



Ambient RF energy harvesting trial in domestic settings

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Abstract: This study investigates the feasibility of ambient radio frequency (RF) energy harvesting for powering low-power electronic devices, in domestic environments. An RF spectrum survey was carried out in a variety of locations around the city of Bristol, UK between 500 MHz and 6 GHz. Locations are limited to indoor residential environments, and as a comparison an office. The measurement setup consists of an omnidirectional, broadband, discone antenna and a handheld spectrum analyser. On the basis of the measured power consumption of a number of low-power electronic devices and the analysed results, the required harvesting time to power each device is calculated. The results show that in order to harvest enough energy to power-up a small calculator ($2 \mu\text{W}$) for 1 s, an antenna array covering 1.7–2.5 GHz with effective area of 1 m^2 requires on average about 10 min of harvesting.

1 Introduction

As minimisation of power consumption and energy autonomy of devices becomes more important, means of prolonging battery life in mobile and low-power devices are becoming increasingly appealing. Energy harvesting from ambient energy sources, such as solar, thermal, radio frequency (RF) energy etc. is attracting attention as it can potentially complement batteries or replace them completely in some applications [1]. In comparison with other means of harvesting ambient energy, RF could be beneficial in environments where solar or other renewable energy sources are not available, such as inside buildings or where the orientation of the harvester cannot be controlled. In applications where a communication device's antenna is already present, there is the possibility of using the existing element for harvesting RF energy.

Ambient RF energy is present in urban and sub-urban environments because of the large number of telecommunication base stations (BST) and high-power digital television (DTV) transmitters present. The density of these sources, and consequently ambient power densities, can vary significantly between locations, especially if the presence of mobile user devices, wireless fidelity (WiFi) access points and domestic appliances such as microwave ovens are taken into consideration.

A number of studies have been carried out to investigate the feasibility of harvesting such ambient energy. Typically, these have looked at office or very dense urban environments [2–5], without addressing the issue of transmitter density in those locations. In [3], the WiFi access point used as an RF source was heavily loaded to determine the power density upper bound. The power densities measured in these environments were shown to be

promising. A thorough assessment of the power density in a variety of scenarios and distances was performed in [6], but was limited to (global system for mobile communications) GSM900/1800 and WiFi bands. Other work has focused on the medium wave range (909 kHz) to benefit from the large transmit powers and low path loss at those frequencies [7, 8] or extremely large transmit powers up to 1 MW over a short distance (a few kilometres) to scavenge tens of microwatts (μW) [9].

Many rectenna circuits have been reported in the literature for a variety of applications from dedicated, near-field power transfer to ambient RF energy harvesting. In general, they can be classified as wireless power transfer systems [10–12] and narrowband or broadband ambient RF energy scavengers [2–9, 13, 14]. The survey performed in this paper is concerned with the latter. The main distinction between the different systems is the reliance on dedicated or random sources of energy (ambient energy). The second is more challenging because of the unknown environments these systems might operate in, and the very low-power densities available.

The focus of this paper is to conduct a survey in semi- and sub-urban domestic environments over a broad range of ultra high frequency (UHF) and microwave frequencies and determine whether RF energy harvesting technology is able to provide sufficient energy to power-up useful, low-power electronic devices. Secondly, it will determine under what restrictions or conditions this may be practical. The contribution of this paper is to look into typical, domestic environments where the ambient power density is expected to be lower than that usually reported in the literature. Additionally, measurements were performed in an office, located in central Bristol, as a reference. This paper is organised as follows: Section 2 gives an overview of the conducted work, the methodology and the choice of survey

antenna. Section 3 presents the measured performance of the survey antenna, whereas Section 4 gives the RF power density at the locations considered and details of the measurement environments. In Section 5, the results are discussed drawing on useful observations related to the design of rectennas before concluding this paper.

2 Bristol ambient RF energy survey

Predicting ambient RF power density even while having knowledge of many critical parameters, such as the distance from the transmitter, transmit power and frequency, is a complex task. Such a task would require the use of accurate path loss models which are usually acquired from complex analytical models or experimental measurements. The situation is further complicated by the presence of multiple sources and the large range over which path loss exponents vary depending on the environment being considered [15]. As a result there exists no general answer. For that reason, it is preferable to conduct ambient power density measurements in a variety of locations and environments to obtain a clearer idea of the available levels.

In this paper, the level of RF power density present in urban, semi- and sub-urban Bristol, UK was quantified by conducting a survey in the UHF and lower super high frequency spectrums occupied by many communication bands. A survey of frequency spectrum usage in the area has been reported in 2001 [16], but that looked only at the peak powers and as such the results cannot provide any useful information in the context of this paper. For the current survey measurements were collected, without interruption, at each location over several days. The details of the methodology are described in Section 2.1.

For each measurement site, location maps of telecommunication and digital video broadcasting-terrestrial (DVB-T) transmitter positions were constructed. The information for the positions of the transmitters in the vicinity, and approximate transmission powers/bands, were found using Ofcom's sifinder tool [17]. Ofcom is the communications regulator in the UK. Although the data available in their database were last updated in mid-2012, they still provide a useful reference to determine the density of transmitters in a certain geographical area.

Floor plans of the measurement sites are also presented, showing the location of the sensing antenna and additional RF sources such as microwave ovens, WiFi access points etc. The floor plans, together with the geographical maps, will allow a better insight in the dominant sources of RF energy.

2.1 Methodology

Measurements were taken at each location over several days during February 2014 using an (Rohde and Schwarz) R&S FSH8 portable spectrum analyser. Each measurement was recorded with its own individual time stamp. A broadband, omnidirectional, discone antenna working over 0.5–6 GHz was designed and characterised for use in the field measurements. More details and measurements of the antenna are presented in Section 3.

The analyser was configured with a start and stop frequency of 0.5–6 GHz, respectively, and with fixed resolution bandwidth of 30 kHz and video bandwidth of 3 MHz. 'Trace mode' was set to 'Clear/Write' so that the maximum levels would not mask the instantaneous power over the measurement period as with the 'Max/Hold'

setting. Although this can lead to an underestimation of RF power levels – especially for transient signals such as OFDM modulated signals – it was preferred over the commonly used Max/Hold function that can sometimes overestimate the available power [2].

The maximum number of points that the analyser can record is 631 and the detector type was set to root mean square (RMS). This means that with the resolution bandwidth set to 30 kHz and the selected span, a total of about 190 thousand points were measured. The RMS value was automatically calculated over blocks of 300 points to reduce the number to 631. The amplitude reference was set to -30 dBm and the pre-amplifier was enabled. The measurement time interval was set to 2 min for all measurements.

The antenna power factor and cable losses were calculated and their effect removed from the measurements. The effective area of the antenna was estimated and is later used to infer the necessary operation to harvest time ratio for a few selected applications. Finally, a vertical orientation of the antenna was used throughout all measurements, in contrast with the evaluation of three orthogonal orientations reported in [2]. This was preferred as there was no major variation observed in the available power between different orientations during the reference office trial presented in Section 4.1.

2.2 Frequency bands

The frequency bands of different communication standards, as they are referred to and used throughout this paper, are summarised in Table 1. These are in-line with previously reported studies in order to facilitate comparisons [2]. The uplink (mobile terminal) and downlink (base station) bands were treated separately and are denoted by MTx and BTx, respectively. Microwave ovens, present at some of the sites, are marked in the floor layouts. Their operation frequency falls within the WiFi low band. Even though they are mentioned here, there was no evidence that radiation from microwave ovens was detected in the measurements because of their distance from the sensing antenna. Other studies have shown that useful energy can be harvested from the leaked microwave field of commercial ovens, if the harvesting antenna is near the microwave oven door (5 cm) [18].

Regarding the fourth generation (4G) service in the UK, which is not included in Table 1, the 800 MHz and 2.6 GHz bands were auctioned for use with 4G by Ofcom in early 2013. Later that year it was also announced by the regulator that operators could repurpose their GSM and 3G spectrum to deliver 4G services and also increase the maximum base station output power by 3 dB [19]. Given that 4G is available in Bristol by some operators, but no power densities were observed at 800 MHz or 2.6 GHz, we assume that 4G is delivered through the existing GSM and 3G bands, at the time of the trials.

Table 1 Frequency bands and ranges

	Band	Frequency, GHz	Notes
DTV		0.47–0.79	
GSM 900	MTx	0.88–0.915	uplink
	BTx	0.925–0.96	downlink
GSM 1800	MTx	1.71–1.785	uplink
	BTx	1.805–1.88	downlink
3G	MTx	1.92–1.98	uplink
	BTx	2.11–2.17	downlink
WiFi	low	2.4–2.5	
	high	5.5–5.6	

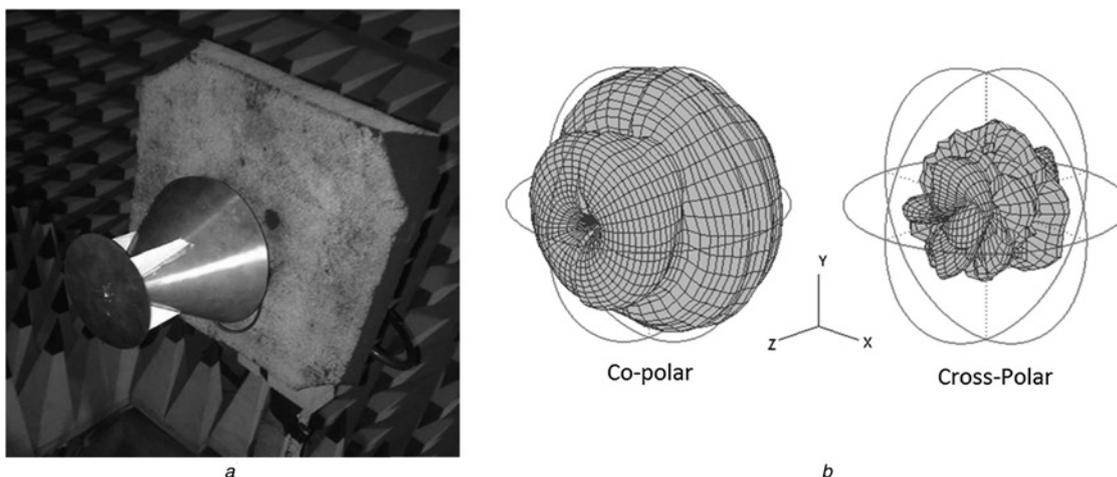


Fig. 1 Discone antenna used during the study

a Antenna photograph

b 3D radiation patterns at 2.5 GHz in the same orientation of the discone antenna used during the study

3 Survey antenna measurements

For the purpose of the survey, an in-house antenna was developed, built and characterised. In contrast to using a commercially available antenna [2], a custom design gives extra flexibility, allows covering specific frequency bands of interest as well as tailoring other aspects of the design such as avoiding dielectric loading and geometry. A discone antenna was chosen because of its stable broadband performance across the wide range of frequencies required for this survey. It was chosen because of its stable broadband performance across the wide range of frequencies required for this survey. In Fig. 1*a*, the antenna is shown in an anechoic chamber during radiation pattern measurement. The antenna has a frequency-stable omnidirectional radiation pattern typified by the three-dimensional (3D) radiation patterns shown in Fig. 1*b* at 2.5 GHz. The measured directivity of the antenna shown in Fig. 2*a* confirms the stability of the patterns, varying by ~ 4.5 dBi across the frequency range 0.5–6 GHz and being relatively flat above 3 GHz. All power density measurements were taken with the antenna orientated with

the z -axis in the vertical plane unless otherwise stated. The 2D radiation patterns at a selection of frequencies are shown in Appendix.

The S_{11} of the antenna shown in Fig. 2*b* also demonstrates the wideband nature of the discone. The -10 dB bandwidth starts at 500 MHz and extends beyond 6 GHz. Across this frequency range the antenna will have sufficient sensitivity for purposes of this study.

An antenna factor (AF) has been calculated to convert the power (P_r) in decibel-milliwatt (dBm) measured with the spectrum analyser into an RF power density (S) in dBm/cm² at the antenna using the formula

$$S = P_r + \text{AF} \quad (1)$$

All values are in decibel (dB). At a particular frequency (ω) the AF is calculated by

$$\text{AF} = -[10 \log [A_{\text{eff}} [1 - |\Gamma|^2]] - C_{\text{dB}}] \quad (2)$$

In (2), Γ is the reflection coefficient of the measurement

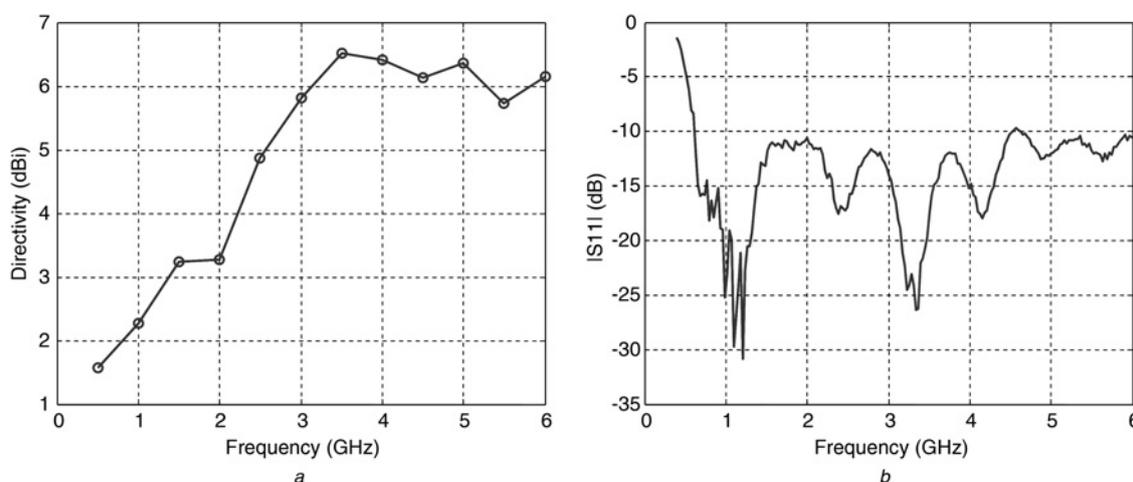


Fig. 2 Measured properties of the antenna used during the study

a Directivity (measurement points indicated with circles)

b S_{11} of the discone antenna

antenna and C_{dB} is the loss in dB of the cable connecting the antenna to the spectrum analyser. All measurements of S shown in this paper are calculated using AF. A_{eff} is the effective area of the antenna and is given by

$$A_{eff} = \frac{\mu D \lambda^2}{4\pi} \quad (3)$$

where D is the directivity of the measurement antenna, λ is the wavelength and μ is the antenna efficiency, which in this case is 100%.

4 Measurements

For each trial a detailed map is presented, with the trial location and RF transmitters present in the vicinity annotated. The RF transmitters include macrocell and microcell mobile phone base stations as well as DVB-T repeaters. The nearest high-power DVB-T transmitter was situated about 30 km south of Bristol, in the Mendips area and is rated at 50 dBW transmission power (100 kW). Owing to the geographical distance from the trial locations, very low received power levels are expected.

For each trial, a floor layout is given with available sources of RF energy indicated. Knowledge of the potential sources of RF energy in the vicinity that the trials are conducted allows

for better insight into the results and further supports the analysis and conclusions. A legend of the RF sources is only given in the first set of figures and is consistent throughout this paper.

Finally, the measurement results are presented on normalised histograms over ten bins, with the power density levels integrated over each frequency band, as these are defined in Table 1. First, the office trial is presented which serves as a reference, followed by four domestic trials.

4.1 Office trial – urban environment

Toshiba's office, a typical urban environment located in central Bristol, was used as a reference site to verify the equipment and principle. The office floor plan is shown in Fig. 3a and the location map in Fig. 3b. As expected, the density of macrocells and microcells around the trial site is high; seven macrocells and five microcells within a radius of 400 m. The measurement results are plotted in Fig. 3c.

An initial set of measurements was conducted with the antenna in three different orthogonal orientations, one vertical and two horizontal. No significant difference in the measured available power was observed in the considered scenario and so a vertical orientation was preferred for all consequent measurements. A total of 3620 measurements were recorded over a week from Tuesday to Monday,

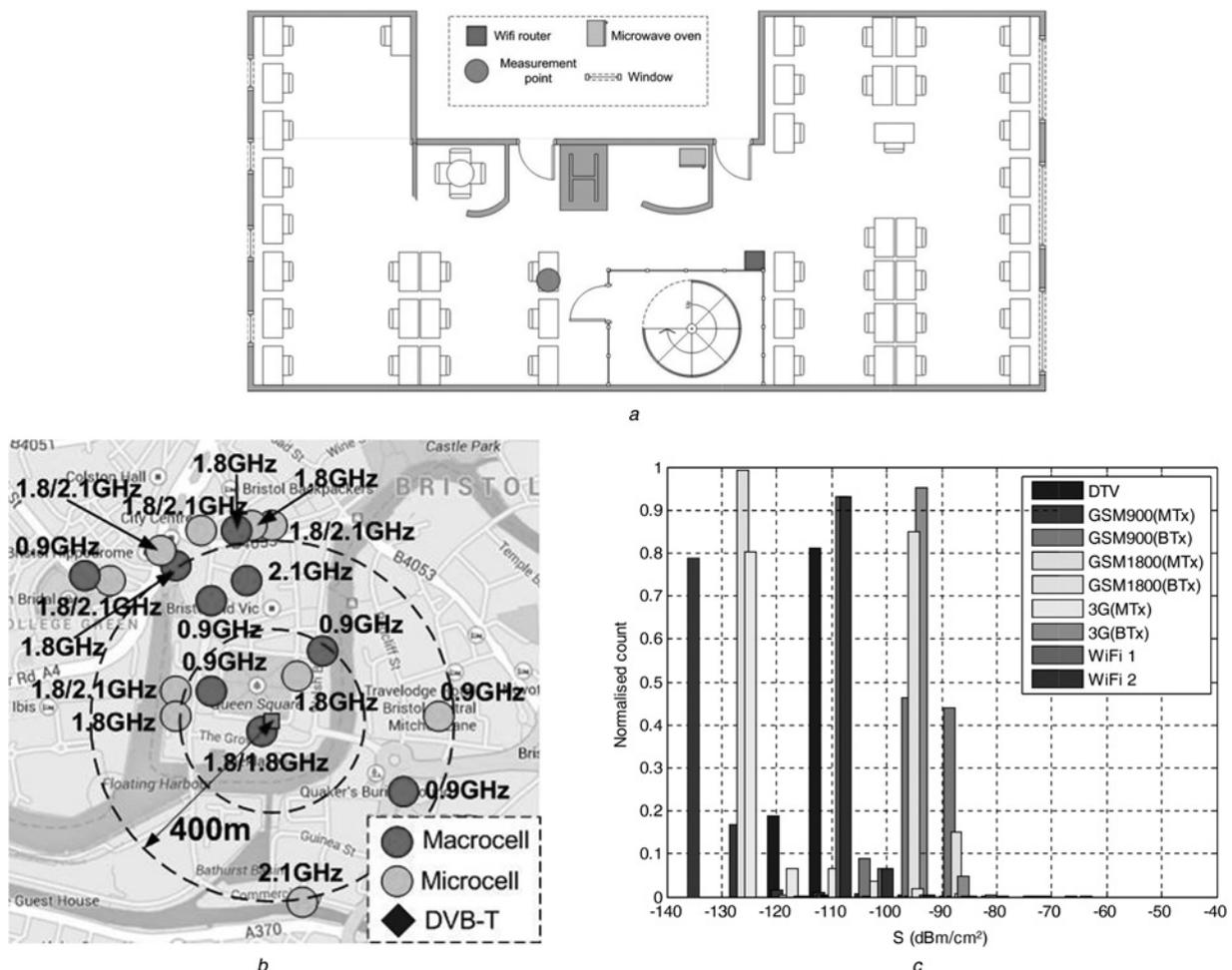


Fig. 3 Office trial

a Office layout
b Location map
c Measurement results

including the weekend. There was no difference observed in the power density levels between days, but rather during the course of each day; there was a doubling of available power between the peak (afternoon/evening) and low (early morning) mobile phone 'traffic' hours. This pattern was clearer in the 3G downlink/uplink and can be accounted to the variable load (number of users in the area).

As can be seen from the histogram in Fig. 3c, the power levels, in general, are extremely low with a few picowatt (pW)/cm² available for harvesting. The most prominent band in this environment is the GSM900, with 3G, GSM1800 and 2.4 GHz WiFi being less prominent. It has to be noted that the three higher frequency bands fall within a 38% fractional bandwidth about 2.1 GHz which can be feasibly covered with a single, compact, broadband antenna.

4.2 Residences – semi-urban and sub-urban environments

In the four trials semi-urban and sub-urban environments, the base station density was significantly lower and this is reflected in the reference office results. As before, measurements took place over a number of days and the details are given in the following sections. This time, there was no significant variation observed in power density levels between weekdays and weekends, days or hours of the day.

The layouts of the four residences are shown in Fig. 4. About 4454 measurements were taken in the first residence (resid. #1) over the period between Tuesday to Monday. In resid. #2, 2815 measurements were performed from Tuesday to Sunday. For resid. #3, 1946 measurements were recorder from Thursday to Sunday, and finally for resid. #4 1761 measurements were taken between Sunday and Wednesday.

Some details to be noted are that in resid. #1 the WiFi was rarely used. In addition, in resid. #2 a WiFi access point was not present at the time but some power density is expected in

the corresponding band because of neighbouring networks. In resid. #3, the WiFi access point also serves as a 3G femto-cell and finally in resid. #4 the distance between the sensing antenna and the WiFi access point is about 2 m, so relatively high-power densities were expected from that source.

Maps of the location of each trial site are shown in Fig. 5 together with the locations of transmitters in the area. The location of the trial sites in relation to the city centre varies. Resid. #1 is 3.5 km east, resid. #2 is 3 km north, resid. #3 is 7.5 km north-east and resid. #4 is 2 km west of the city centre. By looking at a radius of 400 m around the locations, it is clear that the density of transmitters is much lower than that of the office trial. For example one to two macrocells are present and also a few DTV repeaters, but because of their low transmit powers and large distance they are not expected to provide significant power.

The power densities per cm² are plotted on a histogram in Fig. 6 for each residential trial. From the results, it becomes apparent that the power densities acquired are very low, <1 pW/cm². As a first observation, the dominant band varies between locations and this will be analysed in more depth later. DTV, 3G and WiFi were available in all locations. As expected, in residences #1 and #2, there is an absence of WiFi sources and DTV dominates, whereas in #3 and #4 the 3G and WiFi give the highest power densities, respectively. Within the histograms there are some rarely occurring high-power density measurements which are not clearly visible, but as will be shown later they can still provide useful energy for harvesting.

5 Discussion

With all the measured data for each trial location available, the average power density per frequency band was calculated over the whole course of the trails. It was assumed that power density levels will not vary significantly between weeks. It can be seen that depending



Fig. 4 Residence layouts

- a Resid. #1
- b Resid. #2
- c Resid. #3
- d Resid. #4

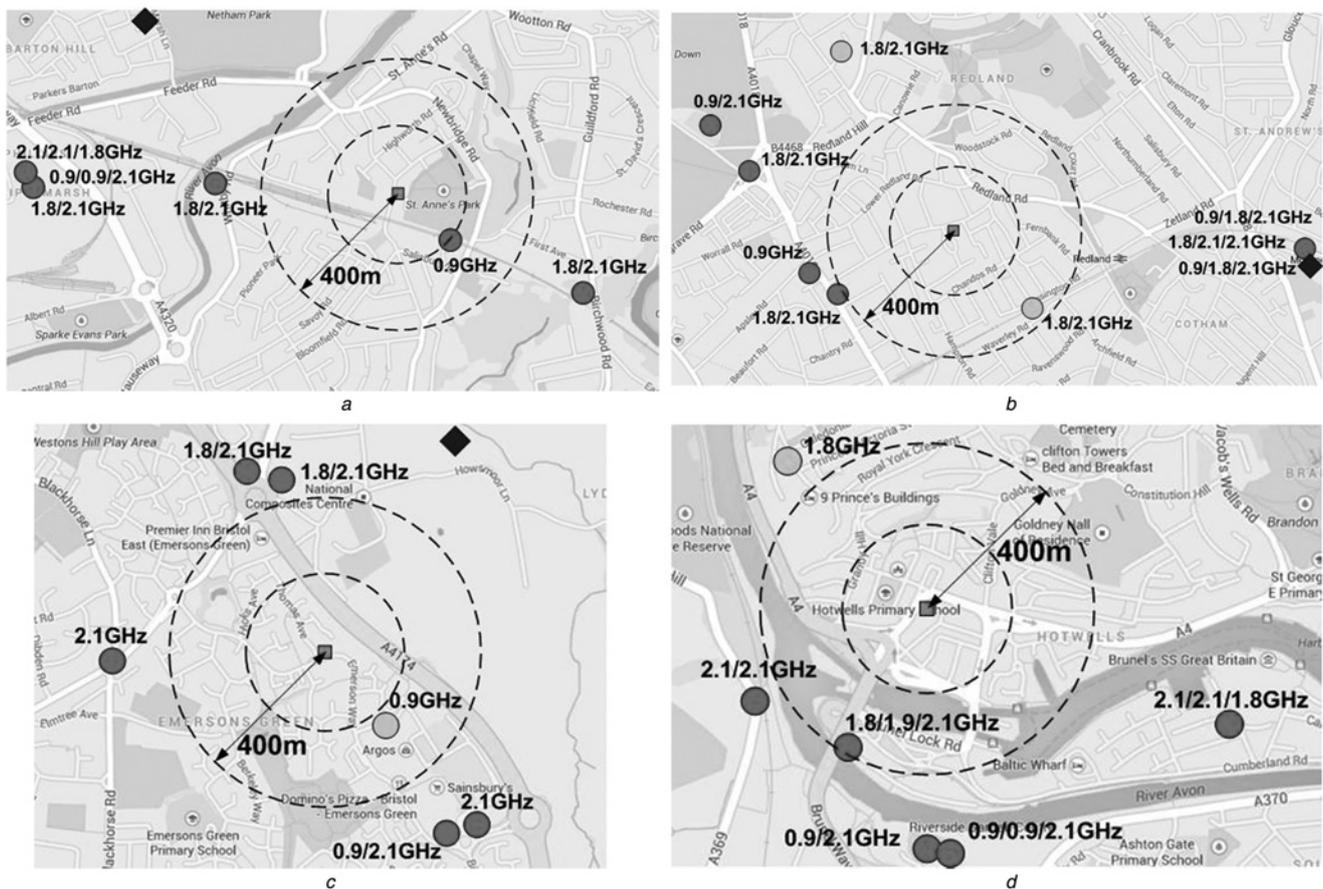


Fig. 5 Location maps for

- a Resid. #1
- b Resid. #2
- c Resid. #3
- d Resid. #4

on the location different bands dominate and various power levels were recorded. In all cases, the power densities are in the order of a $\mu\text{W}/\text{cm}^2$ (-90 dBm). In the following sections detailed results based on the measurements are given, together with estimates of the required harvesting period for collection of sufficient energy to power-up a few common household low-power electronic devices. The 5.5 GHz WiFi power density levels were very low and have not been considered further in this paper.

5.1 Available energy and dominant bands

The average available energy in each band is given in Table 2 in terms of nanojoule (nJ)/min for an antenna with an A_{eff} of 1 cm^2 . The uplink (MTx) and downlink (BTx) are presented separately because especially in the case of the trials in residences mobile devices were used in close proximity to the sensing antenna, significantly boosting the measured power density levels. This is expected to happen in a realistic environment. The highest power densities for MTx and BTx (including DTV and WiFi) are highlighted.

Although the measurements were restricted to indoor environments around Bristol, there is no dominant single frequency band. At the end of the table, a summary of the most prominent bands is given considering BTx frequencies only and BTx and MTx combined. These results implicitly indicate narrowband rectennas, in which case GSM900,

DTV and WiFi seem the most reliable sources if only a BTx is considered, whereas for both BTx and MTx, 3G and GSM900 overtake DTV because of the energy available in the uplink. Moreover, total power available in combinations of bands such as DTV/GSM900 and GSM1800/3G/WiFi, which could potentially be covered by a single antenna are also given in Table 2. These results show the highest potential, but the complexity associated with designing and appropriately matching the antenna to the rectifier over a broad bandwidth should be considered [20] as well as the practicality of using a physically large broadband antenna in the situations discussed.

An interesting note to be drawn from the results is the significant potential of harvesting energy from mobile phones while making calls, texting or Internet browsing. This is evident in all five locations with GSM900-MTx and 3G-MTx showing high potential. Even if these high-power density signals occur rarely (once or twice a day), they are orders of magnitude higher than ambient BTx levels making them particularly interesting and useful.

5.2 Consumption of low-power electronic devices and estimated harvesting potential

Following on from the measurement results, four low-power, electronic devices for domestic/office use were characterised in terms of their power consumption. They are given in

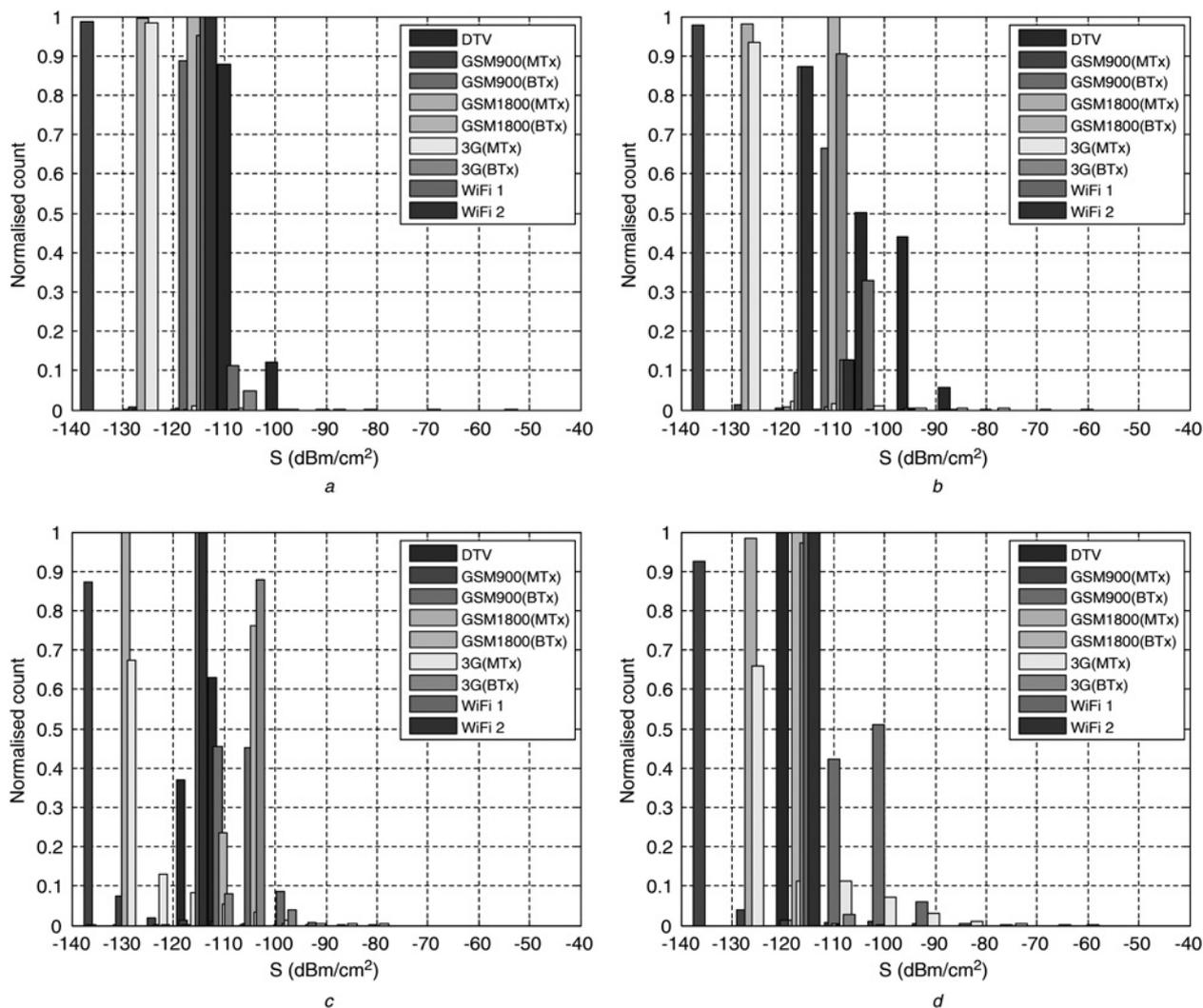


Fig. 6 Histograms of power densities/cm² for

- a Resid. #1
- b Resid. #2
- c Resid. #3
- d Resid. #4

Table 3 and their consumption varies from a few, to over a hundred μ W. On the basis of the best average power density available to a broadband rectenna in each location –

and assuming the antenna has a 1 m² effective area and 50% RF to DC efficiency conversion – the expected harvesting time is given in order to power-up each device

Table 2 Average energy in nJ/min sensed during trial period in each band

Band	Trial location and available energy, nJ/min				
	Office	Resid. #1	Resid. #2	Resid. #3	Resid. #4
DTV	0.0003	0.002	0.0175	0.0004	0.0001
GSM900-MTx	0.0202	0.302	0.0001	0.0004	0.2021
GSM900-BTx	0.054	0.0003	0.0017	0.0024	0.0066
GSM1800-MTx	0	0	0.0001	0	0
GSM1800-BTx	0.0383	0.0001	0.0006	0.0017	0.0001
3G-MTx	0.0161	0.0014	0.1177	0.0035	0.0295
3G-BTx	0.0245	0.0003	0.0004	0.0023	0.0002
WiFi low	0.0162	0.0002	0.0008	0.003	0.2129
		Dominant bands			
BTx only	0.054 (GSM900)	0.002 (DTV)	0.0175 (DTV)	0.003 (WiFi)	0.2129 (WiFi)
MTx + BTx	0.0742 (GSM900)	0.3023 (GSM900)	0.1181 (3G)	0.0058 (3G)	0.2129 (WiFi)
		Band combinations			
DTV/GSM900	0.0745	0.3043	0.0193	0.0032	0.2088
GSM1800/3G/WiFi	0.0951	0.002	0.1196	0.0105	0.2427

Bold values are indicated best values per category

Table 3 Power consumption of low-power devices and estimated harvesting time needed

Device	Power consumption, μW	Harvesting time, h:min:s				
		Office	Resid. #1	Resid. #2	Resid. #3	Resid. #4
small calculator	2	0:04:12	0:01:19	0:03:21	0:38:06	0:01:39
digital thermometer	20	0:42:04	0:13:09	0:33:27	6:20:57	0:16:29
smoke detector	57	1:59:52	0:37:28	1:35:19	18:05:43	0:46:58
wall clock with hands	120	4:12:22	1:18:52	3:20:40	38:05:43	1:38:53

for 1 s. This was calculated based on the following formula

$$t_{\text{harv}} = t_{\text{oper}} E_{\text{cons}} / (E_{\text{harv}} \eta_{\text{RFDC}} A_{\text{eff}}) \quad (4)$$

where t_{harv} is the estimated harvesting time needed, t_{oper} is the operation time, E_{cons} is the energy consumption of the device, E_{harv} is the energy density available for harvesting, while η_{RFDC} and A_{eff} are the RF to direct current (DC) conversion efficiency and the effective area of the rectenna.

The rectenna effective area and RF to DC conversion efficiency are chosen arbitrarily, considering the state-of-the-art results on rectennas available in the literature, the available energy density for harvesting and possible applications. The rectenna RF to DC efficiency is a function of the incident power and frequency of operation as well as the topology chosen. A variety of rectenna designs reported in the literature achieved RF to DC efficiencies between <10% [4, 5, 20] and up to 40% [2] for the ambient energy densities available in practice for a variety of frequency bands. A single, optimistic value for the conversion efficiency of 50% – assuming that rectenna technology will advance – is chosen here as this simplification allows that the measured ambient energy densities are quantified into useful harvestable energy.

The estimated times needed to power-up each device for 1 s are given in Table 3. It becomes clear that RF energy harvesting from ambient sources is insufficient to provide the energy required by even a low-power device such as a calculator. Given the optimistic assumptions made for the rectenna effective area and efficiency, the operation to harvest time ratio for the calculator ranges from 1.3% down to 0.04%. In other words, the calculator would be able to operate for 14 min (Resid. #1) in the best or 38 s (Resid. #3) in the worst case, after harvesting over a whole day. The stated operation to harvest time ratios will scale according to the RF to DC efficiency, for example, for 10% efficiency the needed harvesting times will quintuple.

If narrowband rectennas are considered, the operation to harvest time ratio is even lower than that reported in Table 3. Given the variability in dominant bands between trials, clustering low (below 1 GHz) and high (above 1 GHz) frequency bands and covering them with a compact, broadband antenna array seems the most practical and rewarding way to design rectennas. This would lead to the design of two different devices which could be deployed depending on the environment.

6 Conclusions

An indoor RF power density survey in urban, semi- and sub-urban environments was conducted using a broadband, omnidirectional, discone antenna from 0.5 to 6 GHz. Trials included an urban located office for reference purposes and four semi- and sub-urban residences around the city of

Bristol, UK. The measurements were conducted during February 2014. The power density levels sensed around the locations, in average, were lower than 1 nW/cm².

Analysis and appropriate processing of the results showed that extended periods of harvesting are needed in order to generate enough energy to power-up even simple low-power electronic devices. As an example, a small desktop calculator would be able to operate for 14 min per day if a rectenna with 1 m² effective area and 50% efficiency is assumed. This clearly indicates that RF harvesting is not appropriate for completely eliminating the use of batteries in such applications and especially in domestic semi- or sub-urban environments where the power density levels are extremely low.

On the other hand, such a technology shows potential as a supplementary source of power used to prolong battery life in similar scenarios as the ones considered in this paper, or power-up low-power sensors which would be expected to operate rarely and so the operation to harvest time ratio would be very small. Finally, as a design direction, broadband rectennas operating between 0.5 and 1 GHz or 1.7 and 2.5 GHz seem to be more promising and flexible as indicated by the measurement results and analysis.

7 Acknowledgments

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9 Appendix

See Fig. 7.

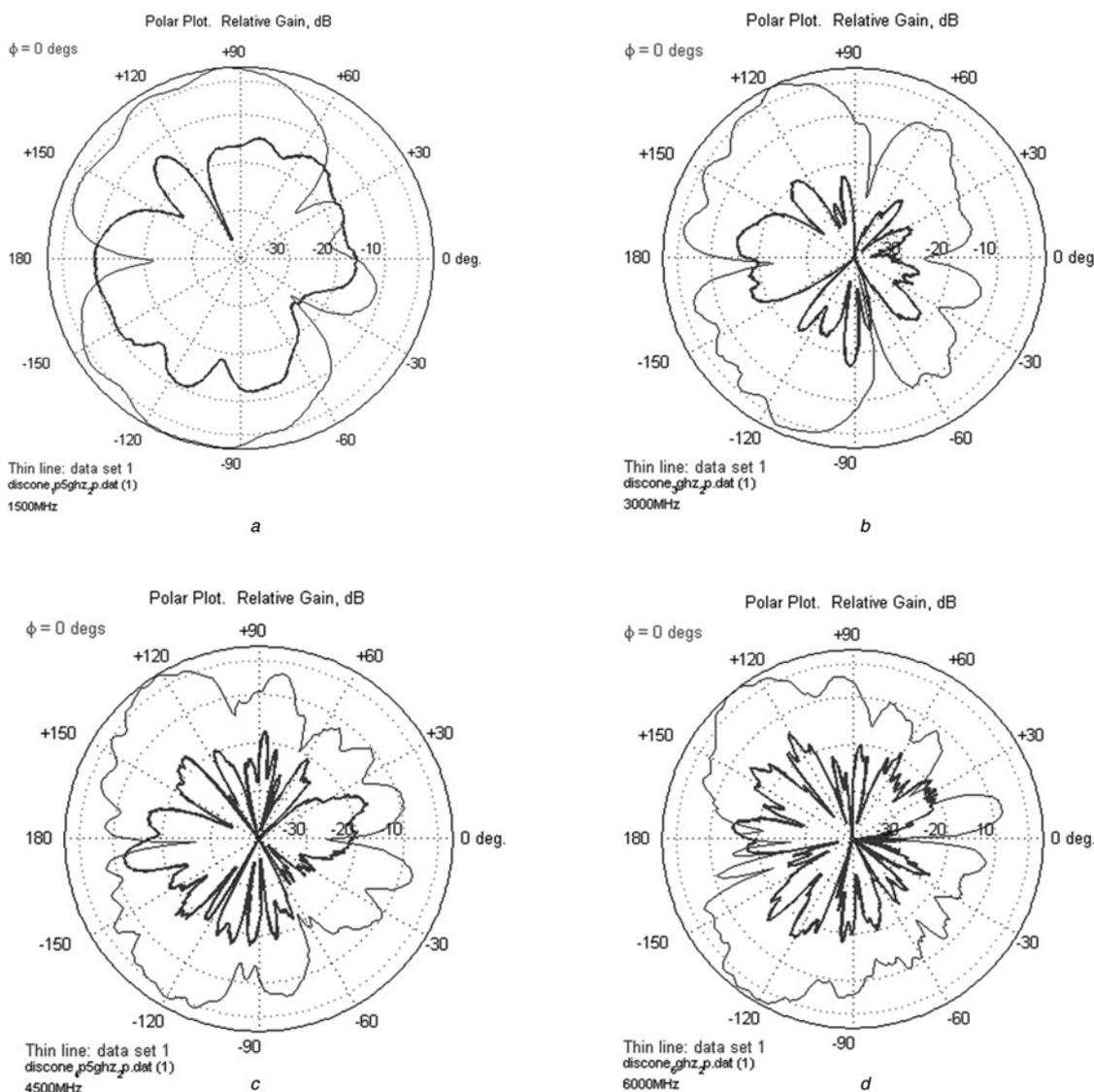


Fig. 7 Selected radiation patterns of the discone antenna at

- a 1.5 GHz
- b 3 GHz
- c 4.5 GHz
- d 6 GHz