poland, no 5G exposure at 3.6 GHz was measured, hence no comparison can be made.

Urbanization: Big cities, secondary cities, and villages were compared: a distinction was noticed between urban areas (big and secondary cities) and rural areas (villages). Table 4 lists the S_{avg} and $S_{\max}$ for the two urbanization types in the four countries, together with the Δ between both urbanization types (in dB). Here, the focus was on cumulative power density to be able to compare all countries.

In all countries, S_{avg} and $S_{\max}$ were lower in the rural areas than in urban areas, −4.8 dB (Switzerland, Max DL) to −10.4 dB (Hungary, Max DL), for both No UE and Max DL. This was expected as the number of base stations in rural areas is lower than in urban areas, the distance to the nearest base station is larger, and there are generally less users in rural areas compared to urban areas.

For the No UE scenario, S_{avg} decreased substantially for all countries in rural areas in comparison with urban areas. In Belgium, the average urban power density was 1.7 mW/m^2, compared to 0.4 mW/m^2 in rural areas, a difference of −6.3 dB. Similarly, in Hungary a difference of −7.4 dB was obtained between the urban areas and rural areas. A similar trend was obtained across Switzerland and Poland, where the urban average power densities were 0.5 and 2.1 mW/m^2, respectively, compared to 0.1 and 0.4 mW/m^2 in rural areas. Regarding $S_{\max}$ for environmental exposure (No UE), in Belgium, $S_{\max}$ results in a −5.6 dB difference. For Hungary, Switzerland and Poland, the difference between the rural areas and the urban areas was −9.9, −7.0, and −7.5 dB, respectively. For Max DL, S_{avg} and $S_{\max}$ decreased substantially for all countries in rural areas in comparison with urban areas. These findings indicate higher downlink RF EMF exposure levels in urban areas compared to rural environments.

TABLE 4 | Comparison between the cumulative measured incident power density in the cities (combined big and secondary cities) and villages for all four European countries.

	S_{avg} (mW/m^2)			$S_{\max}$ (mW/m^2)		
	Urban	**Rural**	**Δ (dB)**	**Urban**	**Rural**	**Δ (dB)**
No UE						
Belgium	1.7	0.4	−6.3	15.1	4.2	−5.6
Hungary	1.1	0.2	−7.4	6.9	0.7	−9.9
Switzerland	0.5	0.1	−7.0	2.5	0.5	−7.0
Poland	2.1	0.4	−7.2	17.6	3.1	−7.5
Max DL						
Belgium	2.6	0.6	−6.4	23.2	5.3	−6.4
Hungary	1.4	0.2	−8.5	11.0	1.0	−10.4
Switzerland	0.6	0.2	−4.8	2.7	0.9	−4.8
Poland	2.0	0.5	−6.0	19.9	3.4	−7.7

Note: The table includes both cumulative power density values (S_{avg} and $S_{\max}$, in mW/m²) and the corresponding Δ from urban and rural areas in dB.

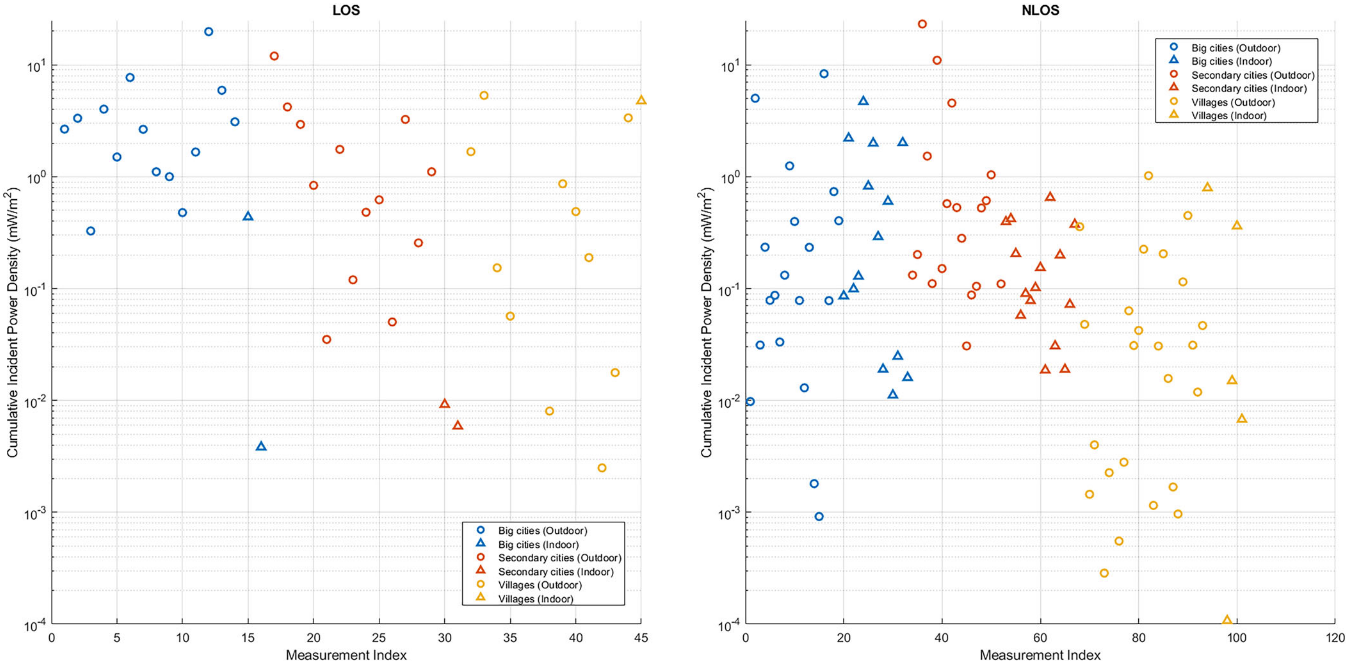

FIGURE 2 | Comparison of the Max DL cumulative incident power density (in mW/m^2) for LOS versus NLOS measurements. Data is categorized by environment type: big cities (blue), secondary cities (orange), and villages (yellow). Furthermore, a distinction is made between outdoor (circle) and indoor (triangle). The x-axis represents the measurement index, which is used to sequentially order the recorded data points.

3.3 | LOS Versus NLOS

Figure 2 shows Max DL cumulative incident power density measurements performed under LOS and NLOS conditions, indoors and outdoors, across the three types of environments: big cities, secondary cities and villages.

Under LOS conditions, the average power density was 2.3 mW/m^2, calculated as the average across all LOS measurements, whereas for NLOS, the average incident power density decreased to 0.9 mW/m^2. Comparing the average power density values between LOS and NLOS conditions across three environments, a reduction in power density was observed for NLOS relative to LOS by 5.8, 1.1, and 10.1 dB for big cities, secondary cities and villages, respectively. Under NLOS conditions, no discernible difference was observed between indoor and outdoor measurements within the grade of urbanization.

Under NLOS conditions, the variability in measured power density was more pronounced across all three environment types. For big cities, the average LOS power density was 3.5 mW/m^2, with a relative variation of 139.1%, while the average NLOS power density was 0.9 mW/m^2, with a relative variation of 198.9%. For the secondary cities and villages, the relative variation under LOS were 168.6% and 139.4%, respectively, while these increased to 304.2% and 181.7% under NLOS conditions.

3.4 | Analysis of Power Density in Educational Institutions

A significant percentage of the measurements performed (33.6%), were executed in educational institutions, including both indoor and outdoor measurements. A comparative analysis was performed between the incident power density levels in these environments versus the incident power density observed in public places. In both environments (educational institutions vs. public places), measurements were performed indoors and outdoors. In Belgium, 17.2% of the measurements in public places were indoors, compared to 53.8% in educational institutions. In Hungary, 12.5% of public locations measurements and 50% of those in educational institutions were indoors. Similarly, in Switzerland, 14.7% of public space measurements and exactly half (50%) of those in educational institutions were indoors. Poland had a higher proportion of indoor measurements in public spaces at 27.8%, while 53.8% of the measurements in educational institutions were indoors.

In educational institutions, proportionately more measurements were performed indoors. As these measurements only focus on mobile telecommunication bands, typical indoor exposure sources such as WiFi were not included in this study.

Figure 3 shows scatter boxplots comparing cumulative incident power density measured in educational institutions vs public places across the three city types, divided over outdoor and indoor measurements. Both measurement scenarios (No UE and Max DL) were included.

As expected, across all environments, the highest incident power density was measured outdoors. In urban areas, the educational institutions include universities, high schools, and primary schools, resulting in a greater number of measurement performed in educational institutions compared to rural areas, as there are normally no universities in rural areas. In the big cities, incident power density measured outdoors at educational institutions was higher than in outdoor public places, with

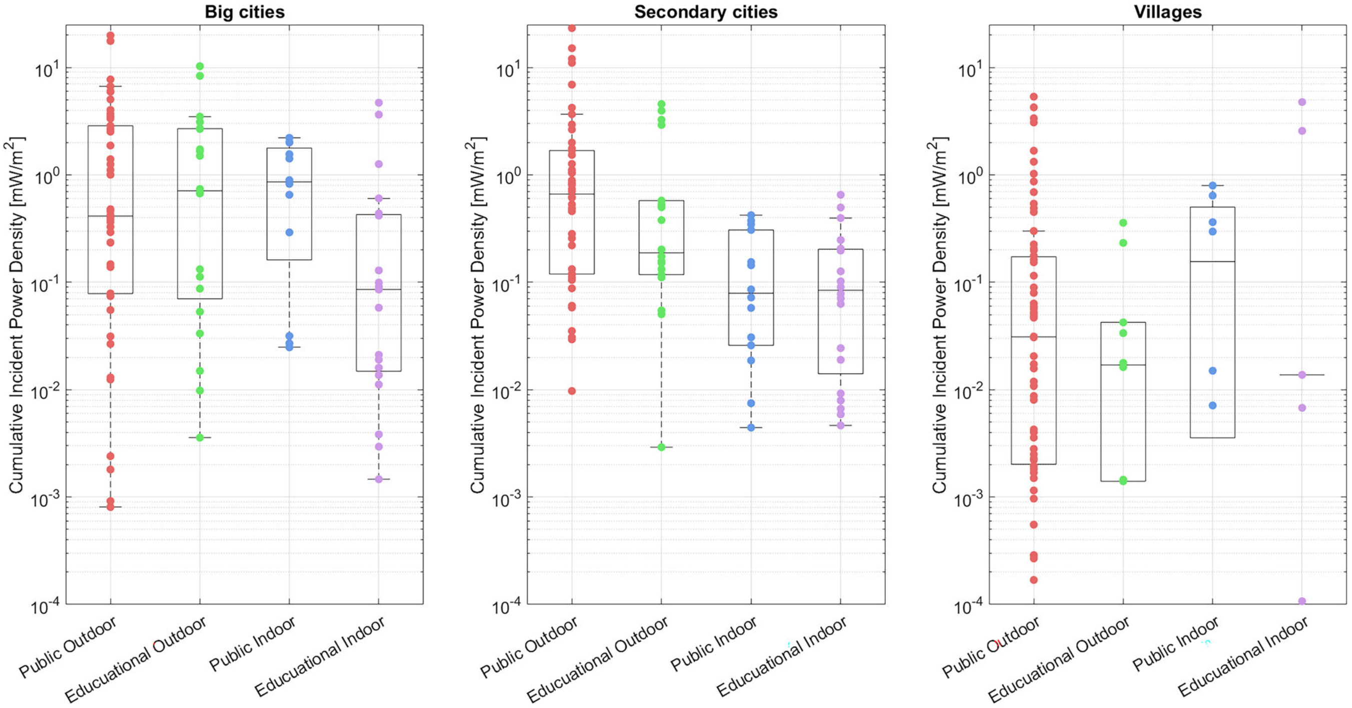

FIGURE 3 | Comparison of cumulative incident power density (mW/m^2) between educational institutions and public places in four European countries, both indoor and outdoor.

median $S_{\max}$ values of 0.7 and 0.4 mW/m^2, respectively. The interquartile range (i.e., the variability) was higher for the public outdoor compared to outdoor educational institutions.

The highest median power density was obtained at public places indoors (0.9 mW/m^2). This can be attributed to the specific location where the measurements were conducted, such as shopping centers and public transport stations. These areas typically attract large crowds, necessitating enhanced network infrastructure to support higher connectivity demands, which likely contributes to the elevated measured power density. Notably, this scenario also exhibited the lowest variability among the measured categories in the big city. Indoor educational institution incident power density was lowest in the big cities, with a median power density of 0.1 mW/m^2.

In secondary cities, the highest median power density was measured at outdoor public places (0.7 mW/m^2). Comparing the ratio of the median power density between the four environments, the median power density was 5.5, 9.2, and 9.0 dB higher for outdoor public places versus outdoor educational institution, indoor public places, and indoor educational institutions, respectively. Both indoor measurement locations had a comparable median power density of 7.9×10^{-2} and 8.4×10^{-2} mW/m^2 for indoor public places and indoor educational institutions, respectively. Both also had a similar variability.

In the villages, the outdoor public places had a very high variability, with power density ranging from 0 to 5.3 mW/m^2. The median power density for the indoor educational institutions was 0 mW/m^2, resulting in the lowest observed median power density across all categories and regions, suggesting limited network activity or reduced infrastructure in these areas. Based on the obtained data and the current analysis, the measured incident power density in or around schools was not significantly lower than in public places across big cities, secondary cities, or villages.

Furthermore, the obtained power density values were compared with those reported in the literature. Karipidis et al. measured RF-EMF levels in 23 schools in Australia, reporting maximum indoor and outdoor power densities of 0.10 and 0.46 mW/m^2, respectively, from mobile telecommunication sources (Karipidis et al. 2017). In Belgium and Greece, Vermeeren et al. reported maximum power densities of 6.8 and 7.3 mW/m^2, respectively (Vermeeren et al. 2013). These reported values are in the same order of magnitude as those obtained in the present study.

4 | Conclusion

The findings of this study provide a comparison of downlink RF EMF exposure from base stations for mobile telecommunications, presented in terms of spectral power density, across Belgium, Switzerland, Hungary, and Poland. First, a comparison was made of the RF EMF exposure regulations of all countries. While all countries follow similar RF EMF exposure regulations, Belgium and Switzerland have additional precautionary limits. In total, 146 measurement locations were assessed in 2023, divided over Belgium (47), Switzerland (38), Hungary (30) and Poland (31). 34.9% of all measurement locations had 5G coverage at 3.6 GHz, although there was a distinction between urban and rural areas in available 3.6 GHz 5G base stations. The study included both average and maximum cumulative incident power densities for two scenarios: "background" (No UE) and "worst-case" (Max DL) exposure. Furthermore, 3.6 GHz 5G-specific average and maximum incident power density ($S_{\text{avg,5G}}$ and $S_{\max,\text{5G}}$) were included as well. The highest maximum cumulative power density for the No UE scenario was 17.6 mW/m^2. For the Max DL scenario, the highest maximum cumulative power density was 23.3 mW/m^2. These cumulative power densities, and by extension all measurements, remain well below 1, indicating compliance with ICNIRP guidelines. The highest 3.6 GHz 5G power density measured over all countries and scenarios was 10.4 mW/m^2, which is 0.1% of the frequency-specific ICNIRP guidelines. The ratio of power density measured in rural areas was significantly lower than in urban areas (−4.8 to −10.4 dB), for all countries over the two scenarios, as expected due to less nearby base stations and generally less users.

A comparison between LOS and NLOS measurement locations is made. Under LOS conditions, the average incident power density was 2.3 mW/m^2, whereas under NLOS conditions, the average incident power density decreases to 0.9 mW/m^2. Furthermore, the relative variation increases under NLOS scenarios. Lastly, an analysis was performed regarding the power density in educational institutions compared to all other measurement locations, both indoors and outdoors for the different city types. The measured incident power density is not extensively lower in or around schools compared to public places, in neither the big cities, secondary cities or the villages. The RF EMF exposure levels in all measured environments were well below the ICNIRP guidelines.

For future work, increasing the number of measurements and regularly reassessing exposure levels will be essential to monitor the continued rollout of 5G networks and related exposure trends. Therefore, these measurements will be repeated in 2025. Furthermore, the different measurement methods within GOLIAT will be combined to achieve an even better understanding regarding RF EMF exposure.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data sets obtained for this study are available from the corresponding authors on reasonable request.

References

3rd Generation Partnership Project (3GPP). 3GPP. Technical Specifications (TS) series 38 2025: 5G NR (New Radio) Specifications. https://www.3gpp.org/dynareport?code=38-series.html.

Aerts, S., L. Verloock, M. Van Den Bossche, et al. 2019. “In-Situ Measurement Methodology for the Assessment of 5G NR Massive MIMO Base Station Exposure at Sub-6 GHz Frequencies.” *IEEE Access* 7: 184658–184667.

Aerts, S., K. Deprez, D. Colombi, et al. 2021. “In Situ Assessment of 5G NR Massive MIMO Base Station Exposure in a Commercial Network in Bern, Switzerland.” *Applied Sciences* 11: 3592. https://www.mdpi.com/2076-3417/11/8/3592.

Aerts, S., G. Vermeeren, M. Van den Bossche, et al. 2022. “Lessons Learned From a Distributed RF-EMF Sensor Network.” *Sensors* 22: 1715. https://www.mdpi.com/1424-8220/22/5/1715.

Belgisch Staatsblad, M. 2022. Belgisch Staatsblad, M. Besluit van de Vlaamse Regering tot wijziging van het besluit van de Vlaamse Regering van 1 juni 1995 houdende algemene en sectorale bepalingen inzake milieuhygiëne en het besluit van de Vlaamse Regering van 12 december 2008 tot uitvoering van titel XVI van het decreet van 5 april 1995 houdende algemene bepalingen inzake milieubeleid, wat betreft vast en tijdelijk opgestelde zendan- tennes voor elektromagnetische golven tussen 100 kHz en 300 GHz. http://www.emis.vito.be.

Bhatt, C. R., S. Henderson, C. Brzozek, and G. Benke. 2022. “Instruments to Measure Environmental and Personal Radiofrequency-Electromagnetic Field Exposures: An Update.” *Physical and Engineering Sciences in Medicine* 45: 687–704. https://doi.org/10.1007/s13246-022-01146-y.

Bieńkowski, P., B. Zubrzak, P. Sobkiewicz, K. Bechta, and M. Rybakowski. 2024. “Simplified Methodology of Electromagnetic Field Measurements in the Vicinity of 5G Massive MIMO Base Station for Environmental Exposure Assessment.” *IEEE Access* 12: 8071–8080.

Brussels Capital Region. 2023. “Brussels Capital Region Ordinance Concerning Protection Against Non-ionising Radiation of 4 April 2023.” Belgian Official Gazette. https://www.ejustice.just.fgov.be/cgi/article.pl?language=nl&numac=2023042811.

Chiaraviglio, L., A. Elzanaty, and M. S. Alouini. 2021. “Health Risks Associated With 5G Exposure: A View From the Communications Engineering Perspective.” *IEEE Open Journal of the Communications Society* 2: 2131–2179.

Deprez, K., L. Verloock, L. Colussi, et al. 2022. “In-Situ 5G NR Base Station Exposure of the General Public: Comparison of Assessment Methods.” *Radiation Protection Dosimetry* 198: 358–369. https://doi.org/10.1093/rpd/ncac061.

Deprez, K., L. Colussi, E. Korkmaz, et al. 2023. “Comparison of Low-Cost 5G Electromagnetic Field Sensors.” *Sensors* 23: 3312. https://doi.org/10.3390/s23063312.

Di Ciaula, A. 2018. “Towards 5G Communication Systems: Are There Health Implications?” *International Journal of Hygiene and Environmental Health* 221: 367–375. https://www.sciencedirect.com/science/article/pii/S1438463917308143.

Gajšek, P., P. Ravazzani, J. Wiart, J. Grellier, T. Samaras, and G. Thuróczy. 2015. “Electromagnetic Field Exposure Assessment in Europe Radiofrequency Fields (10 MHz–6 GHz).” *Journal of Exposure Science & Environmental Epidemiology* 25, no. 1: 37–44. https://doi.org/10.1038/jes.2013.40.

Hirata, A., Y. Diao, T. Onishi, et al. 2021. “Assessment of Human Exposure to Electromagnetic Fields: Review and Future Directions.” *IEEE Transactions on Electromagnetic Compatibility* 63: 1619–1630.

IEEE. 2019. “IEEE Standard for Safety Levels With Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz.” In *IEEE Std C95.1-2019 (Revision of IEEE Std C95.1-2005/Incorporates IEEE Std C95.1-2019/Cor 1-2019)*, 1–312. IEEE.

ICNIRP. 1998. “International Commission on Non-Ionizing Radiation Protection (ICNIRP) Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz).” *Health Physics* 74, no. 4: 494–522. https://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf.

ICNIRP. 2020. “International Commission on Non-Ionizing Radiation Protection (ICNIRP) Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz).” *Health Physics* 118, no. 5: 483–524. https://www.icnirp.org/cms/upload/publications/ICNIRPrfgdl2020.pdf.

IEC. 2022. “Determination of RF Field Strength, Power Density and SAR in the Vicinity of Radiocommunication Base Stations for the Purpose of Evaluating Human Exposure” (EN IEC 62232:2022). International Electro technical Commission (IEC).

Joseph, W., P. Frei, M. Röösli, et al. 2010. “Comparison of Personal Radio Frequency Electromagnetic Field Exposure in Different Urban Areas Across Europe.” *Environmental Research* 110: 658–663. https://www.sciencedirect.com/science/article/pii/S0013935110001015.

Joseph, W., L. Verloock, F. Goeminne, G. Vermeeren, and L. Martens. 2012a. “Assessment of Rf Exposures From Emerging Wireless Communication Technologies in Different Environments.” *Health Physics* 102, no. 2: 161–172. https://doi.org/10.1097/HP.0b013e31822f8e39.

Joseph, W., L. Verloock, F. Goeminne, G. Vermeeren, and L. Martens. 2012b. “In Situ LTE Exposure of the General Public: Characterization and Extrapolation.” *Bioelectromagnetics* 33: 466–475.

Karipidis, K., S. Henderson, D. Wijayasinghe, L. Tjong, and R. Tinker. 2017. “Exposure to Radiofrequency Electromagnetic Fields From Wi-Fi in Australian Schools.” *Radiation Protection Dosimetry* 175, no. 4: 432–439. https://doi.org/10.1093/rpd/ncw370.

Korkmaz, E., S. Aerts, R. Coesoij, et al. 2024. “A Comprehensive Review of 5G NR RF-EMF Exposure Assessment Technologies: Fundamentals, Advancements, Challenges, Niches, and Implications.” *Environmental Research* 260: 119524. https://www.sciencedirect.com/science/article/pii/S0013935124014294.

Loizeau, N., M. Zahner, J. Schindler, et al. 2023. “Comparison of Ambient Radiofrequency Electromagnetic Field (RF-EMF) Levels in Outdoor Areas and Public Transport in Switzerland in 2014 and 2021.” *Environmental Research* 237: 116921. https://www.sciencedirect.com/science/article/pii/S0013935123017255.

ONIR. 1999. Ordinance of 23 December 1999 relating to Protection From Non-Ionizing Radiation (ONIR), SR 814.710.

Ramirez-Vazquez, R., I. Escobar, G. A. E. Vandenbosch, F. Vargas, D. A. Caceres-Monllor, and E. Arribas. 2023. “Measurement Studies of Personal Exposure to Radiofrequency Electro- Magnetic Fields: A Systematic Review.” *Environmental Research* 218: 114979. https://www.sciencedirect.com/science/article/pii/S0013935122023064.

Russell, C. L. 2018. “5 G Wireless Telecommunications Expansion: Public Health and Environmental Implications.” *Environmental Research* 165: 484–495. https://www.sciencedirect.com/science/article/pii/S0013935118300161.

Sagar, S., S. M. Adem, B. Struchen, et al. 2018. “Comparison of Radiofrequency Electromagnetic Field Exposure Levels in Different Everyday Microenvironments in an International Context.” *Environment International* 114: 297–306. https://www.sciencedirect.com/science/article/pii/S016041201731485X.

Sagar, S., S. Dongus, A. Schoeni, et al. 2018. “Radiofrequency Electromagnetic Field Exposure in Everyday Microenvironments in Europe: A Systematic Literature Review.” *Journal of Exposure Science & Environmental Epidemiology* 28, no. 2: 147–160. https://doi.org/10.1038/jes.2017.13.

Sagar, S., B. Struchen, V. Finta, M. Eeftens, and M. Röösli. 2016. “Use of Portable Exposimeters to Monitor Radiofrequency Electromagnetic Field Exposure in the Everyday Environment.” *Environmental Research* 150: 289–298. https://www.sciencedirect.com/science/article/pii/S0013935116302559.

Shikhantsov, S., A. Thielens, S. Aerts, et al. 2020. “Ray- Tracing-Based Numerical Assessment of the Spatiotemporal Duty Cycle of 5G Massive MIMO in an Out- Door Urban Environment.” *Applied Sciences* 10: 7631. https://www.mdpi.com/2076-3417/10/21/7631.

TSGR. 2018. TSGR TS 138 101-1 - V15.3.0 - 5G; NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (3GPP TS 38.101-1 version 15.3.0 Release 15). https://portal.etsi.org/TB/ETSIDeliverableStatus.aspx.

Ulversoy, T. 2010. “Software Defined Radio: Challenges and Opportunities.” *IEEE Communications Surveys & Tutorials* 12: 531–550.

Urbinello, D., W. Joseph, A. Huss, et al. 2014. “Radio-Frequency Electromagnetic Field (RF-EMF) Exposure Levels in Different European Outdoor Urban Environments in Comparison With Regulatory Limits.” *Environment International* 68: 49–54. https://doi.org/10.1016/j.envint.2014.03.007.

Velghe, M., S. Aerts, L. Martens, W. Joseph, and A. Thielens. 2021, 12. “Protocol for Personal RF-EMF Exposure Measurement Studies in 5th Generation Telecommunication Networks.” *Environmental Health* 20: 36.

Veludo, A. F., B. Stroobandt, H. Van Bladel, et al. 2025. “Assessing Radiofrequency Electromagnetic Field Exposure in Multiple Microenvironments Across Ten European Countries With a Focus on 5G.” *Environment International* 200: 109540. https://www.sciencedirect.com/science/article/pii/S0160412025002910.

Vermeeren, G., I. Markakis, F. Goeminne, T. Samaras, L. Martens, and W. Joseph. 2013. “Spatial and Temporal RF Electromagnetic Field Exposure of Children and Adults in Indoor Micro Environments in Belgium and Greece.” *Progress in Biophysics and Molecular Biology* 113, no. Issue 2: 254–263. https://doi.org/10.1016/j.pbiomolbio.2013.07.002.

Wiame, C., S. Demey, L. Vandendorpe, P. De Doncker, and C. Oestges. 2024. “Joint Data Rate and EMF Exposure Analysis in Manhattan Environments: Stochastic Geometry and Ray Tracing Approaches.” *IEEE Transactions on Vehicular Technology* 73: 894–908.

Wydaeghe, R., S. Shikhantsov, E. Tanghe, et al. 2022. “Realistic Human Exposure at 3.5 GHz and 28 GHz for Distributed and Collocated Ma-MIMO in Indoor Environments Using Hybrid Ray-Tracing and FDTD.” *IEEE Access* 10: 130996–131004.

Xu, B., D. Colombi, C. Tornevik, F. Ghasemifard, and J. Chen. 2021. “On Actual Maximum Exposure From 5G Multicolumn Radio Base Station Antennas for Electromagnetic Field Compliance Assessment.” *IEEE Transactions on Electromagnetic Compatibility* 63: 1680–1689.