Exposure to Electromagnetic Fields From Smart Utility Meters in GB; Part I) Laboratory Measurements

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Laboratory measurements of electric fields have been carried out around examples of smart meter devices used in Great Britain. The aim was to quantify exposure of people to radiofrequency signals emitted from smart meter devices operating at 2.4 GHz, and then to compare this with international (ICNIRP) health-related guidelines and with exposures from other telecommunication sources such as mobile phones and Wi-Fi devices. The angular distribution of the electric fields from a sample of 39 smart meter devices was measured in a controlled laboratory environment. The angular direction where the power density was greatest was identified and the equivalent isotropically radiated power was determined in the same direction. Finally, measurements were carried out as a function of distance at the angles where maximum field strengths were recorded around each device. The maximum equivalent power density measured during transmission around smart meter devices at 0.5 m and beyond was 15 mW m⁻², with an estimation of maximum duty factor of only 1%. One outlier device had a maximum power density of 91 mWm⁻². All power density measurements reported in this study were well below the 10 W m⁻² ICNIRP reference level for the general public. Bioelectromagnetics. 2017;38:280–294.

INTRODUCTION

Smart meters are wireless communication devices that allow remote readings of utility meters such as those for electricity and gas consumption (see Fig. 1). Typical monitored parameters include location, consumption units, time, and usage frequency. Introducing smart meters into residential and business properties includes development of a smart grid which would lead to more efficient energy usage. In Great Britain (GB), it is expected that smart meters will be widely adopted in domestic environments within the next few years. The national rollout will involve a visit to every home and the replacement of around 53 million electricity and gas meters.

Smart meters use radiofrequency (RF) signals for communication through a home area network (HAN) as well as a wide area network (WAN). People who are close to smart meter devices are exposed to the RF signals, and their bodies absorb some of the transmitted energy.

As an emerging technology that uses RF electromagnetic fields (EMF), it is necessary to investigate and quantify the RF signals produced by these devices, and ensure that the exposure levels comply with relevant exposure guidelines. In addition, experience from similar projects investigating Wi-Fi RF sources suggests that such quantitative information can be very useful from a consumer perspective in putting exposure into context [Findlay and Dimbylow, 2010; Khalid et al., 2011; Peyman et al., 2011].

Recent studies carrying out field assessment of people’s exposure to RF signals from smart meter devices operating in Australia, Canada, and the United States [Girnara et al., 2011; Tell et al., 2012a,b; Zhou and Schneider, 2012] revealed that exposure levels in the vicinity of the operating meters, based on conservative estimates of duty factor (the proportion of time...
that a device transmits RF signals), are well below the levels recommended by health regulatory guidelines such as the International Commission on Non-Ionizing Radiation (ICNIRP), the US Federal Communications Commission (FCC), and The Institute of Electrical and Electronics Engineers (IEEE), and small compared to other sources of RF such as mobile phones. However, technical specifications of smart meter technology used in these countries differ from each other and from those designed for the market within GB.

To quantify people’s exposure to smart meter devices in GB, Public Health England set up a comprehensive project in 2012 that aimed to investigate exposures that are likely to be incurred as a result of smart meters installed in people’s homes. In the first stage of the project, samples of smart meters were obtained from various manufacturers and utility companies for evaluation under laboratory conditions. First, the power densities were tested and assessed around the devices to establish the radiation patterns, and then electric field strengths were assessed as a function of distance. The next stage of the project involved the calculation and mapping of the body’s specific energy absorption rate (SAR) distribution due to RF signals produced by the devices when in close proximity to the body [Reference to part II].

Smart metering is a developing technology and although the main RF transmission parameters, such as frequency and output power, are broadly defined, some of the more detailed signal characteristics are still evolving. There is currently no universally agreed standard for the production of smart meter devices, and each country may use a different technical specification. Within GB, smart meter devices should comply with Smart Metering Equipment Technical Specifications (SMETS). All the exposure assessments carried out in this work are related to those of SMETS1 compliant devices [SMIPP, 2012] which utilize the ZigBee wireless standard operating at 2.4 GHz.

This paper reports the results of laboratory measurements carried out on a selection of smart meter devices provided by various manufacturers and utility companies during 2013–2015. In reporting the results, the manufacturers’ names and models are not identified and the devices are to be regarded as examples of typical equipment available in GB.

MATERIALS AND METHODS

Technical and Regulatory Standards for ZigBee Technology

SMETS1 compliant devices utilize ZigBee technology, which is based on the US Institute of Electrical and Electronics Engineers standard 802.15.4 [IEEE, 2011]. The IEEE 802.15.4 standard provides a set of communication protocols for low data rate, short range wireless networking with low transmission powers. In most ZigBee applications, the total time the wireless device is engaged in communication is very limited since the device usually remains in sleep mode. Devices periodically “wake up” to transmit and/or receive data, and transmission on- and off-periods depend on specific applications, the amount of data transmitted, and the set up configurations.

The IEEE 802.15.4 standard allows three frequency bands: 868 MHz, 915 MHz, and 2.4 GHz, with associated basic data rates of 20, 40, and 250 kbps, respectively. All the smart meter devices considered in this study operate at 2.4 GHz. The standard divides the 2.4 GHz band into 16 non-overlapping channels, which are 2 MHz wide and 5 MHz apart. The channels start with number 11 centered at 2.405 GHz and end with number 26 centered at 2.480 GHz.

The IEEE 802.15.4 standard does not set a limit on the transmission power; however, it states that devices should transmit lower power when possible in order to reduce interference with other devices and systems. In Europe, the transmit power of wideband devices operating at 2.4 GHz is restricted to a maximum equivalent isotropic radiated power (EIRP) of 100 mW [EN300328 ETSI, 2006]. However, the standard also limits power in terms of the spectral power density and states that for Direct-Sequence Spread Spectrum (DSSS) modulation, the maximum EIRP spectral power density is limited to 10 mW per MHz bandwidth. Since the power in the ZigBee waveform is effectively contained within about 1.5 MHz based on the half-power (3 dB) points in the
the transmit power of the ZigBee signal (EIRP) should not exceed about 15 mW. Figure 2 shows an example of a typical ZigBee waveform with the half-power bandwidth highlighted.

**Parameters Affecting People’s Exposure**

In assessing people’s exposure to RF EMF sources, the following parameters are normally considered:

**Output power.** For any given exposure scenario, the power absorption in body tissues is proportional to a device’s output power. Radiofrequency power density (watts per square meter) is also proportional to output power and electric field strength is proportional to the square root of output power. To protect the public against possible harmful effects of exposure to EMF, there are reference levels in terms of power density set by the ICNIRP. Therefore, an important focus of this study is to assess the output power of various smart meter devices during their normal operation.

**Frequency.** Radio waves become less penetrating in body tissues as frequency increases. The electric field component of a wave penetrating into the body reduces to 36% of its initial value after a distance known as the skin depth. Skin depth is inversely related to the square root of frequency and is larger at lower frequencies, corresponding to deeper energy penetration within the tissue. At higher frequencies, skin depth becomes much smaller, reflecting strong energy absorption.

**Distance.** The antennas inside smart meter devices are usually relatively small (a few cm in length) compared to the distance of a user from the device. This usually means that the exposure reduces very rapidly with increasing distance, broadly according to the inverse square law (far field region). Distance is therefore, an important factor to take into consideration in assessing exposure from smart meters, as the meters tend to be located much further away from the body than other RF devices such as mobile phones, which are normally used very close to head.

**Duty factor.** Another important consideration related to exposure is the proportion of time (duty factor) that radio devices are engaged in communication, that is, transmitting radio signals. In most ZigBee

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**Fig. 2.** Spectral Waveform of typical ZigBee signal ( waveform was generated in laboratory using a simulated ZigBee signal, showing main lobe envelope).
applications, the total time a device transmits tends to be quite limited as it is mostly in sleep mode, waking up periodically to transmit data. The duty factor increases when more data are transmitted in a given time period and when the selected modulation scheme encodes that data onto the RF signals more slowly, for example, if the RF signals are weak. ICNIRP exposure guidelines are based on power absorption in the body tissues averaged over 6 min. The duty factor of smart meter devices is expected to be very low and the time-averaged exposure will be far below that produced by a source continuously transmitting at the same peak power level.

**Devices Under Test**

The smart meter systems evaluated in this study consist of the following elements: Electricity Meter (EM), Communications Hub (CH), In-Home Display unit (IHD), and Gas Meter (GM).

The EM, GM, and IHD are configured to transmit packets to the CH which coordinates all the communication within the HAN. Some manufacturers have incorporated the CH within their EM, thus there is no wireless communication between these two parts of the system. The CH also provides the communication link with the utility company through the WAN.

Assessment of the exposure due to the WAN is outside the scope of this study.

Table 1 lists the devices tested in this work and the frequency channel assigned to each. In total, 39 SMETS1-compliant [SMIPP, 2012] smart meter devices, produced for the GB market by major manufacturers, were tested. The specific makes and models of the devices are not given; each device was assigned a unique reference number for use during the project. Some manufacturers supplied more than one sample of the same make and model; however, all the samples have been measured for comparison with each other and to investigate variation within the same model.

**Configuration of Devices Under Test**

The suppliers were asked to pre-configure the samples so that the EM/GM were paired with the IHD and CH units to form an HAN, and to communicate with each other as they are expected to in normal circumstances. The devices were pre-configured to transmit without having to seek a WAN connection to enable the measurements to be carried out in a controlled laboratory environment.

Within an HAN, the components of a smart meter system would normally communicate with each other roughly every 15 s. However, the transmissions are less frequent in the case of the GMs, and only occur every 30 min, in order to prolong their internal battery’s life for at least 10 years. This long period made it very difficult in practice to carry out the large number of measurements required to characterize the radiation pattern around each GM device. Therefore, the suppliers were asked to reduce the time period between each transmission to around 1–2 min for the supplied GM devices. This reconfiguration was done purely to facilitate the experimental measurements, and the reconfiguration was not considered in subsequent duty factor calculations. The power of individual transmissions was not expected to be affected, as the overall duty factor and consequent energy dissipation in the gas meter’s circuits would have remained small.

**Laboratory Equipment and Measurement Setup**

The first objective of the laboratory measurements was to systematically map the angular distribution of electric field strength around each smart meter device inside the shielded environment of an anechoic chamber. These measurements enabled the integration of the power flowing through a spherical surface enclosing each device to yield the radiated power. The angular direction in which the electric field strength was at a maximum was then identified and used for a series of additional electric field strength measurements as a function of distance.

The measurements were performed in an anechoic chamber with dimensions of $3.6 \times 2.4 \times 2.4$ m. The wooden walls of the chamber were lined internally with a foam-based radiofrequency absorber material (RAM) specified to have a reflection coefficient of $-20$ dB (1%) at 2.4 GHz. In order to maintain the HAN during measurements, the other ZigBee nodes were placed in the chamber but enclosed in absorber blocks to weaken the acknowledgment signals that these devices transmitted back to the device under test and limit their potential impact on the measurements.

To facilitate the angular electric field strength measurements, each meter device was mounted on a purpose-built manual positioning device that consisted of a turntable, which allowed rotation in two orthogonal planes such that the measuring antenna could sample the radiation pattern at any angle, as shown in Figure 3a, b. The turntable was supported by a pillar upon which a horizontal cradle was mounted. The turntable allowed for azimuth rotation and the cradle for elevation. For each device under test, the reference point of the rotational coordinate system was the center of the device, not the transmitting antenna inside the device, whose location was unknown.

The manual positioning system was made from a non-conducting material with a low dielectric
constant, while still providing the necessary rigidity. The pillar and turntable were made of Perspex (relative permittivity $\varepsilon_r = 3.4 - 3.8$), and the cradle was made of polycarbonate (relative permittivity $\varepsilon_r = 2.7 - 3.1$). The bearings and screws were made of nylon (relative permittivity $\varepsilon_r = 3 - 4$).

The electric field strength around the smart meter devices was measured using an Agilent N9020A MXA Signal Analyser (Keysight Technologies UK, Wokingham, UK) connected to a Q-Par horn antenna, and transmitted packets were captured with a packet capturing system, details of which are described in the following sections. The Q-Par horn antenna manufacturer reports a 3db beamwidth of 49° in the H plane and 54° in the E plane.

### Electric field antenna.

A Q-par horn antenna (model SL-2.2–3.3-N-10) was used for the electric field strength measurements. The antenna has a frequency range of 2.2–3.3 GHz and an aperture of 120 mm by 160 mm. The horn antenna was positioned at a predefined distance of 0.5 meters (m) from each sample to ensure that the transmitting device was within the main bore sight of the horn antenna and in the far field, for a frequency of 2.4 GHz. The 0.5 m distance between the measurement antenna and device under test was considered to be the best distance to achieve enough sensitivity to detect the incident signal while maintaining far field measurement conditions and minimizing any possible interference of signals reflected from the chamber walls.
The horn antenna was calibrated to traceable national standards by the National Physical Laboratory (NPL) at the frequencies of interest. The antenna was connected to the signal analyzer via a 5 m co-axial (RG400) cable. The loss of the cable was measured at the frequencies of interest using a calibrated Anritsu 37247D Vector Network Analyzer (VNA). Figure 4a and b show the antenna factor and cable loss over the frequency range of interest.

**Signal analyzer.** In a previous study, we argued against the use of a spectrum analyzer for exposure assessment purposes, mainly due to limitation in their maximum bandwidth [Peyman et al., 2011]. Instead, signal analyzers with a large bandwidth that could detect the whole signal were recommended. An Agilent N9020A MXA signal analyzer with a frequency range from 20 Hz to 8.4 GHz was used to make the measurements, using its Agilent 89601B Vector Signal Analysis (VSA) software (Keysight Technologies UK, Wokingham, UK) mode to allow demodulation and analysis of complex IEEE 802.15.4 waveforms. A bandwidth of 25 MHz enabled detection and demodulation of ZigBee signals.

**Packet capture software.** Packet Capture Software with associated ISA3 adapter (Ember Insight Desktop, Silicon Labs, Austin, TX) with associated hardware, installed on a dedicated laptop, was used to capture data traffic during the measurement program. The captured data provided detailed characteristics of the transmitted packets, including information such as time stamp, packet type, length of the packet (in bytes), and source address of the transmitting device.

The actual sniffer module was placed inside the anechoic chamber at a specific location away from the experimental setup and measuring antenna. The sniffer adaptor was configured to capture live packets transmitted over the air by choosing the select sniffer option at the carrier frequency.

The captured log files were used to determine the types of packets exchanged and their repetition frequencies. All the smart meter devices investigated, except the GMs, were configured as they would be used in real installations; therefore, these log files could be used to estimate the individual devices’ duty factors.

**Calibration Check of the Measurement Setup**

It is important to frequently check the integrity of any measurement system. At the beginning of each measurement session, the devices under test and measuring equipment were warmed up for 30 min to allow thermal equilibrium. The Agilent N9020A MXA signal analyzer has a traceable manufacturer’s calibration. As an additional measure, a signal generator was also used with a calibrated power meter to provide a daily confidence check throughout the measurement sessions.

A known signal was generated and measured before and after each measurement session. The procedure involved generating an Offset Quadrature Phase Shift Keying (OQPSK) modulated ZigBee profile which was then used to produce a known ZigBee waveform for measurements.

**ZigBee signal generation.** An Agilent E4438C Signal Generator (Keysight Technologies UK, Wokingham, UK) with a frequency range from 250 kHz to 4 GHz was used to generate an arbitrary waveform which emulates a ZigBee waveform, using SigWiz Signal generator software for IEEE 802.15.4 (Raon-Dols Technologies, Seoul, Republic of Korea). The software was installed on a computer connected to the Agilent E4438C signal generator via a LAN cable.

The ZigBee waveform consisted of 50 byte packets, transmitted every 192 μs with an output power of 0 dBm. The modulation scheme was OQPSK using a carrier frequency of 2.450 GHz.

**Power meter.** An Agilent E4418B Power Meter (Keysight Technologies UK, Wokingham, UK) provided average power measurements from −30 to +20 dBm. An Agilent 8482A Power Sensor Head (Keysight Technologies UK) operating at a frequency range of 100 kHz – 4.2 GHz covered the range required for smart meter devices operating at 2.4 GHz. The power meter and sensor head were calibrated by the manufacturer to traceable standards, thus allowing
an independent check on MXA measurements through a device with lower measurement uncertainty.

Prior to making the measurement, the power meter was calibrated by connecting the power meter sensor head to the internal power source of the power meter at 2.450 GHz.

The output of the generated ZigBee signal was also measured with the Agilent MXA signal analyzer running VSA 89601B. A connection from the output of the signal generator to the MXA was made via an Agilent N631A Test Port Cable (Keysight Technologies UK) with a known cable loss. The loss of the cable was measured at the frequencies of interest using a calibrated Anritsu 37247D VNA. The MXA was used to demodulate an OQPSK signal and then the spectrum power and burst power were measured. In addition, the quality of the signal was assessed using the constellation diagram and error vector magnitude (EVM).

These measurements were performed at the start and end of each laboratory measurement session to monitor any changes due to the instrument drift throughout the day.

Fig. 4. (a) Q-Par horn antenna factor and (b) 5 metre RG400 Cable Loss in 2.4 GHz frequency band.
Electric Field Strength Measurements Around the Devices Under Test

The main parameter of interest in this study was the electric field strength measured in two orthogonal directions: x, y. The electric field strength component projected along the line connecting the center of the manual positioning system and probe (defined as the z-axis) was assumed to be negligible, given that the distance between the emitting device and probe was much larger compared to the size of the internal antenna and possible displacement of the antenna from the center of the coordinate system during rotation. The angular electric field strength pattern around each device was first established. The angle at which the resultant radiated electric field was at a maximum was then used to perform additional electric field strength measurements as a function of increasing distance away from the device.

Angular distribution of electric fields around smart meter devices. The electric field strength around each smart meter device was measured in two polarizations (horizontal and vertical) and the results were calculated. Figure 5 shows the spherical coordinates used for rotational measurements. The measurements were repeated for different combinations of azimuth and elevation rotation on the manual positioning system: Azimuth rotation (θ), starting from 0° and followed by 30° steps to complete a whole circle (12 positions); elevation rotation (ϕ), starting from 0° and followed by 30° steps to complete a whole circle (12 positions).

That combination was chosen to balance the number of measurements required to establish the electric field pattern and time available to assess each device. It resulted in a total of 288 (144 × 2) measurements. Once a complete set of spherical measurements had been carried out, the resultant field strength was calculated as the Root Sum of Squares (RSS) value of horizontal and vertical values at each position. This established the angular distribution of electromagnetic fields from each smart meter device. The power density over a surface enclosing each device was then integrated to yield the integrated radiated power (IRP). The angular direction where the power density was greatest was identified, and finally the equivalent isotropically radiated power (EIRP) in that direction was determined.

Electric field strength as a function of distance. Following the spherical measurements, the device under test was positioned at the angle that produced the maximum field strength, and measurements were carried out as a function of distance, in 10 cm steps ranging from 0.5–1.7 m.

Duty Factor Calculations

Ember Insight Desktop “sniffing” software was routinely used during the laboratory assessment of electric field around HAN devices (except the gas meters) in the anechoic chamber. The sniffing software recorded all ZigBee wireless communication packets occurring in a known channel at a given location within a given time frame (sampling time was at least 2 h). Once the ZigBee packets had been collected, the Ember software gave the “Source Address” and “Number of Bytes” for each packet and this information, together with a known ZigBee data transmission rate, allowed the duration of each packet to be calculated. By summing the packet durations associated with a particular source and comparing it with the total time frame, it was possible to calculate the duty factor for the source.

GMs are typically configured to transmit every 30 min in normal situations in order to enhance battery life. However, as described before, this poling period was reduced for the laboratory measurements in order to shorten the measurement time. For this reason, the log files captured in the laboratory for gas meter devices could not be considered to determine typical duty factors.

Measurement Uncertainty

The measurement devices used in this study either had a traceable manufacturer’s calibration, or were calibrated to national standards by the UK National Physical Laboratory (NPL). However, as...
with any physical quantity, measurement of electric field strength is associated with a number of uncertainties. Therefore, a simple uncertainty budget was drawn up, taking into consideration different sources of errors. Different elements of uncertainty that would affect the measurement setup were identified and assigned an appropriate statistical distribution and then used to calculate the total combined uncertainty. The uncertainty budget presented in Table 3 was drawn up in accordance with established guidelines [NIST, 1994; UKAS, 2002].

### Processing of Experimental Data

The raw data were converted to electric field strength using the following calculations [NPL, 2004]:

\[
E = V + AF + ATT
\]

where \( E \) is the electric field strength (dB \( \mu \text{V/m} \)), \( V \) is the measured voltage (dB \( \mu \text{V} \)), \( AF \) is the antenna factor (dBm \( \mu \text{V/m} \)), and \( ATT \) is the cable attenuation (dB). Substituting for \( V \) and including the attenuation of cable for the measurement antenna in the antenna factor, Equation (1) can be rewritten as:

\[
E = 107 + P + AF
\]

where \( P \) is the measured power (dBm).

Power density and radiated power were then calculated using the following equations:

\[
S = \frac{E^2}{377}
\]

where the unit of \( S \) is Wm\(^{-2} \) and \( E \) has now been converted to linear units.

To compare the emission levels from devices to limits in technical standards, equivalent isotropically radiated power (EIRP) values were also calculated. EIRP is the power that would have to be emitted if the antenna were isotropic in order to produce a power density equal to that observed in the direction of maximum gain of the actual antenna. In this study the EIRP was calculated using the maximum measurement of power density:

\[
\text{EIRP} = 4.\pi r^2 S_{\text{max}}(r)
\]

where EIRP is in units of \( W \), \( r \) is the distance to the antenna in meters, and \( S_{\text{max}}(r) \) is the maximum power density measured at that distance, in Wm\(^{-2} \).

For real antennas, which are not isotropic, the EIRP is greater than the true radiated power by an amount known as the antenna gain. The total radiated power was evaluated by integrating the power flowing through a spherical surface enclosing the device. Therefore, to calculate the integrated radiated power (IRP) the power density at each measurement point is multiplied by the area of the spherical surface that it represented:

\[
S_{\text{tot}} = \sum_i \sum_j A(\theta_i, \phi_j) \cdot S(\theta_i, \phi_j)
\]

where \( S(\theta_i, \phi_j) \) is the measured power density at each position and \( A(\theta_i, \phi_j) \) is the area represented by that sample.

### Measurement Results

Figure 6a–d show the power density distribution, in spherical coordinates, for one example of each type of the measured devices (EM, GM, IHD, and CH). The angular coordinate system used to display the radiation pattern is presented in Figure 5. Table 3 contains the maximum recorded value of power density at 0.5 m for each device. The angles \( \theta \) and \( \phi \) define the position at which the maximum power density value is recorded. The correspondent EIRP and spherically integrated radiated power (IRP) values calculated for each device at 0.5 m are also included in Table 3.

Figure 7a–d show power density values calculated from maximum electric field strength as a function of distance for the smart meter devices measured in this study. The solid curves represent the power density calculated from a theoretical antenna having an EIRP equal to 15 mW (as the limit implied by the ETSI [2006] harmonized technical standard). Error bars are not included for clarity; however, measurement uncertainties are evaluated as shown in Table 2. Numerical values of power density at selected distances are also summarized in Table 4. Finally, Table 5 contains calculated levels of power density taking into account the recorded duty factors for each smart meter device.

### DISCUSSION

#### Variation of Measured Power Density

Power density levels were recorded for each smart meter device as it was rotated in front of the measuring probe. Peaks and troughs in power density could be seen reflecting the inherent radiation pattern of the transmitting antenna and its...
(unknown) displacement from the center of rotation, causing it to approach and recede from the measuring probe. The measurements could also be affected by various metallic non-transmitting parts of the device moving between the antenna and probe during rotation.

The recorded power densities showed appreciable variation in strength as differing positions were considered. However, when a set of measurements was repeated for a particular device, there was good agreement between data sets in respect of the position and strength of peak levels. Discrepancies in position and size of peaks were more noticeable with IHD units than with other components. Moreover, there was good agreement in the power levels emitted by duplicate devices of same make and model. This wasn’t the case for different makes of the same type of device where there was appreciable variation in the emission levels (see Table 3).

For all devices assessed, the maximum power density recorded ranged from 0.17 to 15 mW/m² at 0.5 m, with the exception of one “outlier” device (EM05) that had a power density of 91 mW/m².

**Emission Levels**

For all the EMs measured, the EIRP ranged from 0.54 to 17 mW (except that of EM05 which had EIRP of about 290 mW), for CHs from 8.8 to 48 mW, for IHDs from 1.4 to 24 mW, and for GMs from 12 to 16 mW.

For EMs the IRP levels ranged from 0.12 to 2.9 mW (with the exception of EM05 which had an IRP of 53 mW), for CHs from 1.4 to 16 mW, for IHDs from 0.21 to 5.0 mW, and for GMs from 2.4 to 4.0 mW.

The good agreement in IRP levels for sets of devices of the same make and model points to reproducibility in device specification and
manufacture as well as a consistent measurement methodology.

As shown in Table 3, all EMs (except one model), GMs, and IHDs (except two models) had EIRP values within or close to the limit of 15 mW implied by the ETSI EN 300 328 technical standard. EIRP values obtained for communication hubs considered in this study were generally a few times higher than for other devices within the HAN and above the 15 mW limit.

The calculated EIRP for one electricity meter (EM05) was several orders of magnitude higher than that of other devices. This could be due to special design considerations and amplifiers being added to the circuit for power enhancement. It is also important to note that the measurement protocol used in this work did not follow the precise testing schedule required under the emission standards mentioned earlier (EN300328). The EIRP limit in the ETSI standard is based on spectrum efficiency considerations, rather than health.

Radiation Pattern

Graphical representations of the radiation patterns for a few examples of different smart meter devices are shown in Figure 6a–d. The other devices (not shown in the paper) produce similar patterns. About half of the devices of the same make and model produced similar directions of maximum power density (i.e., θ and φ). The other devices of the same model produced different directions of maximum power density. This may be due to the fact that in these particular cases there was more than one lobe in the radiation pattern of only slightly different amplitude such that a slight change in measurement position could alter which lobe is dominant.

Variation of Power Density as a Function of Distance

Systematic measurements as a function of distance showed that, beyond 0.5 m distance, the decay of power density levels around smart meter devices approximated to an inverse square law, as shown in Figure 7a–d.

Fig. 7. Variation of power density as a function of distance for all measured (a) electricity meters (except EM05), (b) gas meters, (c) communication hubs, and (d) in-home displays. Power density calculated from an EIRP equal to 15 mW is also shown for comparison.
It is difficult to visually separate some of the curves in the graphs presented in Figure 7a–d; nevertheless, the results show that all five EM06 devices and EM01 produced more or less similar power density, so they are grouped together. The fall off with distance is also similar for EM06 and EM01 devices, though for those with smaller power density this trend is harder to observe in the plotted graph with the linear Y axis.

Equations for power trend lines (not shown here) have exponents ranging from $1.78$ to $2.29$. Reasons for departure from a perfect inverse square law would have included displacement of the antenna from center of the coordinate system and some influence of reflections, possibly from the turntable.

Taking into account the uncertainty values calculated in Table 2, it is clear that some of the highest EIRP values recorded could be above the $15 \text{ mW}$ emission limit. However, this work was not performed as part of an accreditation process and, as explained before, the measurement protocol used in this work did not follow the precise testing schedule required under ETSI emission standards.

Power density measurements at selected distances are shown in Table 4. The values recorded at $0.5 \text{ m}$ are comparable with those carried out during the spherical measurements, within estimated uncertainty levels.

**Duty Factor Considerations**

It is important to note that the duty factors estimated in this study were evaluated during the assessment of the smart meter devices in the anechoic chamber under laboratory conditions. Duty factor values were obtained over a given period of time (minimum of $2 \text{ h}$). This approach represents an idealized situation where there are no interruptions to the working HAN once communication had been established and there are no corrupted/lost data needing to be retransmitted. The number of devices within each HAN varied in each measurement scenario; some had only two and others up to four devices connected together. For practical reasons, in this work gas meters were configured to emit more frequently (every $2 \text{ min}$ instead of the typical $30 \text{ min}$). Therefore, the duty factor values recorded for gas meters are significantly (about 15-fold) overestimated.

For the majority of the devices considered in this study, the duty factor was well below $1\%$, although a few devices had duty factors up to a maximum of $1\%$. These figures are in line with other values reported in the literature that suggest the duty factor of individual smart meter devices tends to be less than $5\%$ and more usually $1\%$ [Girnara et al., 2011; Tell et al., 2012a,b].

Applying the calculated duty factors to the maximum recorded power density data yields a more realistic representation of typical power density for smart meter devices as shown in Table 5 (note the change in power density unit from mWm$^{-2}$ to $\mu\text{W m}^{-2}$). Taking into account the estimated duty factors, and excluding EM05, calculated power densities for all devices range from $0.2$ to $26 \mu\text{W m}^{-2}$.

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**TABLE 2. Elements of Uncertainty and the Total Combined Uncertainty Associated With the Measurements of Electric Field Strength Around Smart Meter Devices Operating at 2.4 GHz [NIST 1994; UKAS 2002].**

| Source     | Parameter                        | Specific uncertainty (dB) | Distribution | Division factor | Standard uncertainty | Reference               |
|------------|----------------------------------|---------------------------|--------------|----------------|----------------------|-------------------------|
| MXA        | Frequency response               | 0.055                     | Normal       | 2              | 0.028                | Calibration certificate |
| MXA        | Absolute amplitude accuracy      | 0.073                     | Normal       | 2              | 0.037                | Calibration certificate |
| MXA        | Display scale fidelity           | 0.022                     | Rectangular  | 1.65           | 0.013                | Calibration certificate |
| MXA        | IF amplifier                     | 0.044                     | Normal       | 2              | 0.022                | Calibration certificate |
| MXA        | Power bandwidth accuracy         | 0.005                     | Normal       | 2              | 0.003                | Calibration certificate |
| MXA        | Drift                            | 0.747                     | Rectangular  | 1.73           | 0.432                | Estimate                |
| Antenna    | Antenna factor at 1m             | 0.800                     | Normal       | 2              | 0.400                | Calibration certificate |
| Antenna    | Positioning error$^a$            | 0.400                     | Rectangular  | 1.73           | 0.231                | UKAS LAB34 & estimate   |
| Cable      | Cable loss                       | 0.150                     | Normal       | 2              | 0.075                | Anritsu 37247D data sheet |
| Mismatch   | Signal reflection at junctions   | 0.082                     | U shaped     | 1.41           | 0.058                | MXA data sheet & antenna’s Calibration certificate |

Combined standard uncertainty (dB): 0.64
Expanded uncertainty ($K = 1.96$) (dB): 1.26

$^a$Positioning error includes the distance from manual positioning system (0.1 dB), height (0.1 dB), and alignment (0.2 dB).
Comparison With Exposure Guidelines and Mobile Phone Exposure

All power density measurements reported in this study (including those carried out radially at distances of 0.5–1.7 m from devices) were well below the 10 W m$^{-2}$ ICNIRP reference level (Tables 3 and 4), and exposures would be even lower if the spatial and time averaging advised by ICNIRP are taken into account.

The location of the user has not been taken into account explicitly in how electric field strengths around smart meter devices have been measured. Explicit consideration of the user position in assessing exposures was conducted in the computer modeling part of this project, which forms another publication.

To consider the results in a wider context, comparison is made with exposure arising from the use of mobile phones and Wi-Fi devices, which are commonly used wireless communication technologies. In making this comparison, we consider three main factors affecting people’s exposure to radio-frequency sources: the output power of the device, duration of exposure, and proximity to the body during use.

Mobile phones have greater maximum transmit powers than Wi-Fi and smart meter devices. Second generation (2G) Global System for Mobile Communications mobile phones have maximum (peak) powers of 1 or 2 W according to frequency band. However, each device is given an ID and similar makes and models are grouped together.

### TABLE 3. Maximum Recorded Value of Power Density, EIRP, IRP at 0.5 m and Corresponding Coordinates for all Measured Smart Meter Devices

| Device under test ID | Max power density (mW m$^{-2}$) | Coordinates ($\theta, \phi$) | EIRP (mW) | IRP (mW) |
|----------------------|-----------------------------|-------------------------|--------|--------|
| EM01                 | 0.21                        | 150,120                 | 0.67   | 0.15   |
| EM06-1               | 0.23                        | 240,0                   | 0.71   | 0.16   |
| EM06-2               | 0.29                        | 210,300                 | 0.92   | 0.16   |
| EM06-3               | 0.22                        | 120,180                 | 0.70   | 0.15   |
| EM06-4               | 0.17                        | 210,300                 | 0.54   | 0.12   |
| EM06-5               | 0.26                        | 210,300                 | 0.83   | 0.16   |
| EM02                 | 2.17                        | 150,180                 | 6.83   | 1.23   |
| EM05                 | 91.06                       | 60,240                  | 286.08 | 52.71  |
| EM03-1               | 4.14                        | 60,240                  | 13.02  | 2.52   |
| EM03-2               | 5.31                        | 60,240                  | 16.67  | 2.90   |
| EM04-1               | 4.18                        | 60,240                  | 13.14  | 2.65   |
| EM04-2               | 3.89                        | 60,240                  | 12.23  | 2.48   |
| CH02                 | 2.81                        | 210,270                 | 8.83   | 1.37   |
| CH01                 | 9.98                        | 90,300                  | 31.37  | 9.99   |
| CH06-1               | 11.46                       | 270,60                  | 36.01  | 13.42  |
| CH06-2               | 10.32                       | 90,240                  | 32.41  | 8.83   |
| CH06-3               | 15.37                       | 270,60                  | 48.28  | 15.60  |
| CH06-4               | 10.19                       | 270,60                  | 32.01  | 11.12  |
| CH06-5               | 8.47                        | 270,60                  | 26.61  | 9.12   |
| IHD01                | 0.65                        | 60,180                  | 2.03   | 0.35   |
| IHD06-1              | 0.67                        | 60,180                  | 2.09   | 0.30   |
| IHD06-2              | 0.56                        | 60,180                  | 1.74   | 0.32   |
| IHD06-3              | 0.55                        | 60,180                  | 1.71   | 0.29   |
| IHD06-4              | 0.58                        | 60,180                  | 1.83   | 0.29   |
| IHD06-5              | 0.45                        | 60,180                  | 1.42   | 0.21   |
| IHD02                | 1.30                        | 210,180                 | 4.07   | 0.68   |
| IHD05                | 0.60                        | 120,270                 | 1.90   | 0.52   |
| IHD03-1              | 3.84                        | 90,60                   | 12.05  | 2.53   |
| IHD03-2              | 2.67                        | 120,60                  | 8.40   | 1.97   |
| IHD04-1              | 7.68                        | 210,240                 | 24.14  | 4.99   |
| IHD04-2              | 6.96                        | 210,180                 | 21.86  | 4.77   |
| GM05                 | 5.09                        | 30,270                  | 15.99  | 3.69   |
| GM04-1               | 3.91                        | 270,90                  | 12.27  | 2.35   |
| GM04-2               | 4.00                        | 270,90                  | 12.58  | 2.35   |
| GM06-1               | 4.14                        | 240,120                 | 13.00  | 3.61   |
| GM06-2               | 4.12                        | 240,120                 | 12.95  | 3.92   |
| GM06-3               | 3.78                        | 240,150                 | 11.87  | 3.14   |
| GM06-4               | 4.48                        | 240,120                 | 14.09  | 3.62   |
| GM06-5               | 5.05                        | 240,120                 | 15.86  | 3.98   |

Each device is given an ID and similar makes and models are grouped together.
they use Time Division Multiple Access (TMDA), in which one out of eight time slots is used for transmission, resulting in a maximum time-averaged output power during calls of either 125 or 250 mW. Third Generation (3G) phones transmit continuously during calls with a maximum of 250 mW power. Wi-Fi devices have maximum licensed transmit powers of either 100, 200, or 1000 mW according to frequency band. No minimum power is specified and practical experience is that the device powers are lower than the licensed maxima. Smart meter devices, on the other hand, are limited to the maximum transmit power of no more than 15 mW for HANs. Furthermore, these devices are not allowed to transmit continuously, as demonstrated in this study in which the duty factor of the individual devices is shown to be less than 1%.

As mentioned before, the recorded EIRP value for one device (EM05) was significantly higher than the 15 mW limit. This, however, does not imply any health-related concern as exposures will be much smaller than the ICNIRP guidelines’ limit. The emitted power during transmission for EM05 is comparable to that of a mobile phone when transmission occurs, but the duty factor is much smaller. Moreover, distance from the body will be much smaller.

| Device under test ID | Power density (mWm⁻²) | Duty factor recorded over minimum of 2h (%) | Calculated power density (µWm⁻²) |
|----------------------|-----------------------|------------------------------------------|---------------------------------|
| EM01                 | 0.21                  | 0.31                                     | 0.65                            |
| EM06-1               | 0.23                  | 0.10                                     | 0.23                            |
| EM06-2               | 0.29                  | 0.10                                     | 0.28                            |
| EM06-3               | 0.22                  | 0.09                                     | 0.21                            |
| EM06-4               | 0.17                  | 0.12                                     | 0.20                            |
| EM06-5               | 0.26                  | 0.13                                     | 0.33                            |
| EM02                 | 2.17                  | 1.06                                     | 23.02                           |
| EM05                 | 91.06                 | 0.23                                     | 207.62                          |
| EM03-1               | 4.14                  | 0.126                                    | 5.22                            |
| EM03-2               | 5.31                  | 0.398                                    | 21.13                           |
| EM04-1               | 4.18                  | 0.129                                    | 5.39                            |
| EM04-2               | 3.89                  | 0.124                                    | 4.82                            |
| EM06-1               | 2.81                  | 0.90                                     | 25.23                           |
| EM06-2               | 9.98                  | 0.24                                     | 24.25                           |
| EM06-3               | 11.46                 | 0.116                                    | 18.11                           |
| EM06-4               | 10.32                 | 0.05                                     | 4.64                            |
| EM06-5               | 13.57                 | 0.17                                     | 25.98                           |
| EM02                 | 10.19                 | 0.16                                     | 16.57                           |
| EM05                 | 8.47                  | 0.18                                     | 15.58                           |
| EM03-1               | 0.65                  | 0.09                                     | 0.56                            |
| EM03-2               | 0.67                  | 0.09                                     | 0.56                            |
| EM04-1               | 0.56                  | 0.11                                     | 0.61                            |
| EM04-2               | 0.55                  | 0.08                                     | 0.46                            |
| EM06-1               | 0.58                  | 0.13                                     | 0.77                            |
| EM06-2               | 0.45                  | 0.09                                     | 0.38                            |
| EM06-3               | 1.30                  | 0.54                                     | 7.07                            |
| EM06-4               | 0.60                  | 0.13                                     | 0.80                            |
| EM06-5               | 3.84                  | 0.10                                     | 3.72                            |
| EM02                 | 2.67                  | 0.41                                     | 10.81                           |
| EM05                 | 7.68                  | 0.10                                     | 7.60                            |
| EM03-1               | 9.69                  | 0.10                                     | 6.75                            |
| EM03-2               | 5.09                  | 0.01                                     | 0.41                            |
| EM04-1               | 3.91                  | 0.02                                     | 0.59                            |
| EM04-2               | 4.00                  | 0.01                                     | 0.56                            |
| EM06-1               | 4.14                  | 0.02                                     | 0.62                            |
| EM06-2               | 4.12                  | 0.01                                     | 0.58                            |
| EM06-3               | 3.78                  | 0.01                                     | 0.49                            |
| EM06-4               | 4.48                  | 0.04                                     | 1.79                            |
| EM06-5               | 5.05                  | 0.02                                     | 0.76                            |
greater than from a phone, with typically installed systems leading to much lower exposures.

Exposure from smart meter devices in general is likely to be significantly lower than that from mobile phones and lower than from Wi-Fi devices because the antennas will tend to be further away from the body. The highest exposures would arise from mobile phones when the phone is used next to the head, as is normally the case, but such a situation is difficult to conceive of with smart meters.

CONCLUSION

This study represents the first comprehensive evaluation of RF EMFs produced by smart meter devices to be installed in homes in GB. The maximum value of power density measured around all smart meter devices at 0.5 m and beyond was well below the 10 Wm$^{-2}$ ICNIRP reference level. Beyond 0.5 m distance, the decay of power density levels around smart meter devices approximated to an inverse square law. This is expected and is an important factor to consider when evaluating exposure of people who have the devices in their homes.

The data collected in this study are reassuring in that they demonstrate that the exposure from smart meter devices is likely to be lower than that resulting from everyday devices such as mobile phones and Wi-Fi equipment, mainly because of very low duty factor values and greater distance of the transmitting antennas from the body.

Some devices had EIRP values above the 15 mW emission limit in harmonized standards. However, these values have no health-related consequence as this limit is based on technical rather than health considerations. One device had a significantly higher transmit power level than all of the other devices, but even the power of that device was only comparable with that from a mobile phone (about 250 mW).

For all HAN devices considered, the duty factor ranged from below 0.1 to 1% of the total time. These findings are in line with values given in other studies where the duty factor estimates of operating smart meters were generally less than 1% with an absolute maximum less than 5%.

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