EMISSIONS FROM SMART METERS AND OTHER RESIDENTIAL RADIOFREQUENCY SOURCES

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Abstract- The advent of the Internet of Things (IoT) comes with a huge increase in wirelessly communicating devices in our environment. For example, smart energy consumption meters are being widely deployed in residences from which they communicate their state using radiofrequency (RF) networks. Accurate characterization of the RF emissions from emerging residential wireless solutions is important to inform the public about the potential impact on their exposure to RF electromagnetic fields. A new measurement procedure to determine the exposure from residential RF devices is proposed by assessing the peak emitted fields at various distances and the proportion of time they transmit (duty cycle). RF emissions from 55 residential devices were measured in ten residences (Belgium and France) and compared to environmental levels, emissions from 41 mobile phones, and international standards. Overall, residential levels of RF-EMF exposure are low. In addition to the continuous environmental exposure, wireless access points (due to frequent use) and especially mobile phones and other personal communication devices (due to their use close to the body) continue to represent the bulk of the RF-EMF exposure in the smart home. However, some residential devices can significantly increase the exposure if their duty cycle is high enough (>10%), especially when held or used close to the body. Individual smart meters, on the other hand, will contribute only little in general, despite emissions of up to 20 V m^{-1} at 50 cm, due to their low duty cycles (maximum 1%) and locations.

I. INTRODUCTION

This paper addresses the issues concerning human exposure to radiofrequency (RF) electromagnetic fields (EMF) as consumer-driven, wirelessly communicating systems are deployed in homes as part of the emerging Internet of Things (IoT), likely to be adopted everywhere in the future (WHO 2010). The integrated energy network (or “Smart Grid”), for example, utilizes smart energy delivery systems deployed in consumer residences that rely on bidirectional communications using existing telecommunications or newly developed (e.g. mesh) RF networks to constantly adapt and tune the delivery of energy to the consumer. However, even though public understanding and acceptance are critical for the adoption of these new technologies likely to be implemented by a host of companies (including electricity and other utility companies), members of the general public may be concerned about the potentially heightened levels of RF radiation in their home environment. Furthermore, the World Health Organization (WHO) identified in its International RF Research Agenda a need for measurement surveys to characterize population exposures to all RF sources, with a particular emphasis on new wireless technologies, including smart meters and other novel residential wireless communication systems (WHO 2010). Assessment of the RF emission levels of new wireless technologies in residential environments can address these concerns.

In the context of IoT, commonly installed RF-emitting devices in homes can be broadly categorized as devices for energy monitoring, devices for automatic light control, devices for heating or cooling, security systems, or smart meters. To the authors’ knowledge, only a limited number of studies have investigated the RF emissions from residential appliances other than communications devices, and predominantly of smart meters. In the USA, for example, two specific types of smart meters were investigated by the Electric Power Research Institute (EPRI 2010, 2011; Foster and Tell, 2013; Tell et al. 2012a, 2012b). In the United Kingdom, comprehensive studies on smart meters were performed by Peyman et al. (2017, 2018), and in Australia by Girnara et al. (2011) and by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA 2013). In general, the most important parameters to be considered for the assessment of smart-metering devices were: the output power of the device, the frequency of the emitted signal, the distance to the device, and the duty cycle of the device (i.e. the proportion of time the device actually transmits a signal).

The objective of this study was to develop a novel measurement method to characterize a wide array of in-situ RF IoT devices, smart meters, and other sources of residential RF-EMF exposure using a wide range of technologies (Wireless Fidelity (Wi-Fi), Long Range (LoRa), Zigbee, Sigfox, General Packet Radio Service (GPRS), etc.) and frequency bands (e.g. the Industrial, Scientific and Medical (ISM) 41 MHz, 433 MHz, 868 MHz, and 2400 MHz bands), and to compare their emissions with levels of telecommunication and broadcasting signals present in the residence. For this, a new duty cycle assessment method is used incorporating the spectrogram mode of spectum analyzer, which allows a graphical overview of the variations in transmission frequency or signal amplitude over time. The proposed method was applied to a convenience sample of ten residences in Belgium and France, resulting in a total of 55 devices characterized.

II. MATERIALS AND METHODS

A. Selection of residences

A convenience sample of ten residences was selected (in Belgium and France) in which a relevant number of devices of the above-mentioned categories were present, i.e. energy monitoring, devices for automatic light control, devices for heating or cooling, security systems, or smart meters. In Table 1, the details of this sample are listed, including the number of devices per residence as well as wireless technologies that could be identified. Different smart meters (electricity, gas, and water) are highlighted. The measurements were performed in the period of April, 2017, to November, 2017.

B. Measurement equipment

The RF-EMF levels (i.e. the electric-field strength E, in volt per meter or V m^{-1}, or the power density S, in watt per square meter or W m^{-2}) were assessed using both broadband and frequency-selective narrowband measurement equipment.

A broadband measurement consisted in measuring the total (i.e. within a large frequency span) electric-field value E_{bb} at a given position using a Narda NBM-550 field meter equipped with an EF0391 (dynamic range: 0.2 – 320 V m^{-1}; frequency range: 100 kHz – 3 GHz) or EF0691 probe (dynamic range: 0.35 – 650 V m^{-1}; frequency range: 100 kHz – 6 GHz) (Narda, San Diego, USA). Although this type of measurement is useful to identify residential sources of RF-EMF (by holding the probe close to a suspected source) or locations of maximum exposure (in terms of electric-field strength), no frequency-specific information can be obtained. Hence, it is unable to identify the source's emission frequencies and the specific contribution of the source to the total electric-field strength remains uncertain.

For this, a spectrum analyzer setup is needed, which, in this case, consisted of a tri-axial R&S TS-EMF isotropic antenna (dynamic range: 1 mV m^{-1} – 100 V m^{-1} for the frequency range 30 MHz – 3 GHz) (Rhode & Schwarz, Munich, Germany) in combination with an R&S FSL6 spectrum analyzer (frequency range: 9 kHz – 6 GHz) for narrowband measurements (SA I), or a PCD 8250 Precision Conical Dipole antenna (dynamic range: 1.1 mV m^{-1} – 100 V m^{-1} for the frequency range 30 MHz – 3 GHz) (Seibersdorf Laboratories, Seibersdorf, Austria) in combination R&S FSVA40 signal and spectrum analyzer (frequency range: 10 Hz – 40 GHz) (SA II). The measurement uncertainty of the considered setups was ±3 dB for (CENELEC 2008; Joseph et al. 2012a). This uncertainty represents the expanded uncertainty evaluated using a confidence interval of 95%.

Beside the emission levels and frequencies of the assessed RF-emitting device, a third important factor in the exposure assessment is the duty cycle (DC), i.e. the proportion of time the device actually transmits. To measure the DC, the R&S FSV30 signal and spectrum analyzer was equipped with firmware option FSV-K14 which enables the spectrogram mode. A spectrogram is a graphical overview of a measurement as a function of time, and is obtained by capturing at a certain speed [defined by the sweep time (SWT)] successive traces of either a part of the spectrum (i.e. in the frequency domain, defined by a certain frequency span) or in the time domain (i.e. with a frequency span of 0 Hz, or “zero span” mode), according to the objective. The former type is used to e.g. detect frequency-hopping channels and the latter determine the DC of a non-continuous signal.

C. Measurement procedure

A flowchart of the proposed procedure to assess the residential exposures to RF-EMF is shown in Fig. 1. First, a frequently used room of the residence (usually the living room) is scanned with the broadband probe to locate the maximum field level. At that location, a spectral survey is performed to identify continuously present RF signals, which are then measured more in detail. Finally, all RF-emitting devices (e.g. smart meters and IoT devices) present in the residence are characterized for which the proposed method comprised three parts: determination of the transmission frequencies, measurement of the maximum emitted fields, and calculation of the duty cycle. All steps are explained in more detail in the following sections.

1) Spectral survey and assessment of continuously present signals

At the location of highest electric-field level in the selected room, a spectral survey is performed, after which the relevant, continuously present signals are assessed more accurately, according to the measurement procedures proposed by Joseph et al. (2012a, 2012b, 2013) and Verloock et al. (2014). The considered signals are predominantly outdoor signals, such as telecommunications and radio downlink (DL) signals, and, if present, also Wi-Fi and cordless phone signals. For this part, SA I is used with the specific settings listed in Table 2.

This measurement gives a baseline to put in perspective the subsequent measurements of residential RF-emitting devices.

2) Characterization of residential RF-emitting devices

As many residential sources of RF-EMF do not transmit continuously, their signals are seldom detected in the spectral survey. In fact, the length and frequency of the signals depend on the specific use and/or transmission technology of these devices. As most of them do transmit at a fixed power (only advanced two-way communications devices – such as mobile phones – can make use of power control), it is sufficient to determine at certain distances from the device, the maximum received power (P_{max}) – which is then used to calculate the maximum electric-field strength (E_{max}) or power density (S_{max}) (Table 3) – as well as a typical DC in order to determine the time-averaged exposure level, which can be finally compared to exposure-limiting guidelines such as issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP 1998) or the Federal Communications Commission (FCC 2001, IEEE 2005),. In Table 3, an overview is given of the measured quantities and exposure metrics (and their relation) used in this study.

An inventory of the present IoT devices, smart meters, and other RF-emitting devices was created and for each a defined set of procedures was performed (bottom-right part of Fig. 1). First, using SA I, the frequencies of the RF signal(s) transmitted by the device was (were) determined. Specific SA settings for this step included a wide frequency span, a short SWT (i.e. a fast measurement, in order to capture short pulses), and the maximum hold mode ("max hold") to retain all transmission frequencies. Using the same setup, the peak emitted electric-field values (E_{max}) (Table 3) were then measured at three different measuring distances, i.e. at 0.2 m, 0.5 m, and 1 m, defined as the distance between the surface of the device and the middle of the measurement probe.

The final step comprised the accurate determination of the DC, since for non-continuous signals, E_{max} (which assumes DC = 100%) can result in a significant overestimation of the exposure. For this, a (large) number of subsequent time domain traces of the power within a certain frequency bandwidth were captured using the spectrogram mode of SA II. These traces were then analyzed to determine the total time the device actually transmitted (T_{transm}) during the period of observation (T_{obs}), and the DC was calculated as

$$DC = \frac{T_{transm}}{T_{obs}}. \tag{1}$$

This measurement involved a zero frequency span setting (i.e. time domain measurement), a short SWT (i.e. high temporal resolution), a resolution bandwidth (RBW) at least as large as the signal bandwidth, and max hold mode.

In this study, three types of signals were observed: periodically (at a fixed interval) transmitted signals; arbitrarily transmitted signals, for which transmission depended on the occurrence of (random) events such as a change in temperature, a user interaction, etc.; and signals with a combination of a fixed and an arbitrarily transmitted active signal, e.g. in the case of a signal containing management and user data (e.g. transmissions by a wireless access point).

In the case of a periodically transmitted signal, both the duration of the periodically transmitted pulse (i.e. the pulse time, T_{pulse}) as the period between pulses (i.e. the repetition time, T_{rep}) are defined. This results in a fixed duty cycle

$$DC = \frac{T_{pulse}}{T_{rep}}, \tag{2}$$

which is valid independent of the observation time T_{obs}. Since at least two pulses should be correctly measured to determine T_{rep} and thus DC, it requires $T_{obs} > T_{rep}$.

In the case of a non-periodically transmitted signal, neither the pulse time nor the period between two pulses are necessarily fixed or are easily defined. In this case, an “action” is defined (e.g. a push on a button) and the total signal transmission time when such an action occurs, T_{action} (= T_{transm}) which can consist of multiple pulses of varying length $T_{pulse,i}$. Now, the DC is calculated as follows,

$$DC = \frac{T_{action}}{T_{obs}} = \frac{\sum_i T_{pulse,i}}{T_{obs}}, \tag{3}$$

where the observation time T_{obs} corresponds to a defined period. For example, for comparison to RF safety guidelines issued by ICNIRP (ICNIRP 1998) or the FCC (FCC 2001, IEEE 2005), T_{obs} is defined as 6 min and 30 min, respectively.

Finally, in the case of a combined signal (e.g. Wi-Fi), the resulting DC is the sum of the periodic and non-periodic signals. But it should be noted here that the DC of a Wi-Fi signal [i.e. the DC of the dominant Wi-Fi channel(s)] was determined using the measurement method proposed by Joseph et al. (2013), and in this case, no distinction could be made between UL and DL traffic as both are present in the same frequency band.

Assessment of fields emitted by mobile phones

In addition to the assessment of continuously present RF signals and the characterization of residential (IoT) devices, the uplink (UL) communication between a mobile phone and an outdoor telecommunication base station was also investigated to establish context. In each residence, at least one mobile-phone measurement was performed, where the fields emitted by the phone were recorded at a distance of 0.5 m, hand-held and operational in either Global System for Mobile Communications (GSM; voice call), Universal Mobile Telecommunications System (UMTS; voice call or data transfer), or Long Term Evolution (LTE; data transfer) mode. For the mobile-phone assessment, the duty cycle was assumed to be 100% during the entire observation time, except for GSM, which uses time division multiple access (TDMA) and has an inherent DC_{max} of 12.5%. In each case, DC may be overestimated.

3) *Metric for comparison to exposure guidelines*

Finally, to enable comparison with exposure limits issued by ICNIRP (or the FCC), the time-averaged electric-field strength E_{avg} is calculated using

$$E_{avg} = \sqrt{DC}\,E_{max} \tag{4}$$

with DC calculated for T_{obs} 6 min (ICNIRP) or 30 min (FCC, IEEE), and subsequently used to calculated the exposure ratio R_S:

$$R_S = \left(\frac{E_{avg}}{E_{ref}}\right)^2 = \frac{S_{avg}}{S_{ref}}, \tag{5}$$

with S_{avg} the time-averaged power density (Table 3) and S_{ref} and E_{ref} the ICNIRP (or FCC) general public reference levels for the power density and electric-field strength, respectively. R_S indicates the number of times the measured power density is higher or lower than the power density reference level (or maximum permissible level). The closer R_S is to 1, the closer the measured power density S_{avg} is to the reference level, with the reference level being exceeded if R_S is higher than 1.

III. RESULTS

A. *Spectral survey and assessment of continuously present signals*

1) *Example – residence 1*

To illustrate the first part of the proposed method (Fig. 1), the electromagnetic spectrum from 30 MHz to 3 GHz measured in the living room of residence 1 is shown in Fig. 2. The spectrum comprises LTE 800 signals (UL and DL), signals in the 868 MHz ISM band (transmitted by smart home devices), GSM and UMTS900 (UL and DL) signals, and signals in the 2400 MHz ISM band (Wi-Fi, magnetron, etc.). Additionally, a 1.29 GHz signal was observed, probably transmitted by a surveillance or navigation system. However, only one component was detected and as it was not reproducible, it was disregarded. Next, narrowband measurements of the continuously present signals and of the Wi-Fi signal in the ISM 2400 MHz band were performed (Table 4). To determine the Wi-Fi exposure, both the duty cycle of the dominant channel (i.e. Channel 11, with center frequency 2.462 GHz; $DC_{ch11} = 3.7\%$) (Joseph et al. 2013) and the worst-case duty cycle ($DC_{Wi\text{-}Fi} = 100\%$) were used to determine the corresponding field level. In this case, all the measurements, including the cumulative exposure level of the considered signals ($E_{cum} = 0.076$ V m^{-1}, or 0.370 V m^{-1} with $DC_{Wi\text{-}Fi} = 100\%$), were well below the FCC and ICNIRP guidelines, with a maximum R_S of 3.6 x 10^{-5}.

2) *Overview*

Table 4 further lists the measurements performed in all ten residences. On average, the cumulative exposure level in the residences was 0.225 V m^{-1} (0.497 V m^{-1} with $DC_{Wi\text{-}Fi} = 100\%$), due to continuously present signals ranging from Frequency Modulation (FM; radio) at 100 MHz to Wi-Fi at 2400 MHz. The most frequently present signals were LTE800, GSM900, UMTS900, and Wi-Fi (at 2400 MHz), which were observed in all ten residences. Of the three telecommunications signals, GSM900 was the most dominant (only in residence 10 (France) did LTE800 contribute more than GSM900). In fact, its exposure level was similar to that of Wi-Fi (average $DC_{Wi\text{-}Fi} = 4.89\%$). When present, other telecommunications signals such as GSM1800 (number of occurrences, n = 2), LTE1800 (n = 4), and UMTS2100 (n = 4), often contributed greatly to the total residential exposure. Also often present was Digital Enhanced Cordless Telecommunications (DECT; cordless phone) (n = 7), with an average of 0.135 V m^{-1} a dominant contributor as well. In addition, in some cases, FM signals, digital radio and television (TV) signals, and signals in the ISM 868 MHz or 2400 MHz (besides Wi-Fi) bands were detected, but their contributions were limited. On average, the exposure ratio was 5.5 x 10^{-6}, while the maximum exposure was found in residence 6, with R_S = 1.3 x 10^{-4} (and worst-case 1.9 x 10^{-3}) due to the larger (in relation to the other residence) presence of ISM868, GSM900, DECT, UMTS2100, and Wi-Fi.

B. Characterization of residential RF-emitting devices

1) Example – smart electricity meter

In Belgium, where a smart-meter pilot project is underway, smart electricity meters are usually networked to the central system of the energy supplier via a communications module (CoMo). Other smart meters (for water and gas) present at the same property connect into this CoMo using either a wired or a wireless link (e.g. via wireless M-Bus or Wi-Fi). In this section, a specific measurement of an electricity meter's CoMo is described. In total, five wireless CoMo's were assessed in this study, and all but one communicated with the grid through GPRS technology (similar to GSM). Fig. 3 presents the frequency spectrum of the CoMo signal, measured with SA I in max hold mode. The CoMo UL signal used three frequencies: 903.2 MHz, 904.2 MHz, and 908.0 MHz. Using a wide enough RBW to capture the three frequencies at once, the signal amplitude was subsequently measured as a function of time using the zero span spectrogram mode of SA II to obtain more detailed information about the rate of transmission, and hence to determine the duty cycle. Part of the CoMo's transmission as a function time is shown in Fig. 4. In theory, a CoMo should transmit once every 15 min, following the logging of the data. However, signal repetitions as fast as every 43 s were observed. Furthermore, each transmission consisted of a series of bursts sent over a 3.6 s interval, although in the DC calculation, a continuous signal was assumed. Combined with the communication technology's inherent duty cycle of 1:8 (like GSM, GPRS uses time division multiple access or TDMA), the CoMo's theoretical DC was 0.05%, while the maximum observed DC was 1.05%.

2) Overview

Table 5 summarizes the measurements at 0.2 m from the 55 investigated devices: the maximum electric-field level, the 6-min averaged duty cycle, and the comparison to the ICNIRP exposure guidelines. The measurements at 0.5 m were compared with the mobile-phone UL measurements and the impact of the (6-min averaged) duty cycle on the average exposure is shown in Fig. 5. In the following, the considered RF devices are described as a number of broad grouped categories (in Fig. 5 as well, but less broad).

Smart meters

In the acquired sample, smart meters came in two categories: those that transmitted data to the central system of the utility company (all electricity meters and one water meter, in a residence where no smart electricity meter was present), and those that transmitted their data in-house to a smart meter of the first category (all other smart gas and water meters). Both types were usually deployed in more remote locations in the residence such as the garage, storage room, or hallway.

For indoor-outdoor communications (i.e. the first category), the electricity meters used GPRS (CF = 899–908 MHz; GSM900 UL band) and the water meter used Sigfox (CF = 868 MHz; ISM 868 MHz band). In theory, the electricity meter's CoMo transmits once every 15 min (DC = 0.05%, including TDMA). However the maximum duty cycle was 1.05% (including TDMA) in this sample. With E_{max} between 11 V m^{-1} and 20 V m^{-1} at 0.2 m, using the latter DC resulted in R_S = 8 x 10^{-4} – 2.5 x 10^{-3}, a higher exposure compared to the other smart meter results (Table 5), though still significantly lower than the ICNIRP limits. The water meter, on the other hand, transmitted only once per day a signal with T_{pulse} = 6.49 s (DC = 0.008%) making the field strength of the signal difficult to measure. For completeness, E_{max} at 0.5 m was 0.072 V m^{-1} with a single (random) electric-field component measured (R_S = 2.4 x 10^{-10}).

Another electricity meter transmitted its data via a Wi-Fi backchannel. In this case, both E_{max} and DC were slightly lower (7 V m^{-1} and 0.08%, respectively), and correspondingly the R_S (1.1 x 10^{-5}).

For in-house communications, the smart meters in the sample used wireless M-Bus (CF = 869 MHz; ISM 868 MHz band) with a DC of 0.002% (one signal of T_{pulse} = 15 – 18 ms every 15 min). None of them were measured at 0.2 m, but at 0.5 m, E_{max} were lower than 1 V m^{-1} and significantly below the emissions from the smart meter of the first category (Fig. 5).

Smart home devices

In this residential sample, a number of devices could be characterized as "smart home devices" (e.g. weather station and temperature sensor, Philips Hue device, smart toothbrush, and motion sensor). Most of these devices were continuous, periodic transmitters, with a duty cycle of the order of 0.01% up to a few percent (weather station (DC = 0.31 – 2.90%), energy monitoring plug and gateway (DC = 0.05%), heat alarm (DC = 0.02%), temperature sensor – with a user-defined DC = 23.76% (in theory, max 1% because LoRa) – Philips Hue gateway DC = 0.25%), one was a periodic transmitter when in use (toothbrush, with DC = 33.63%), and one (a motion sensor) actually transmitted continuously (DC = 100%). One other device detected changes in the environment to commence a certain action (thermostat, DC = 0.02%, with one signal during a 6-min interval). All smart home devices operated in the ISM bands: three devices in the 2400 MHz band (energy monitoring device, using Wi-Fi; motion sensor, CF = 2450 MHz; and Philips Hue gateway, using Zigbee, with CF = 2475 MHz), two weather stations in the 434 MHz band, and the others in the 868 MHz band. The peak electric-field strengths measured at 0.2 m ranged from 2×10^{-3} V m^{-1} (weather station receiver) to 5.1 V m^{-1} (Philips Hue gateway), with >1 V m^{-1} fields for five of the assessed devices (temperature sensor, Philips Hue gateway, motion sensor, thermostat, and smart toothbrush). Taking into account the 6-min duty cycles and the transmission frequencies, the highest exposures were found for the smart toothbrush ($R_S = 4.8 \times 10^{-3}$), the temperature sensor ($R_S = 6.0 \times 10^{-4}$), and the motion detector ($R_S = 5.0 \times 10^{-4}$).

Remote controls

Remote controls rely on user-control and transmit at arbitrary moments. Their transmission frequencies are usually in the ISM 433 MHz and 868 MHz bands, with two exceptions: TV remotes working at Wi-Fi 2400 MHz and 41 MHz. A single push of a remote control button defined the action and the minimum observation time was the minimum time between two pushes (i.e. 0.6 μs, as timed by the investigators). Depending on the device, the transmitted signal was either continuous during the action (in this case, $\mathrm{DC}_{\max} = 100\%$) or comprised one or multiple pulses ($\mathrm{DC}_{\max} < 100\%$, unless $T_{pulse} > 0.6$ µs). The maximum field levels measured at 0.2 m were in the range 0.16 – 6.0 V m^{-1}, the duty cycles for T_{obs} 6 min (for comparison with ICNIRP guidelines) between 0.003% and 0.19%**,** and the maximum R_S at 0.2 m was 1.5 x 10^{-5} (TV remote at 41 MHz).

Bluetooth devices

One Bluetooth-connected computer mouse and two speakers were assessed during a (failed) pairing initialization process. In this case, the duty cycle was found to be 2.84%. With peak electric-field strengths varied around 0.4 V m^{-1}, corresponding to an exposure ratio of approximately 1.5 x 10^{-6}.

Wireless access points

In this sample, all Wi-Fi cable modems and range extenders transmitted in the Wi-Fi 2400 MHz band. Their duty cycles ranged between 2.46% and 15.80%, and with peak electric-field strengths of 2.75 – 12.51 V m^{-1}, this resulted in exposure ratios of 1.0 x 10^{-4} to 1.2 x 10^{-4} at 0.2 m.

Other

Other devices assessed included a doorbell transmitting at 868 MHz; two DECT cordless phones and a DECT base station (maximum R_S of 2.2 x 10^{-3} at 0.2 m); a Wi-Fi printer; a walkie-talkie (PMR 446 MHz band) with a worst-case (i.e. during a 6-min call) R_S of 0.53 at 0.2 m; two wireless (non-Bluetooth) computer mice transmitting in the ISM 2400 MHz band with a worst-case (i.e. 6-min use) R_S of 4.3 x 10^{-3} at 0.2 m; and two pairs of baby monitors (separate parent and baby units), one using DECT (max. $R_S = 1.9 \times 10^{-3}$ for the parent unit), the other transmitting in the ISM 868 MHz band (max. $R_S = 0.013$ for the baby unit).

Mobile phones

The UL signals of mobile phones were measured at one distance, 0.5 m. In Fig. 5, the maximum and time-averaged field levels are depicted. On average, the field levels of GSM UL communications were the highest (up to 11 V m^{-1}), and for UMTS UL the lowest (up to 2 V m^{-1}). However, GSM has an inherent DC of 12.5% due to its TDMA structure. After taking this into account, the highest E_{avg} were found for LTE UL.

IV. DISCUSSION

A. Potential impact on residential RF-EMF exposure

Residential RF emissions from a total of 55 devices (e.g. IoT devices and smart meters) were characterized by determining the transmission frequencies, peak emitted fields at various distances, and duty cycles. The emissions were compared to the ICNIRP guidelines for public RF-EMF exposure, as well as to the present exposure levels resulting from environmental sources (telecommunications and broadcasting signals) and emissions of mobile phones in order to identify the potential impact on the residential RF exposure. When comparing Figs. 5a and b, one can see that mere comparison of the peak electric-field strength E_{max} may result in a wrong exposure ranking. Moreover, to further assess the potential impact on the exposure of a non-user-controlled device, the deployment location is highly important. For example, the highest field strengths at 0.5 m were measured for three CoMo's (smart meters), but the resulting exposures (considering a 1% duty cycle) rank between wireless access points and

GSM and LTE UL emissions, while their deployment out of sight of the residents ensures that the exposure potential remains limited.

The results obtained in the considered (convenience) sample of residences demonstrate that, in addition to the exposure due to environmental sources, wireless access points – due to their usual deployment in highly frequented rooms combined with a DC of several % – and mobile phones and other personal communication devices (e.g. DECT cordless phones, walkie-talkies) – due to their typically high emissions and use close to the body – will probably continue to represent the bulk of the residential exposure to RF-EMF in the smart home. A surprising addition to these dominant RF sources in this sample was the (albeit non-commercial) smart toothbrush (which may be characterized under "personal IoT device"), due to its relatively high emissions, high duty cycles, and conditions of use (i.e. close to the body). Furthermore, monitoring devices such as motion sensors (with DC = 100%) and baby monitors (also high DCs) may additionally increase one's residential RF exposure. Smart meters, on the other hand, and in particular communications modules wirelessly linked to the utility company's central network, may contribute little to the RF exposure. Although field levels at 0.2 m reached as high as 20 V m^{-1}, the potential for exposure is small given the rare transmissions and deployment in locations away from the residents.

B. Comparison to literature (smart meters)

Despite the fact that smart-metering systems are not universal, the results obtained in this study are similar to those found in the literature. Girnara et al. (2011), Tell et al. (2012), and Peyman et al. (2017) found duty cycles typically lower than 1% for most smart meters and lower than 5% for heavily loaded smart meters. In the laboratory measurements of Peyman et al. (2017), a maximal power density of 15 mW m^{-2} (2.38 V m^{-1}) was measured at 0.5 m distance from the radiating smart meter. However, overall, the maximum time-averaged exposure level was 6 μW m^{-2} (0.05 V m^{-1}; measured at a distance of 0.3 m from a single smart meter acting as wireless access point), and all of the exposure levels assessed at distances of 0.2 m and beyond around smart meters were well below the levels recommended by the regulatory guidelines such as the FCC (FCC 2001, IEEE 2005) and ICNIRP (1998).

It should perhaps be noted that the ICNIRP guidelines (i.e. the reference levels and averaging time, here T_{obs}) are currently being revised. However, there is no indication that the new guidelines would have any impact on our conclusions.

Furthermore, in comparison the RF exposure from mobile phones and Wi-Fi networks, it was concluded by Peyman et al. (2017) that exposure from smart meters is lower due to their low duty cycle and the typically large distance to the human body in normal circumstances.

1) *Strengths & Limitations*

In this study, a wide range of RF-emitting residential devices were assessed (55 in total), using a wide range of RF communications technologies (Wi-Fi, LoRa, Zigbee, Sigfox, EnOcean, Bluetooth, etc.) for various purposes. To this aim, a novel measurement procedure was developed using the spectrum analyzer spectrogram mode to capture the signal amplitude in time and thus characterize the temporal structure of the emissions from a device.

During all of the described measurements, the investigators' phones and laptops were turned off or in flight mode.

Two factors may have overestimated the exposure ratio R_S. First, it was assumed that the device's output power remained constant, and the peak electric-field strength was used to calculate the eventual exposure ratio. Secondly, in the determination of the duty cycle of a device, whenever burst signals occurred, their envelope (as captured by the spectrogram) was considered to calculate T_{pulse} or T_{action}. Doing so overestimated the DC and thus the exposure ratios R_S of some of the considered devices.

Although some devices are meant to be used close(r) to the body, only whole-body exposure was considered here, using the peak incident power density at certain distances from the source in combination (with the duty cycle). Both factors ensured a conservative approach to calculate the resulting exposure ratio.

It should be noted that measurements were also performed using the Narda broadband meter. This measurement probe is a handheld system that is very easy and practical to use. However, a large disadvantage is that the pulse length of an RF signal has to be long enough in comparison to the integration time of the system (270 ms) and that the signal level must be high enough (> 0.2 V m^{-1}) to enable its detection. Additionally, the contribution of different RF sources cannot be distinguished. Consequently, a broadband setup was not suitable to characterize the RF fields around the smart devices installed in houses, and its results were omitted from this paper.

Finally, it should also be noted that, as the specific physical placement of RF sources is unique to the assessed environments, the measurements presented here represent a sample cross-section in space and time and are not generalizable to a broader number of smart homes. However, the described results may illustrate the potential RF environment of the near future, in which everything is connected.

V. CONCLUSIONS

In this study, a novel measurement method was designed to characterize in-situ residential RF emissions from emerging wireless solutions (e.g. IoT sources and smart meters) by determining the RF transmission frequency, the peak emitted fields at various distances, and the proportion of transmission time (i.e. duty cycle), for which the spectrogram mode of a spectrum analyzer was used. This method was applied to a convenience sample of ten residences in Belgium and France containing, in total, 55 IoT devices, smart meters, and other RF-emitting devices. The measured emissions were also compared to present levels of telecommunications and broadcasting signals, emissions by a mobile phone using three current telecommunications technologies (GSM, UMTS, and LTE), as well as to the ICNIRP guidelines for general public RF-EMF exposure.

Overall, low to very low emissions were measured for nearly all of the devices, and it is concluded that, in addition to the continuous exposure due to environmental sources, when used, wireless access points and especially mobile phones and other personal communication devices (e.g. DECT cordless phones, walkie-talkies) will continue to represent the bulk of our exposure to radiofrequency electromagnetic fields in the smart home, due to their typically high emissions and use close to the body. However, RF-emitting devices with high duty cycles (e.g. in this sample: motion sensor, baby monitor, and an IoT toothbrush) may significantly increase the potential for exposure, especially when used or located close to the body. The potential impact on the exposure due to individual smart meters, on the other hand, and in particular due to the communications modules wirelessly linked to a utility company’s central network, is small, regardless of their emissions up to 20 V m^{-1} at 0.2 m, given their rare transmissions and usual deployment away from the residents.

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LIST OF CAPTIONS

Fig. 1: Flow graph of the measurement procedure for residential RF-emitting devices and present radiofrequency signals.

Fig. 2: Overview of the electromagnetic spectrum from 30 MHz to 3 GHz measured in the living room of residence 1. The electric-field strength E was normalized to the maximum value. In this case, signals were detected in the LTE800 downlink and uplink bands, the ISM 868 MHz band, the telecommunications 900 MHz downlink and uplink bands, and the ISM 2400 MHz band. In addition, a surveillance or navigation signal was observed at 1.29 GHz – however, only one component was detected and it could not be reproduced, so it was disregarded in the ensuing analysis.

Fig. 3: Frequency spectrum [maximum power P_{max} received by the spectrum analyzer (in decibel milliwatt or dBm) vs. frequency f in megahertz or MHz] of the signal transmitted by a smart electricity meter's communications module to the central system of the energy supplier (using General Packet Radio Service). In this case, the transmission frequencies of the communications module's signal are 903.2 MHz, 904.2 MHz, and 908.0 MHz.

Fig. 4: Series of pulses transmitted by a smart electricity meter's communications module, measured with the zero span spectrogram mode (received power P, in dBm) of spectrum analyzer II. Each pulse has the same duration, i.e. T_{pulse} = 3.6 s. However, the repetition time is variable. In this case, the repetition time between the first and second pulse is 212.5 s, and between the second and third 43 s.

Fig. 5: (a) Peak electric-field strengths E_{max} at a distance of 0.5 m from the devices under test, and (b) the ICNIRP exposure ratios R_S (T_{obs} = 6 min) at the same distance, for various categories

of residential RF-emitting devices. In the case of mobile phones, the uplink signal (i.e. signal from device to base station) was measured (DCs for LTE and UMTS were assumed to be 100%, for GSM 12.5%). Each dot represents a measurement of a device within the category on the y-axis.

Table 1: Convenient sample of residences.

ID	**Region**	**#**	**IoT Technology**			
			Electricity meter	**Water meter**	**Gas meter**	**Other**
r1	Nazareth	5	*wired*	--	M-Bus	--
r2	Melle	4	GPRS	M-Bus	*outdoor*	--
r3	Edegem	7	--	Sigfox	--	LoRa, Zigbee
r4	Melle	5	GPRS	--	--	Wi-Fi
r5	Stekene	7	Wi-Fi	--	--	Zigbee, Wi-Fi
r6	Wommelgem	4	GPRS	--	--	GPRS, Wi-Fi
r7	Wommelgem	5	GPRS	--	M-Bus	Wi-Fi, Bluetooth
r8	Deinze	8	--	--	--	PMR, Bluetooth
r9	Zomergem	8	--	--	-	--
r10	Arras (France)	2	--	--	-	EnOcean

--: Meter with wired communication or not present in the residence.
#: Number of residential sources of RF-EMF measured.
GPRS = General Packet Radio Service, LoRa = Long Range, PMR = Personal Mobile Radio, M-Bus = Meter-Bus.

Table 2: Typical spectrum analyzer settings for different measurements of RF signals (Joseph et al. 2012a, 2012b, 2013; Verloock et al. 2014).

Signal	**Frequency (MHz)**	**Detector mode**	**RBW (MHz)**	**SWT (ms)**	**Sensitivity[a] ($\mathrm{mV\,m^{-1}}$)**	**Remark**
Spectrum overview measurement						
whole frequency range	variable[b]	peak	1	2.5	10	Frequency[c] + maximum hold mode (T_{meas} = 15 s)
Narrowband measurement						
FM	100	rms	0.3	2.5	14	Frequency mode[c]
T-DAB	220	rms	3	100	9	Frequency mode[c]
TETRA	390	rms	0.03	25	2	Frequency mode[c]
ISM 433 MHz	433	peak[d]	0.3 or 1	2.5	3	Frequency[c] + maximum hold mode (T_{meas} = 60 s)
DVB-T	470	rms	5	800	3	Frequency mode[c]
ISM 868 MHz	868	peak[d]	0.3 or 1	2.5	3 or 7	Frequency[c] + maximum hold mode (T_{meas} = 60 s)
DL telecom	800, 900, or 1800	rms	0.3	300	2	Frequency mode[3]
UL telecom	800, 900, or 1800	peak[d]	0.3	2.5	4	Frequency[c] + maximum hold mode (T_{meas} = 60 s)
DECT	1880	rms	2	200	5	Frequency mode[3]
Wi-Fi 2400 MHz	2400	rms	1	10	6	Frequency[c] + maximum hold mode (T_{meas} = 60 s) Additional determination of DC
Duty cycle measurement						
variable	variable[b]	peak	0.3 or 1	variable[b]	-95 dBm	zero-span mode (span = 0 Hz)

RBW = resolution bandwidth, SWT = sweep time, T_{meas} = measurement time, ISM = Industrial, Scientific, Medical; DL = downlink, UL = uplink, rms = root mean square, T-DAB = Terrestrial Digital Audio Broadcasting, TETRA = Terrestrial Trunked Radio, DVB-T = Digital Video Broadcasting Terrestrial, ISM = Industrial, Scientific, and Medical, DECT = Digital Enhanced Cordless Telecommunications, UMTS = Universal Mobile Telecommunications System, Wi-Fi = Wireless Fidelity.

[a] *The minimum sensitivity, which depends on different parameters of the SA (e.g., RBW).*

[b] *Dependent on the (type of the) considered signal(s).*

[c] *Frequency mode is the default SA mode; this means span is not 0 Hz (SPAN ≠ 0).*

[d] *A peak detector can lead to an overestimation of the signal*

Table 3: Overview of the RF-EMF quantities and exposure metrics used in this study.

Quantity	***Symbol***	***Unit***	***Relation to other metric(s)***
Power received by spectrum analyzer	P	*decibel milliwatt (dBm)*	--
Voltage measured by spectrum analyzer	V	*volt (V)*	$V = \sqrt{Z\ 10^{P/10}}$
Electric-field strength	E	*volt per meter (V/m)*	$E = V\ 10^{AF/20}$
Power density	S	*watt per square meter (W/m^2)*	$S = \frac{E^2}{Z_0}$
Exposure ratio	R_S	--	$R_S = \frac{S_{avg}}{S_{ref}} = \left(\frac{E_{avg}}{E_{ref}}\right)^2$

$Z = 50\ \Omega$, input impedance of the spectrum analyzer.
AF = antenna factor, obtained through calibration of the spectrum analyzer setup (in decibel per meter, dB/m)
$Z_0 = 377\ \Omega$, characteristic impedance of free space.
S_{ref} = power density reference level (ICNIRP 1998, IEEE 2005).
E_{ref} = electric-field reference level (ICNIRP 1998, IEEE 2005).

Table4

Table 4: Overview of the RF signals continuously present in the residence sample. The presented electric-field strengths were determined at a height of 1.5 m in the middle of an often frequented room (which was the living room in all cases except in residence 3, the garage) using the measurement settings listed in Table 2.

Signal [*f* (MHz)]	**r1**	**r2**	**r3**	**r4**	**r5**	**r6**	**r7**	**r8**	**r9**	**r10**	***avg.***
FM	--	--	--	--	--	--	0.033	0.019	0.011	0.023	*0.023*
PMR 169	--	--	--	--	--	0.065	--	--	--	--	*0.065*
T-DAB	--	--	--	--	--	--	0.004	--	--	--	*0.004*
ASTRID	--	--	--	--	--	0.049	0.005	--	--	--	*0.035*
DVB-T	--	--	--	--	--	--	0.004	--	--	--	*0.004*
LTE 800	0.013	0.006	0.050	0.004	0.008	0.001	0.012	0.006	0.004	0.023	*0.019*
ISM 868	--	--	--	--	--	0.191	--	--	--	--	*0.191*
GSM 900	0.022	0.009	0.205	0.028	0.015	0.316	0.018	0.008	0.014	0.013	*0.120*
GSM-R 900	--	--	0.001	0.015	--	--	--	0.010		0.001	*0.009*
UMTS 900	0.012	0.007	0.004	0.013	0.007	0.052	0.007	0.006	0.005	0.012	*0.018*
GSM 1800	--	--	--	--	--	--	0.002	--	--	0.002	*0.002*
LTE 1800	--	--	0.053	--	--	0.093	0.008	--	--	0.012	*0.054*
DECT	--	0.125	--	0.027	0.160	0.188	0.003	0.003	0.223	--	*0.135*
UMTS 2100	--	--	0.064	--	--	0.218	0.013	--	--	0.026	*0.115*
Motion sensor	--	--	--	--	--	--	0.027	--	--	--	*0.027*
ISM 2400	--	--	--	--	--	--	0.028	0.027	--	--	*0.028*
Wi-Fi 2400	0.071	0.237	0.018	0.029	0.033	0.190	0.025	0.020	0.094	0.081	*0.108*
$DC_{Wi\text{-}Fi}$ (%)	3.70	7.50	0.35	7.50	10.12	7.40	3.30	3.34	2.41	3.26	*4.89*
Wi-Fi 2400 *(worst-case)*	0.369	0.865	0.304	0.106	0.104	0.698	0.138	0.110	0.606	0.447	*0.457*
Cumulative	**0.076**	**0.268**	**0.228**	**0.053**	**0.164**	**0.523**	**0.064**	**0.042**	**0.243**	**0.094**	***0.225***
Cumulative *(worst-case)*	**0.370**	**0.874**	**0.379**	**0.115**	**0.192**	**0.851**	**0.150**	**0.115**	**0.646**	**0.449**	***0.497***

r# = residence ID (Table 1).

FM = frequency modulation, PMR = personal mobile radio, T-DAB = Terrestrial Digital Audio Broadcasting, ASTRID = All-round Semi-cellular Trunking Radio communication system with Integrated Dispatching, DVB-T = Digital Video Broadcasting Terrestrial, LTE = Long Term Evolution, ISM = Industrial, Scientific, and Medical, GSM = Global System for Mobile Communications, GSMR = GSM – Railways, DECT = Digital Enhanced Cordless Telecommunications, UMTS = Universal Mobile Telecommunications System, Wi-Fi = Wireless Fidelity.

All values are in V m^{-1} *except for* $DC_{Wi\text{-}Fi}$.

Table5

Table 5: Smart meters, IoT devices, and other residential sources of RF-EMF, characterized and grouped per residence, along with the maximum electric-field strength (E_{max}*) measured at 0.2 m, the duty cycle assessed over a 6-min period (one device action, where applicable, and unless otherwise stated), and the power density ratio *R_S* (at 0.2 m) for comparison with the ICNIRP guidelines.*

Device	**CF (MHz)**	E_{max} **(V m^{-1})**	**DC$_{6min}$ (%)**	R_S **(-)**
Velux remote control	869	0.612	0.19	4.4×10^{-7}
thermostat	868	0.606	0.004	8.7×10^{-9}
weather station *(transmitter)*	434	0.305	2.43	2.8×10^{-6}
weather station *(receiver)*	440	0.002	5.80	3.3×10^{-10}
gas meter	869	0.911	0.002	4.6×10^{-9}
electricity meter	903 – 908	n.m.	1.05	-
water meter	869	n.m.	0.002	-
weather station *(transmitter)*	434	0.095	2.90	3.2×10^{-7}
heat alarm	868	n.m.	0.02	-
water meter	868	n.m.	0.008	-
garage remote control	869	0.821	0.17	6.9×10^{-7}
temperature sensor	868	2.008	23.76	5.9×10^{-4}
sun shade remote control	433	1.251	0.15	2.9×10^{-6}
Philips Hue gateway	2475	5.140	0.25	1.7×10^{-5}
awning remote control	870	0.487	0.003	4.1×10^{-9}
TV remote control	2433 – 2475	2.440	n.m.	-
electricity meter	899	11.823	1.05	8.4×10^{-4}
Wi-Fi range extender	2412	12.505	2.46	1.0×10^{-3}
fan remote control	868	0.163	0.04	6.5×10^{-9}
sun shade remote control	433	0.806	0.06	4.6×10^{-7}
doorbell	868	0.655	0.34	8.8×10^{-7}
electricity meter	2462	6.967	0.08	1.1×10^{-5}
Wi-Fi cable modem	2462	2.745	15.80	3.2×10^{-4}
energy monitoring gateway *(initialization)*	2425	0.778	5.28	8.5×10^{-6}
energy monitoring gateway *(regime)*			0.05	7.5×10^{-8}
energy monitoring plug *(initialization)*	2425	0.948	5.28	2.1×10^{-5}
energy monitoring plug *(regime)*			0.05	2.3×10^{-7}
TV remote control	41	6.005	0.03	1.5×10^{-5}
cooker hood remote control	434	0.259	0.08	6.5×10^{-8}
carport remote control	434	0.259	0.13	1.1×10^{-7}

electricity meter	902 – 903	14.859	1.05	1.3×10^{-3}
access gate remote control	434	0.234	0.14	9.4×10^{-8}
cordless phone (DECT)	1884	n.a.	n.a.	1.5×10^{-4}
Wi-Fi cable modem	2462	7.662	7.40	1.2×10^{-3}
electricity meter	899	20.319	1.05	2.5×10^{-3}
gas meter	869	0.855	0.004	2.0×10^{-8}
Wi-Fi cable modem	2412	10.941	3.30	1.0×10^{-3}
RF motion sensor	2450	1.428	100.00	5.4×10^{-4}
Bluetooth speaker	2474	0.472	2.84	1.7×10^{-6}
Bluetooth speaker	2420	0.411	2.84	1.3×10^{-6}
dimmer remote control	434	0.213	0.16	8.8×10^{-9}
cordless phone (DECT)	1884	n.a.	n.a.	1.8×10^{-4}
Bluetooth mouse	2420	0.395	2.84	1.2×10^{-6}
thermostat	868	2.627	0.02	6.3×10^{-7}
walkie-talkie *(push talk button once)*	446	21.207	0.83	4.5×10^{-3}
walkie-talkie *(push to talk)*			100.00	5.3×10^{-1}
wireless mouse #1 *(continuous use)*	2402 – 2479	2.074	100.00	1.1×10^{-3}
wireless mouse #2 *(continuous use)*	2405 – 2474	4.045	100.00	4.3×10^{-3}
weather station *(transmitter)*	868	n.m.	0.31	-
baby monitor #1 *(parent unit)*	868	5.132	2.92	4.7×10^{-4}
baby monitor #1 *(baby unit)*	863 – 870	5.420	73.4	1.3×10^{-2}
baby monitor #2 *(parent unit)*	1880 – 1900	n.a.	n.a.	1.9×10^{-3}
baby monitor #2 *(baby unit)*	1880 – 1900	n.a.	n.a.	6.0×10^{-4}
DECT base station *(standby)*	1880 – 1900	n.a.	n.a.	4.2×10^{-4}
DECT base station *(live)*				2.2×10^{-3}
Wi-Fi cable modem	2437	4.690	1.97	1.1×10^{-4}
Wi-Fi printer	2437	3.594	0.04	4.8×10^{-7}
EnOcean switch	868	0.329	0.003	2.0×10^{-9}
smart toothbrush	865 – 868	4.820	33.63	4.8×10^{-3}

TV = television; DECT = Digital Enhanced Cordless Telecommunications, Wi-Fi = Wireless Fidelity.

CF = center frequency; E_{max} = peak electric-field strength measured at 0.2 m from the device, measurement performed with SA I in maximum-hold mode; DC_{6min} = duty cycle determined in 6-min interval; R_S = power density ratio for comparison with ICNIRP guidelines.

n.a. = not applicable; in the case of DECT, the time-averaged E_{rms} was directly measured.

n.m. = not measured; due to time or distance constraints. In this case, no R_S value could be provided.

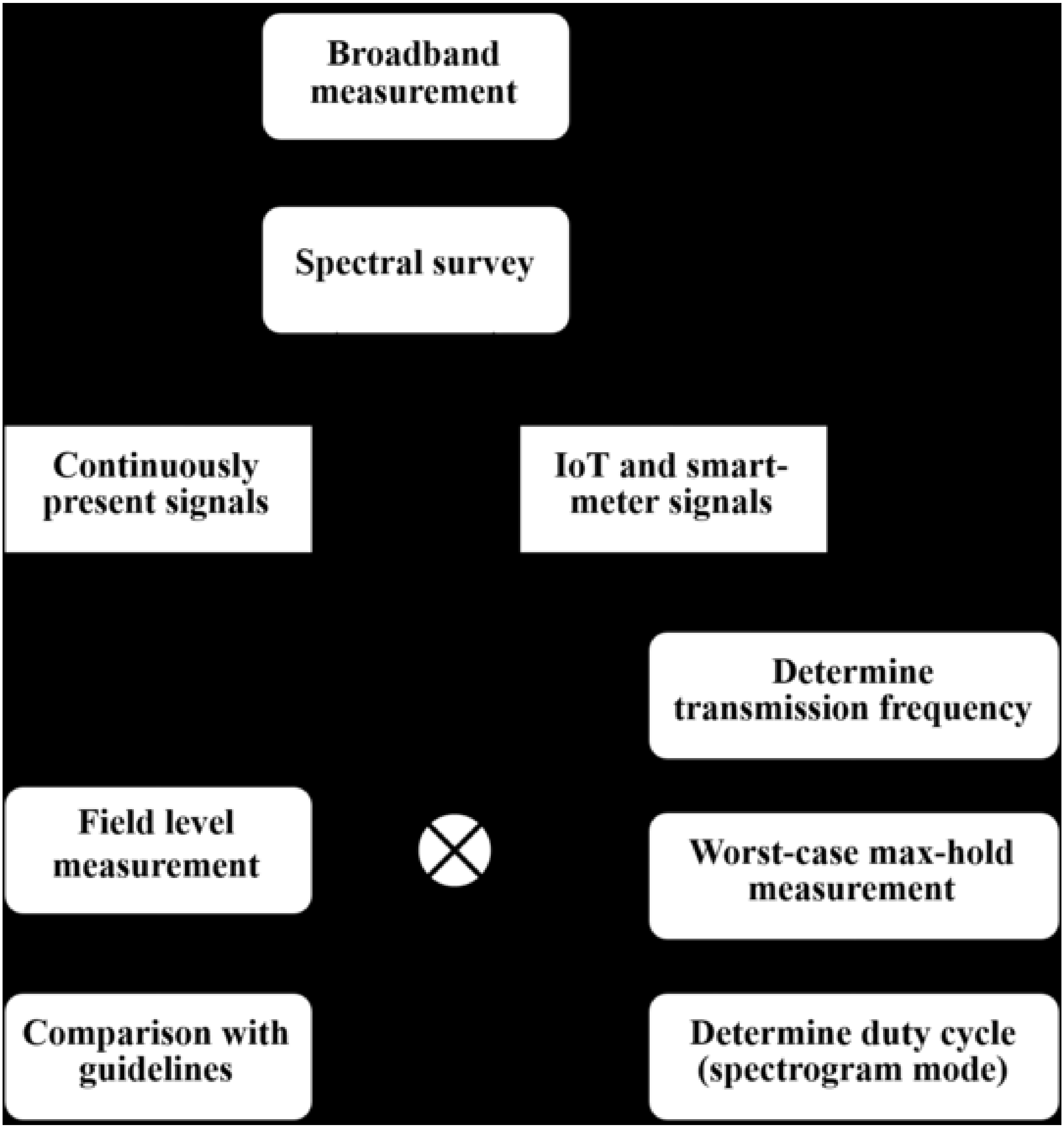
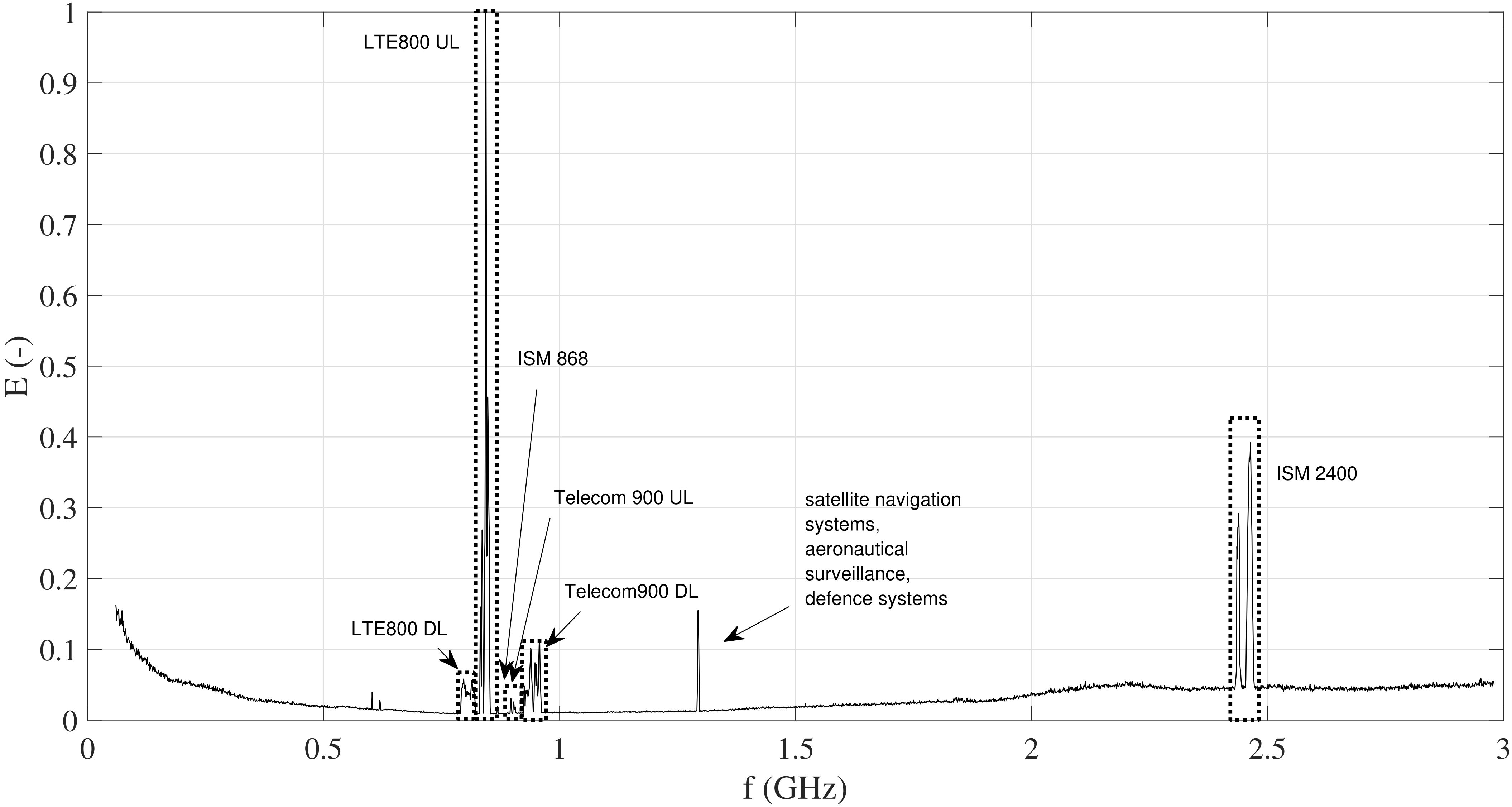

Broadband measurement
Spectral survey
Continuously present signals
IoT and smart-meter signals
Determine transmission frequency
Field level measurement
Worst-case max-hold measurement
Comparison with guidelines
Determine duty cycle (spectrogram mode)

Figure2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ISM 868
Telecom 900 UL
Telecom900 DL
LTE800 DL
satellite navigation systems, aeronautical surveillance, defence systems
ISM 2400
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2
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3

Figure4

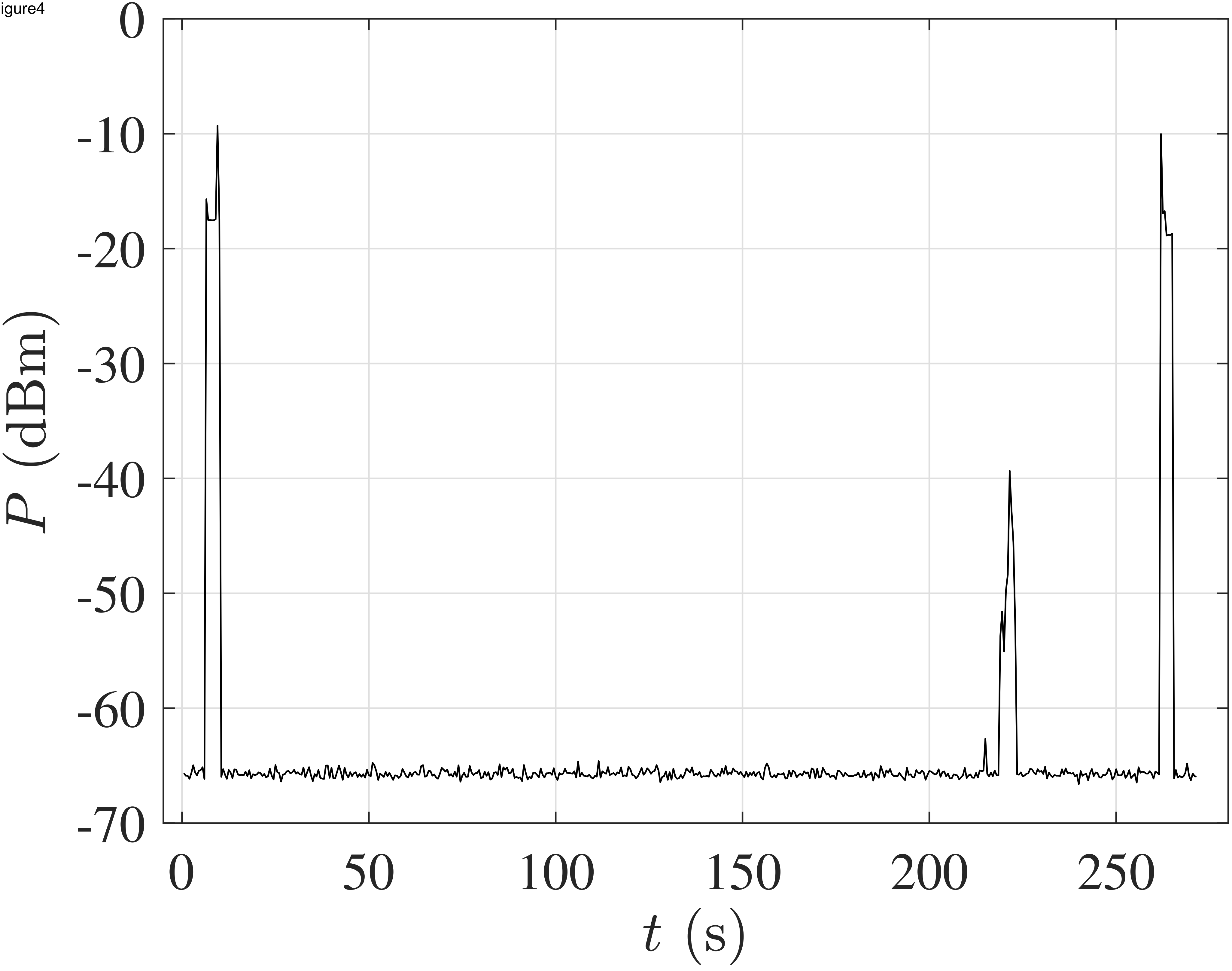

Figure3

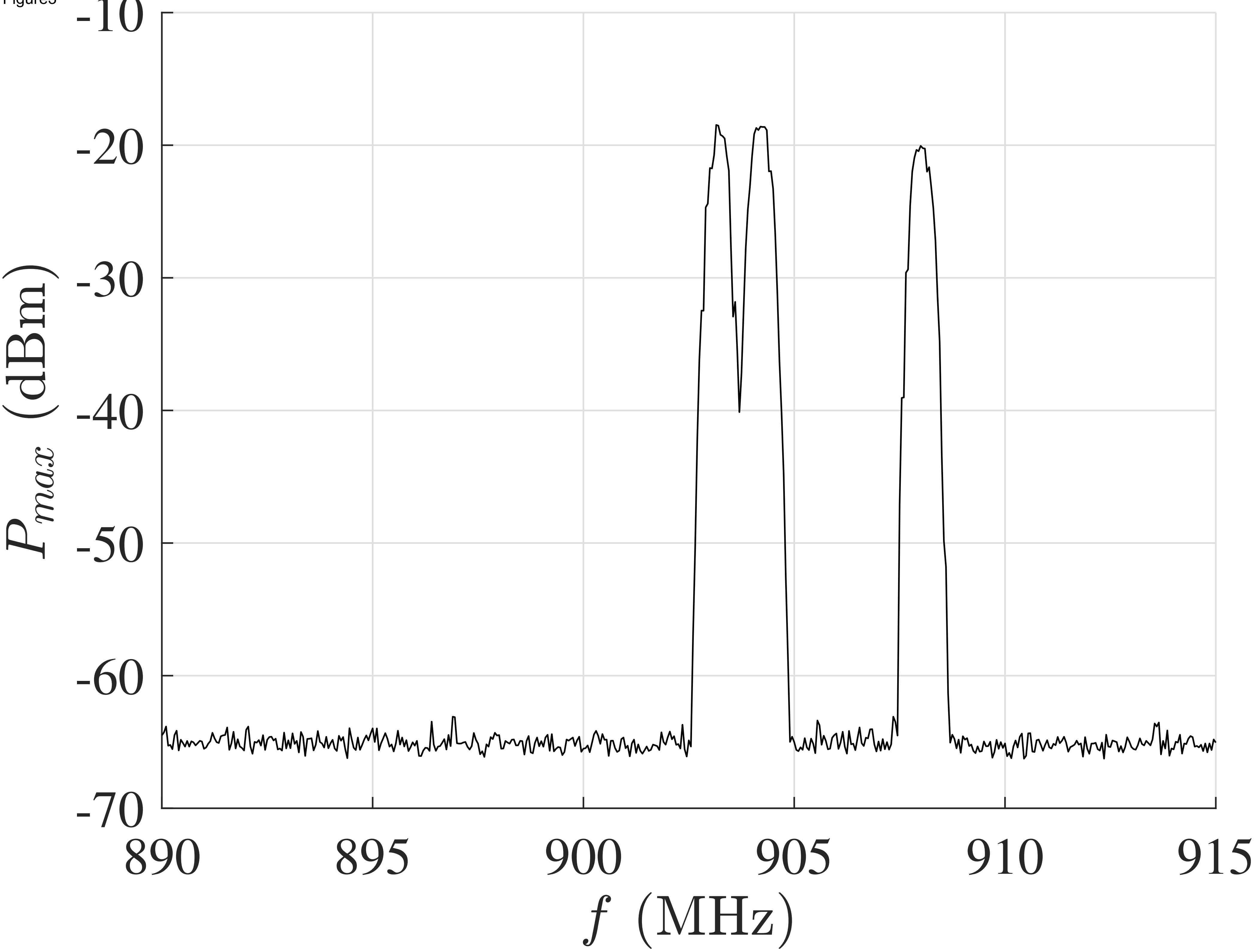

Figure5a

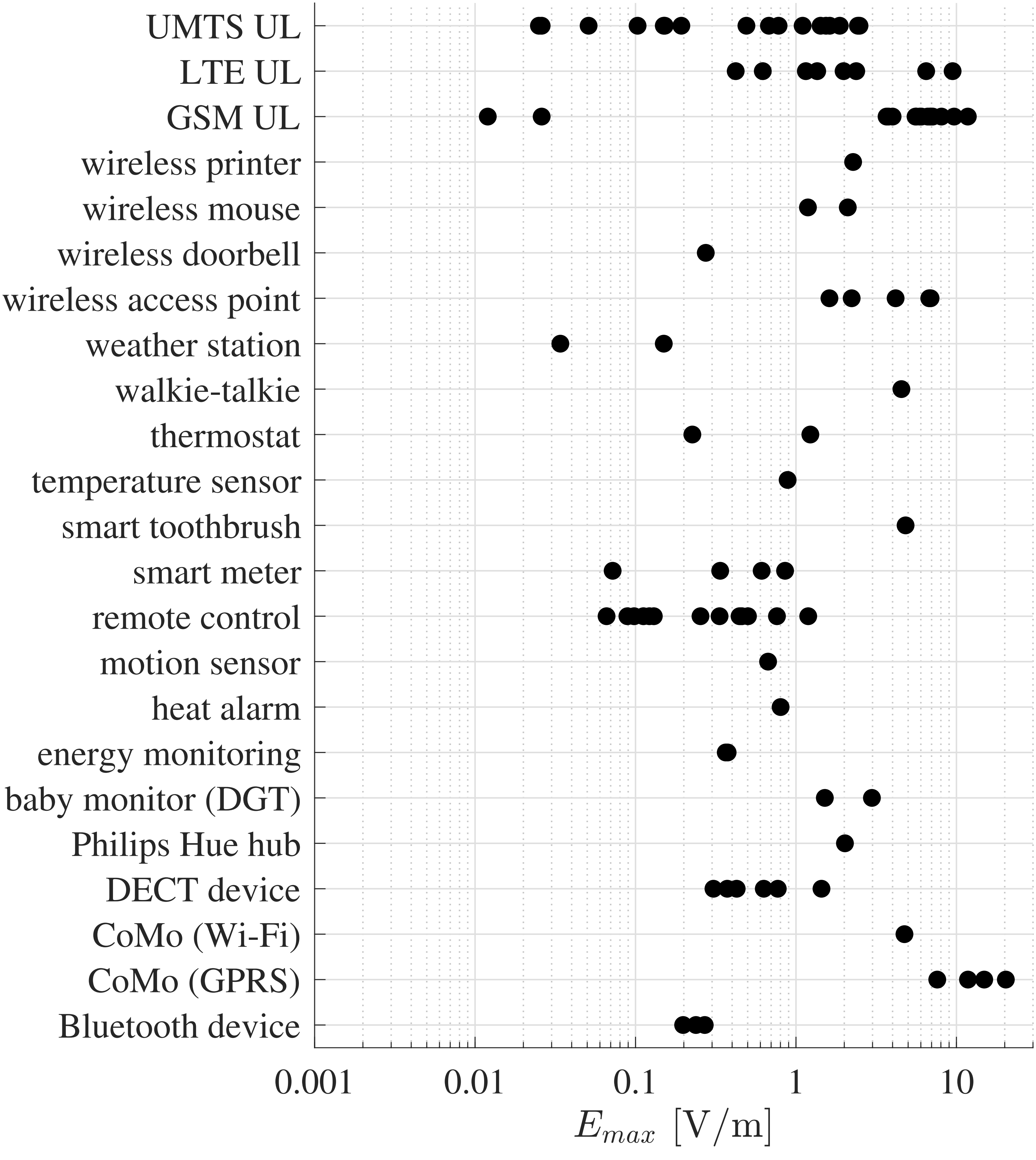
UMTS UL
LTE UL
GSM UL
wireless printer
wireless mouse
wireless doorbell
wireless access point
weather station
walkie-talkie
thermostat
temperature sensor
smart toothbrush
smart meter
remote control
motion sensor
heat alarm
energy monitoring
baby monitor (DGT)
Philips Hue hub
DECT device
CoMo (Wi-Fi)
CoMo (GPRS)
Bluetooth device
0.001
0.01
0.1
1
10
E_{max} [V/m]

Figure5b