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Exploratory analysis of 4G and 5G uplink RF-EMF exposure using network parameters in outdoor microenvironments in Belgium during a maximum uplink usage scenario

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Abstract Subject Area(s)

["Experimental dosimetry","RF/Microwave"]

Summary

In this study, a novel methodology using a mobile network monitoring application (QualiPoc) is used to analyse 4G and 5G uplink (UL) radiofrequency electromagnetic field (RF-EMF) exposure during a maximum UL usage scenario in a commercial mobile network. The measurements were performed in five different types of outdoor microenvironments in five areas in Belgium, classified by their degree of urbanization. Whereas microenvironmental studies typically only discuss environmental RF-EMF exposure, this study investigated the UL exposure distributions and frequency band usage, based on network parameters. Negatively skewed distributions of the 1-s-averaged transmit (Tx) power were found and multimodality was observed for the first time, where a combination of 4G and 5G UL frequency bands was present. The largest median 1-s-averaged Tx power of 22.0 dBm was found in the rural area, followed by suburban (21.5 and 20.0 dBm) and urban (20.2 and 19.0 dBm) areas.

Full abstract

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SUMMARY

In this study, a novel methodology using a mobile network monitoring application (QualiPoc) is used to analyse 4G and 5G uplink (UL) radiofrequency electromagnetic field (RF-EMF) exposure during a maximum UL usage scenario in a commercial mobile network. The measurements were performed in five different types of outdoor microenvironments in five areas in Belgium, classified by their degree of urbanization. Whereas microenvironmental studies typically only discuss environmental RF-EMF exposure, this study investigated the UL exposure distributions and frequency band usage, based on network parameters. Negatively skewed distributions of the 1-s-averaged transmit (Tx) power were found and multimodality was observed for the first time, where a combination of 4G and 5G UL frequency bands was present. The largest median 1-s-averaged Tx power of 22.0 dBm was found in the rural area, followed by suburban (21.5 and 20.0 dBm) and urban (20.2 and 19.0 dBm) areas.

INTRODUCTION

Microenvironmental studies are a common type of radiofrequency electromagnetic field (RF-EMF) measurement to characterize typical exposure during a predefined usage scenario [1-4]. Often only environmental exposure is assessed. However, less attention is devoted to potential differences in distribution of the RF-EMF within the defined classifications (i.e., different microenvironments, countries, etc.) and the underlying causes of the variability. This study focuses on the auto-induced uplink (UL) exposure, which can make up a substantial part of the total RF-EMF exposure [3-5].

New challenges are introduced by the deployment of the fifth generation (5G) mobile networks. Its dynamic capabilities in terms of channel bandwidth, subcarrier spacing (SCS), and the use of beamforming [6], lead to different exposure conditions, which demands for monitoring equipment that is able to gain insight into these complex network usage patterns and their implications for exposure assessment. A mobile network monitoring application is capable of collecting many network parameters directly from the chipset of the mobile phone or user equipment (UE). It has been successfully used previously for small-cell [7, 8] and epidemiological (pilot) studies [9, 10] and was used in this study to obtain uplink transmit (Tx) powers and frequency band usage from the UE.

The goal of this study was to perform an exploratory analysis of the 4G and 5G mobile phone's average UL Tx power and frequency band usage, using the network monitoring application QualiPoc, during a maximum uplink usage scenario in different outdoor microenvironments in different areas, classified by their degree of urbanization. This was a pilot study for further research on UL exposure variability.

METHODS

Measurement configuration

The measurements were performed in 26 microenvironments (MEs) in Belgium, during several working days in the period between February and April 2023. There were five different study areas defined, classified by their degree of urbanization: two urban centers were classified as a big city (BC) and a secondary city (SC), two suburban areas as villages (V1 and V3), and a rural area as small village (V2).

Within each study area, a distinction was made between five different types of MEs: center/downtown, residential, business, industrial, and parks. Residential areas and parks were subdivided in central, non-central, and outskirt areas for the urban centers. This resulted in nine MEs in the BC and SC and three MEs in each village, since business or industrial areas were not present in all villages. However, due to measurement failure, there was no measurement in the residential area of V3.

A trained researcher performed a predefined walk of approximately 15 minutes (1 - 1.5 km) in each ME, following the measurement protocol presented in [11]. Network parameters were obtained with QualiPoc (QP, i.e., a commercial network monitoring application by Rohde & Schwarz) on a OnePlus 9 Pro smartphone. A 5G unlimited subscription to one of the main mobile network providers in Belgium was used and a maximum UL (Max. UL) exposure usage scenario was defined in which the mobile phone repeatedly uploaded a file of 500 MB to an FTP server located at Ghent University. The mobile phone was not forced to use specific frequency bands during the Max. UL scenario.

Data processing

From QP, various network parameters that are registered by the chipset of the mobile phone were obtained, such as uplink throughput [bit/s], transport block size (TBS) [bit], and power of the physical uplink shared channel (PUSCH Tx power) [dBm]. PUSCH contains the user data, sent by the UE. The average power per second P_{avg} [W] was assessed as follows,

$$P_{avg} = DC_{4G} \cdot P_{PUSCH,4G} + DC_{5G} \cdot P_{PUSCH,5G} \tag{1}$$

with P_{PUSCH} the PUSCH Tx power converted to [W] and averaged over one second, and DC the duty cycle of the specified mobile technology. Other uplink signals, e.g., for network control, were not considered. The DC is defined as the percentage of active UL slots with respect to the total number of slots, which can be both UL and downlink (DL) in a time division duplexing (TDD) system, in one second. It was computed for 4G and 5G separately using equation (2), with $Thrpt_{PUSCH}$ the 1s-average PUSCH throughput [bit/s], TBS_{avg} the 1-s-averaged TBS [bit] and TTI the transmission time interval, a synonym for the slot length [s].

$$DC = \frac{amount\ of\ active\ UL\ slots}{total\ amount\ of\ slots\ (1/TTI)} = \frac{Thrpt_{PUSCH}}{TBS_{avg}}\ TTI \tag{2}$$

Since every slot contains either zero (i.e., no transmission) or one (i.e., transmission) transport block [12], TBS_{avg} can be used as a proxy for the maximum possible UL slot occupation [bits/slot]. This method was used because the amount of UL transport blocks was not available in the version of QP. The TTI is equal to 1 ms for 4G and depends on the subcarrier-spacing (SCS) for 5G, following equation (3). The inverse of the TTI is the total amount of slots (both UL and DL in TDD) in an interval of 1 s.

$$TTI = \frac{15\ [kHz]}{SCS\ [kHz]}\ 1\ [ms] \tag{3}$$

This post-processing step was necessary because the reported PUSCH Tx power is an average over an observation period of approximately 500 ms, only including values that are reported by the chipset, which is different from instantaneous power measurements with a predefined sampling time. Using these values directly could cause a significant overestimation of the exposure as they are an extrapolation of the active UL slots (i.e., the UL slots used to transmit data at the reported power) to all data slots within that second. The real average of the Tx power is therefore obtained by taking into account the slots where no transmission occurred as well, i.e., by multiplication with the DC.

Table 1 lists the considered 4G and 5G frequency bands. The SCS was assumed to be fixed for each of the 5G frequency bands and derived from observations in extracted network messages, because it could not be obtained directly from QP. For bands n1 and n28, an SCS of 15 kHz was assumed, which is the same as all 4G bands, and for Band n78 a SCS of 30 kHz was used. The DC calculation is performed for every frequency band separately, such that for each the correct TTI could be used. They are aggregated again by combining all 1-s-samples of the ME and calculating P_{avg}, where 1-s-samples of the same technology but from different bands are add up in the same way as 4G and 5G in equation (1). The percentage of band usage is defined as the number of 1s-samples of the specific band present in the ME divided by the total measurement time. The latter varied between 616 s and 1062 s, except for the outskirt residential area of the BC that contained only 278 s after data cleaning.

Table 1: Frequency ranges of uplink bands and their corresponding name (as provided by QualiPoc) in increasing order. Between brackets is the duplexing scheme. FDD = Frequency Division Duplexing, TDD = Time Division Duplexing.

Frequency range [MHz]	Band names and their duplexing scheme
703 – 748	5G Band n28 (FDD)
832 – 862	4G Band 20 (FDD)
1710 – 1785	4G Band 3 (FDD)
1920 – 1980	4G Band 1 (FDD), 5G Band n1 (FDD)
2500 – 2570	4G Band 7 (FDD)
3300 – 3800	5G Band n78 (TDD)

Data cleaning

During some of the measurements, the Max. UL scenario failed (e.g., the phone stopped working due to overheating or because the network provider prevented the high uplink usage). Since we are assessing the exposure during this specific use case (Max. UL scenario) where maximum exposure is desired, the throughput of every ME was checked. If the total throughput stayed below 350 kbps for at least 30 s, failure of the Max. UL scenario was assumed. This happened for 85 s in the center of V3, 38 s in the center of V2, and 915 s in the outskirt residential area of the BC. Those periods were omitted from the data. Moreover, since the network parameters were averaged over 500 ms and a switch to a different frequency band (called a handover) might have happened in the meantime, only averages over parameter values with the same frequency band usage were taken into account to avoid over- or underestimation of the Tx power at handovers.

RESULTS

Power distributions for different degrees of urbanization

Figure 1 shows boxplots of P_{avg} for the Max. UL exposure scenario per study area. All distributions are negatively skewed, since a Max. UL scenario was used, which results in high UL powers in general.

The highest median P_{avg} was 22.0 dBm and found in the rural area (V2). The suburban areas had different median P_{avg} of 21.5 dBm and 20.0 dBm for V3 and V1 respectively. The median in the SC was 20.2 dBm, only slightly above V1. The lowest median of 19.0 dBm was found in the capital (BC). It should be noted that legislation is more strict in the BC, which causes exposure limits to be lower than in the other study areas.

The smallest inter-quartile ranges (IQR) are found in the rural area V2 and suburban village V3, with 1.7 dB and 1.8 dB, respectively, where high values of P_{avg} are found. The low IQR shows that those high P_{avg} values were present for all MEs within those villages. This is expected in situations with bad network connection due to power control of the UE (i.e., sending at high Tx powers in the case of a bad connection). For all other study areas, more variability in the data is present. The largest variability is found in the BC, with an IQR of 4.7 dB. It may be attributed to the differences between the MEs, similar as for the SC, for which a differing distribution in one ME will be discussed in the next subsection.

Note that the maximum value, indicated by the top whiskers, was below the maximum value of 23 dBm except for the SC where it is 24.7 dBm. However, this is still within the tolerance of +2/-3 dB defined by 3GPP for inter-band dual connectivity (EN-DC, i.e., a 4G core network with 5G on top) [13, section 6.2B.1.3]. The maximum 95th percentile is 22.5 dBm in the rural area V2.

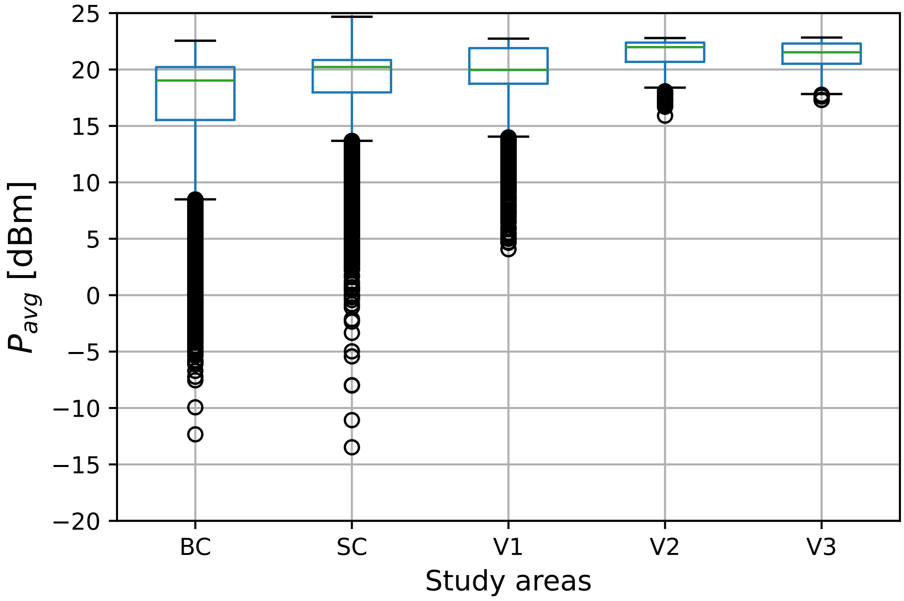

Figure 1: 1-s-average transmit powers (4G + 5G) during the Max. UL scenario in different microenvironments within each study area. The whiskers represent the lowest and highest data points that are found within 1.5 IQR difference from the median (green line). All other samples are represented as outliers (black dots). BC = Big City, SC = Secondary City, V1 = Village 1 (Suburban), V2 = Village 2 (rural), V3 = Village 3 (Suburban).

Frequency utilization for different degrees of urbanization

Figure 2 shows the uplink frequency band usage during the Max. UL scenario per study area in Belgium. Overall, 99% 4G and 19% 5G was observed. 5G was always used on top of 4G.

Figure 2 shows that, in study areas SC, V2, and V3, more than 80% of the measurement time was occupied by either 4G Band 20 or Band 3. In the BC, Band 3 was used 46% of the time, followed by 43% of Band 7. V1 is an exception, where Band 7 was used 88% of the time and Band 3 the other 12%. Band 20, with the lowest frequency of all 4G bands considered (Table 1), was present more than 30% of the time in those study areas (SC, V2, and V3) where the largest median values for P_{avg} were found. Across the villages, the lowest P_{avg} values were found for V1 where Band 7, the band with the highest frequency of all 4G bands considered, was most commonly used. It is expected, when only considering the usage of one technology at the same time, that low frequency bands are used for a larger coverage. When the UE is in the neighborhood of a multi-frequency cell edge, where higher Tx powers are needed to reach the base station, it is thus likely to be connected to, and sending UL data at, a lower frequency.

Only in the study areas SC and V1, 5G bands were observed (Figure 2). For 42% and 35% of the time, respectively. No 5G was found in the BC, V2, and V3. In V1 this includes only the frequency division duplexing (FDD) n1-band, which is a “re-farmed 3G band” denoted by QP as 5G, but with the same properties as 4G Band 1. In the SC, 25% of the time was occupied by the time division duplexing (TDD) Band n78, which is the main 5G band that is being deployed in Belgium. The current non-standalone 5G implementation implies that most signals are still sent over the 4G network, which is the core network, and 5G may be used to have a larger bandwidth where 5G base station antennas are present. No 5G base stations were present along the routes in the BC, V2, and V3 at the time of measurement.

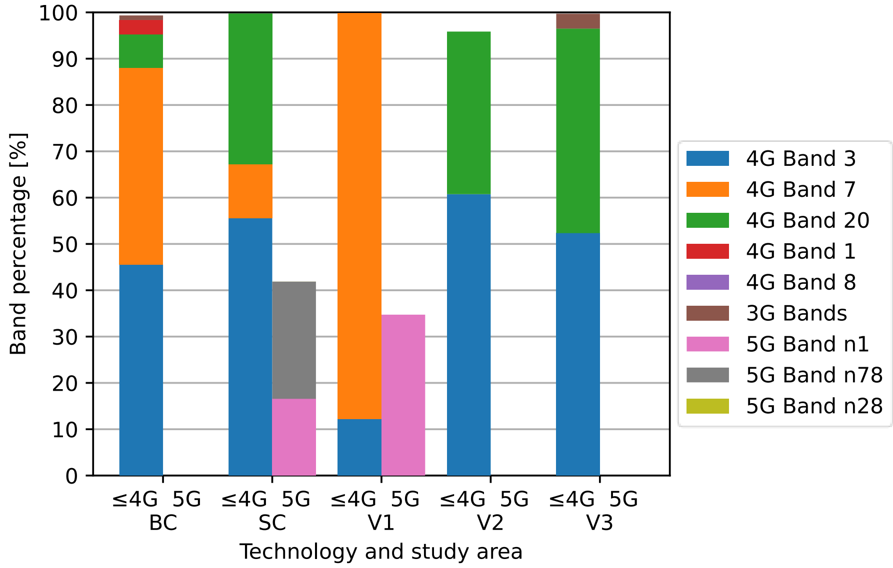

Figure 2: Percentage of seconds where 3G, 4G, or 5G bands were present, as indicated by QualiPoc (QP) during the Max. UL exposure scenario for each study area. BC = Big City, SC = Secondary City, V1 = Village 1 (Suburban), V2 = Village 2 (rural), V3 = Village 3 (Suburban). Where the ≤4G bars do not reach 100%, there was a connection with the 3G network without any UL transmission over the network.

Variability analysis of the Tx power distribution in the SC non-central residential area

The variability of the P_{avg} distribution in the non-central residential area of the SC was investigated. Due to the presence of both 4G and 5G bands (both TDD and FDD), variations in line-of-sight and non-line-of-sight connections to the base stations, and the Max. UL scenario performed by the UE, this distribution will not be lognormal anymore [3, 4, 10] and a multimodal distribution is expected. Figure 3 shows the histogram of P_{avg} together with a kernel density estimation. Indeed, two modes are observed (red line) at 11.3 dBm, and 20.2 dBm. The band percentages for this microenvironment are 55% of 4G Band 3, 45% of 4G Band 20, and 45% of 5G Band n78. Their sum is larger than 100% because 5G is used on top of 4G during the same observation period of 1 s. These modes are attributed to the usage of multiple bands. Further research is necessary to provide a full analysis.

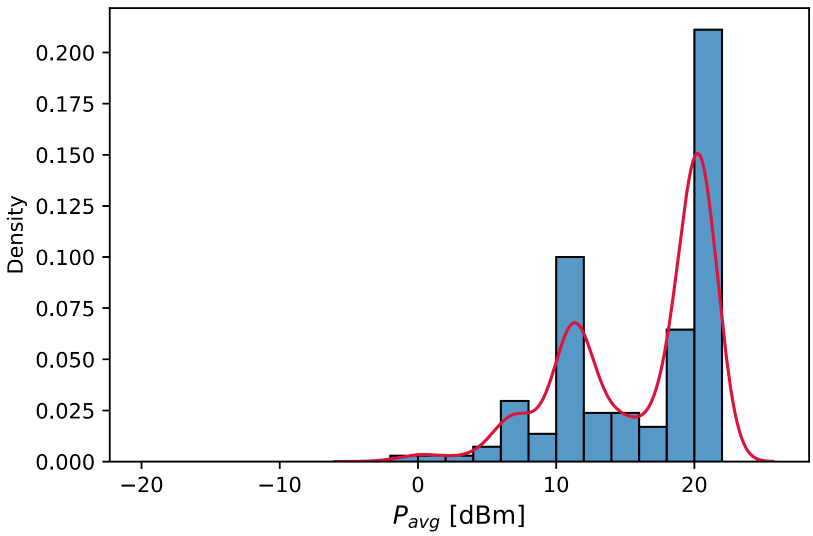

Figure 3: Histogram of the 1-s-average transmit powers (4G + 5G) during the Max. UL scenario in a non-central residential area in a secondary city (SC) in Belgium. The continuous (red) line is a kernel density estimation made by the Seaborn package in Python.

CONCLUSIONS

Measurements of the 4G and 5G uplink (UL) transmit (Tx) powers were performed during a Max. UL scenario in different outdoor microenvironments using the mobile network monitoring application QualiPoc. Both distributions of the 1-s-averaged Tx power P_{avg} and the percentages of UL frequency band usage were analyzed for different study areas, classified by their degree of urbanization. The highest median 1-s-averaged Tx power was 22.0 dBm and was found in a rural area, followed by suburban (21.5 and 20.0 dBm) and urban (20.2 and 19.0 dBm) areas. UL 4G bands were present 99% and 5G bands 19% of the time. A multimodal distribution of the 1-s-average Tx power was observed for the first time in a microenvironment where a combination of 4G and 5G UL frequency bands were present. Future work will consist of an analysis for different countries, the inclusion of other network parameters such as the received signal strength or base station identifiers, and investigating different usage scenarios and the influence of connection loss. Machine learning models can be used to improve the classification of the UL exposure using the network parameters obtained from QualiPoc.

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