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The ant and the elephant: ambient RF harvesting from the uplink

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Abstract: This work investigates the available ambient radio frequency (RF) power density in dynamic, outdoor environments with a specific focus in the uplink. A spectrum survey was carried out around Bristol, UK between 500 MHz and 3 GHz using a handheld spectrum analyser and an omnidirectional broadband discone antenna. Measurements were performed while walking, travelling in a car and on a train. The results are compared with baseline indoors measurements, and as expected, ambient RF power densities in the outdoor environments were significantly higher. Interestingly, in some cases the power contained in the uplink of cellular communication networks is shown to be a better energy source than the downlink. It was found that in a train during rush hour, there is 17 times the mean power density and 45 times the peak power density in the uplink compared with the downlink. This shows that there is scope for ambient energy harvesting in environments with a large density of user equipment. Finally, by accounting for the rectifier efficiency it is estimated that during the train commute between Bristol and Bath in the UK a total of 27.2 mJ of energy could be collected.

1 Introduction

Wireless power transmission has been proposed and researched for many decades as a means to remove or complement batteries and realise energy autonomous devices amongst other applications [1]. Far-field radio frequency (RF) power transfer is an attractive solution in applications where an antenna is already present for data transmission purposes. One possibility that has recently attracted a lot of attention is the harvesting of ambient, RF energy which is present in urban and sub-urban environments. This energy can be rectified and used to power-up low-power sensors that, due to their location or number of, makes it difficult or costly to power-up through wires or batteries.

This RF energy mainly comes from high power digital television (DTV) transmitters and telecommunication base stations (BST). The spatial density of the transmitters has been steadily increasing to provide more coverage, but still varies significantly between locations. This is why a number of surveys have been conducted in selected locations both for identifying spectrum utilisation for software defined radio [2, 3] and for energy harvesting applications [4–7] and also the creation of a global information database has been proposed [8]. Nevertheless, BST and DTV transmitters are considered a ‘stable’ source of energy as their output does not vary significantly versus load and consequently over time. Various trials performed at different locations have shown that depending on the environment (i.e. indoors, outdoor, urban etc.) and frequency the ambient RF power densities can vary anywhere between −90 and −40.8 dBm/cm^2 or even higher [4–6].

Due to the aforementioned reasons, in typical environments such as offices, most studies have focused on either harvesting energy from BST and DVB transmitters or Wi-Fi access points. Typically, existing work has looked at both downlink and uplink transmissions [or in other words the base station and user equipment (UE)] collectively assuming that the BST is the dominant source. The aforementioned studies focused on ‘static’ environments, with the goal of implementing an immobile device that collects and rectifies RF energy to perform some tasks.

In this work, experimental RF power density data from dynamic environments is presented with a non-static receiver (e.g. in a moving car or while walking), while also treating the available energy in the uplink and downlink separately. Such environments are interesting because the rectenna not only moves inside one cell, but also leaves that cell and enters another at significant speed. Depending on the environment the uplink or UE transmissions can have higher signal levels and be of more interest than the BST. Even though the transmission power from a handset is just a fraction of that of a BST, the higher density of UE and their proximity to the rectenna can transform them into a useful source of energy. Finally, in certain environments such as inside trains, there are also additional sources of RF energy due to the presence of the railway communication system (GSM-R).

The paper is organised as follows: After a short introduction in Section 1, Section 2 discusses transmission power control in handsets and the characterisation of a typical handset performing various tasks while also introduces the GSM-R system. Section 3 presents the measurements in the various environments and Section 4 discusses and compares the results with other measurements from indoors/outdoors environments. Finally, conclusions are drawn in Section 5.

2 Uplink characterisation

Even though the UE is in most cases not considered as a potential source of RF energy due to its unpredictable transmission usage and location, it can still prove to be useful in certain scenarios. In order to quantify the available energy, the output power of a few different mobile phones was characterised while they perform various tasks. First, a short introduction on the output power management strategies of mobile terminals is given for the different technologies in order to get a feel for the expected power levels. Then, a set of measurements is presented that show how the output power of a handset varies over time while making or receiving a phone call, texting and browsing the internet.

2.1 Output power control in cellular handsets

Handsets regulate their output power while transmitting to prolong battery life and minimise interference to other users. At the same time they must transmit sufficient power to maintain the communication link. Such output power control is present in all cellular technologies, but its implementation varies significantly between each. In Global System for Mobile Communications (GSM) termed 2G, various power classes are defined with allowed

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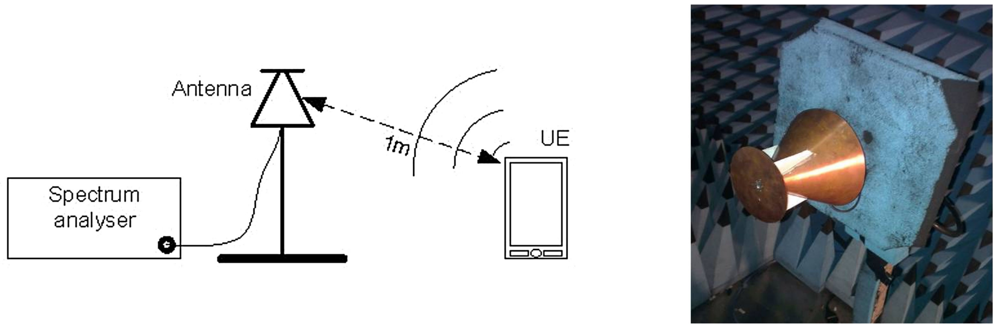

Fig. 1 *Simplified measurement setup used for characterising UE transmission power (left) and photograph of the discone antenna in an anechoic chamber (right)*

peak transmission powers between 24 dBm (Class 2 at 1800 MHz) and 39 dBm (Class 2 at 900 MHz), depending on the frequency of operation [9]. A 2G handset starts by transmitting at peak power and over time adjusts its transmission power in 2 dB steps, at 60 ms intervals. It is apparent that in such a case, significant energy is available for harvesting from a 2G phone. Unfortunately – from an energy harvesting point of view – such handsets are being ‘pushed’ out of the network, as 2G is a legacy technology with some operators having already announced their intention to switch off these networks by 2017 [10, 11].

In Universal Mobile Telecommunications System (UMTS), mostly known as 3G, the situation is somewhat different. Strict output power control is imposed due to the use of the Wideband Code Division Multiple Access (WCDMA) interface, which is very sensitive to interference. Maximum transmission power levels are set at 33 dBm for power Class 1 at all frequencies [12]. The handset initiates its transmission from minimum output power and adjusts it in 1, 2 or 3 dB steps at a rate of 1.5 kHz (0.666 ms). Finally, in Evolved Universal Terrestrial Radio Access (E-UTRA) termed as 4G, only a single power class is defined (Class 3) with an output power of 23 dBm [13]. Output power is adjusted every 2–3 ms and the initial output power is decided based on an estimate of the path loss between the handset and the BST.

It becomes evident, that a 2G handset in proximity to the rectenna is the best choice for harvesting purposes. This fact can be counter-balanced by the ability of modern handsets to perform more functionality, e.g. connect to the internet. Due to this, people use their phones more often if not continuously and not only to perform occasional phone calls. This can potentially transform the UE into a more robust source of RF energy than it is traditionally believed to be.

2.2 Measurements

Following the previous discussion and in order to quantify the available energy for harvesting a number of measurements were performed using a plurality of mobile phones on different operators. The measurements aimed to characterise the mobile phone transmit power, and consequently the available energy for harvesting, while performing various activities, e.g. texting, receiving a call or browsing the internet. The measurement setup used is depicted in Fig. 1. A broadband discone antenna was used, placed vertically using a fibreglass pole and a wooden base. The broadband, omnidirectional, discone antenna operating from a lower frequency of 0.5 up to 6 GHz (bandwidth of 5.5 GHz) and also is the same as that used in the field measurements. The antenna was connected to a spectrum analyser (Keysight E4440A) and the cable losses and antenna factor accounted for. The UE was kept in place using a wooden base at a distance of 1 m away from the antenna. The analyser was configured to measure the power only at the uplink frequencies that the phone was transmitting, at 2 ms intervals. It was controlled through a GPIB connection and all data was captured in Matlab.

As these measurements were performed in a single location with certain link conditions, the absolute power density values recorded are not ‘global’. Instead, the transmission power levels used to achieve sufficient connectivity/throughput for each function will differ depending on the environment, location, distance to the base station and so on [14]. The measurements were performed in a typical office environment in the centre of Bristol, UK, in the vicinity of a large number of cellular BSTs.

The various handsets were found to have similar transmission profiles. The measured power density (S) in dBm/cm^2 for a representative 3G UE is given in Fig. 2 for receiving missed calls, answered/making calls, receiving and sending texts and browsing the internet. The power densities of calling and texting are similar, with the time required for transmitting the text being very short. In the case of texts shown in Fig. 2*c* sending a text might consist of two phases – identified as two peaks, one for the text transmitted and one for the delivery report. Clearly, browsing the internet requires higher transmit power due to the higher data rates involved, and so represents a better case for energy harvesting.

2.3 GSM-R network

GSM-R is a communication standard for railway communication and applications. It is used to deliver several services such as train control and protection, communication of on-board working people, communication of train driver to regulation centre and so on. As in one of the scenarios measurements of a moving train are performed, a basic working knowledge of the GSM-R network becomes relevant to help post-process the measured data.

The GSM-R network base stations are placed along the train lines in 8–20 km intervals and can transmit up to 30 W of power. Also, lower power repeaters are often used. The mobile terminals present on the train – which act as transceivers – can be of two types, hand-held and train mounted. The former have transmission powers up to 2 W while the latter can transmit up to 8 W peak power. In Europe the GSM-R network operates over fixed frequencies for the uplink and downlink using GMSK modulation [15]. The frequencies are given in Table 1. This makes it easy to separate the available power from the GSM-R system in our study.

3 Outdoor measurements

Different scenarios were considered for the outdoors measurements which relate to dynamic environments and more specifically to commuting. Measurements were taken at each scenario using an R&S FSH8 portable spectrum analyser. Each measurement was recorded with its own individual time stamp and was later associated with the position. The same antenna was used as for the UE characterisation in Section 2. More details and measurements of the antenna can be found elsewhere [4], including radiation patterns at various frequencies. The antenna was mounted vertically on a fibreglass pole and kept at a height of 1.6 m for all measurements.

The analyser was configured with a start and stop frequency of 0.5 and 3 GHz, respectively, and with a fixed resolution bandwidth of 30 kHz and video bandwidth of 3 MHz. The FSH8 analyser saves the data in 630 frequency bins, so with the selected bandwidth each bin corresponds to less than 4 MHz of spectrum. As the resolution bandwidth is set to 30 kHz, each bin represents 133 measured points within that frequency range. The value of each bin is the RMS value of the 133 measured points as the detector setting has been set to ‘RMS’.

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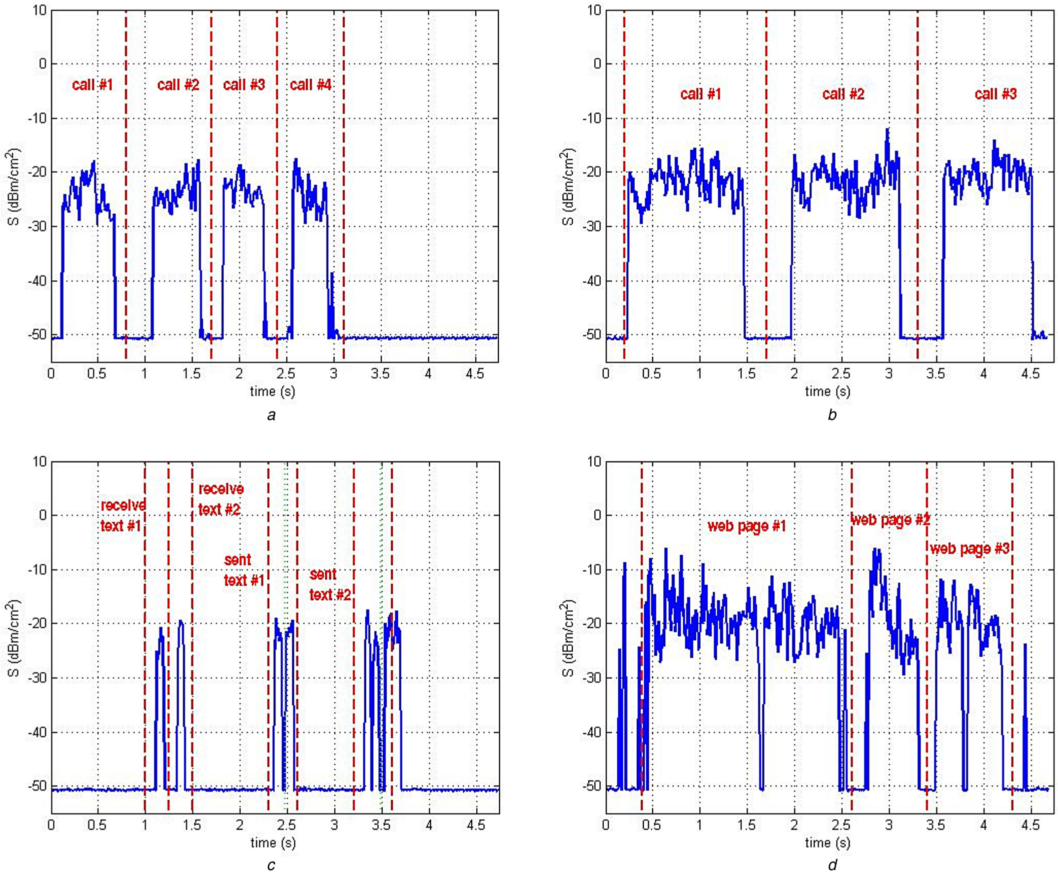

Fig. 2 *Representative power density measurements in the presence of a 3G mobile phone performing different activities*
(a) Receiving missed calls, ***(b)*** Receiving short calls, ***(c)*** Receiving and sending texts, ***(d)*** Browsing the internet

The bandwidth of the measured signal should be larger than the bandwidth covered by each bin or the resolution bandwidth, whichever is larger, otherwise the reported power will be lower than the true value due to the inclusion of power outside the signal, e.g. noise. Moreover, if the resolution bandwidth is large, due to the imperfections of the used filter, power in the neighbouring frequencies will be over reported leading to higher values [16]. In this work, we have chosen to compromise between reasonable sweep times (about 20 s) and a fine resolution bandwidth of 30 kHz, while being limited by the number of frequency bins that the analyser offers due to the wide measurement bandwidth.

Finally, the 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. These settings were set exactly as in [4] so that a direct comparison can be performed. The measurement time interval was about 20 s for all measurements. The frequency bands summarised in Table 1 were used to distinguish the uplink (MTx) and downlink (BTx) channels.

Four different scenarios were considered, three of which relate directly to commuting. In one case measurements were taken while travelling by foot, in a second by car with the antenna placed inside the car, and finally a third by train at evening rush hour. A fourth scenario was also measured, that of driving a car in a circular route starting and ending at the centre of Bristol, where the majority of the route was in the outskirts of the city. A summary of the number of measurements, measurement times and distances is given in Table 2.

In all the measurement scenarios the antenna was mounted vertically, on a fibreglass pole to avoid interfering with the antenna radiation pattern. The pole was hollow and had a length of about 1 m, allowing the feeding cable to pass through conveniently. In the measurements conducted by foot and train, the antenna was kept on a constant height of about 1.6 m and at a minimum distance of 0.5 m from the person conducting the measurements. During the car measurements, the antenna was placed at the rear seats of the car, at a height of 1 m from the seat.

The measurements are presented in three forms, the first is power densities plotted on a map together with the followed route, the second is in tabular form with separate treatment of the uplink and the downlink and finally a time discrete plot only for the train commuting case to investigate it in more detail.

Table 1 Frequency bands and ranges

Band		Frequency, GHz	Notes
DTV		0.47–0.79	
GSM-R	MTx	0.876–0.880	uplink
	BTx	0.921–0.925	downlink
GSM 900	MTx	0.880–0.915	uplink
	BTx	0.925–0.960	downlink
GSM 1800	MTx	1.710–1.785	uplink
	BTx	1.805–1.880	downlink
3G	MTx	1.92–1.98	uplink
	BTx	2.11–2.17	downlink

Table 2 Summary of parameters for different measurement scenarios

Commuting scenario	Measurement time		Number of measurements	Distance covered, km
	Intervals, s	Total (h:min:s)		
on foot	18.5	0:27:11	89	2.4
by car	19.6	0:25:28	79	12.9
long car drive	23.8	1:33:43	237	39.1
on foot and by train	18.5	1:17:11	252	1 on foot, 20 by train[a]

[a]One way.

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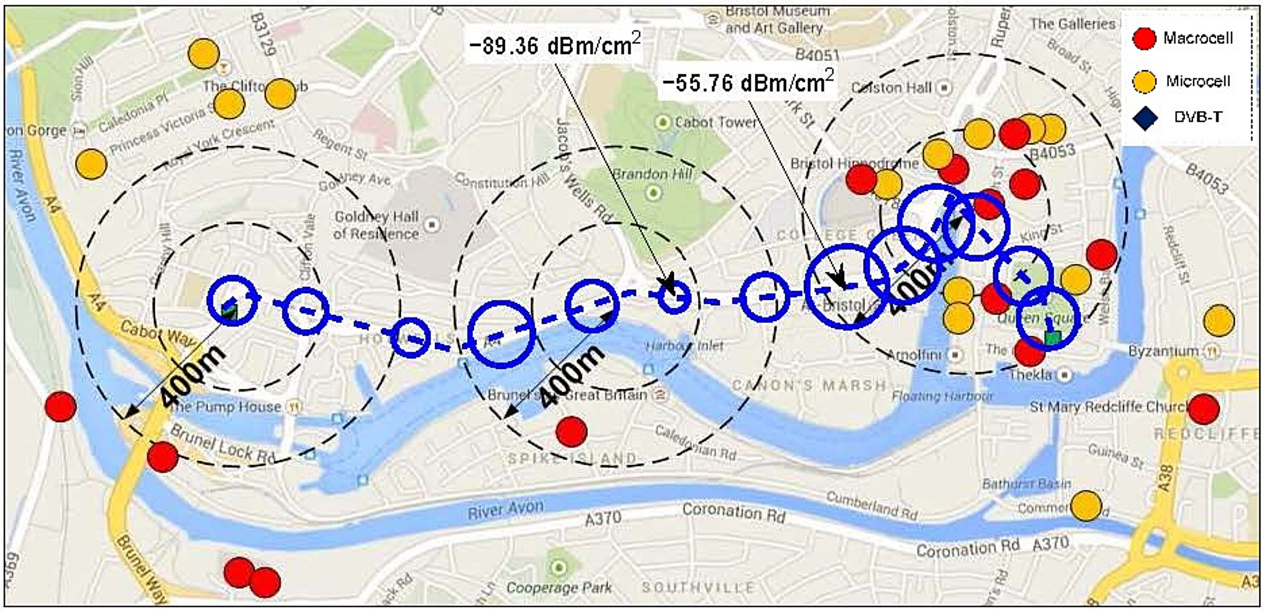

Fig. 3 *Commuting on foot*

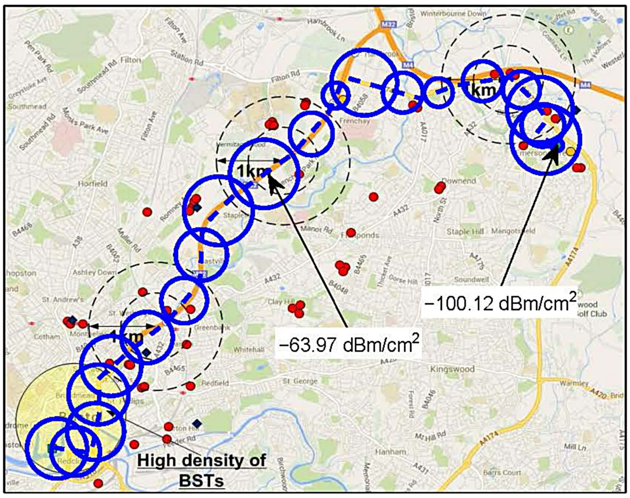

Fig. 4 *Commuting by car*

3.1 Maps

In each of the four maps, the route followed is plotted as a dashed line, and divided into segments. Over each segment the available power in the DTV and GSM900 bands is averaged for all the measurements performed within that segment, and is plotted in the middle of the segment using a circular marker. The size of the marker is proportional to the log average power density in dBm/cm^2. In all maps the maximum and minimum average power densities are marked to give a feeling of absolute power density values. Moreover, on all maps the position of macrocells, microcells and DVB-T transmitters is shown, as reported in the Ofcom database [17].

Fig. 3 shows a commute on foot from a semi-urban environment to the city centre of Bristol. All the measurements are performed in open space and the power density increases significantly where transmitter density is high. A commute by car from the city centre to a sub-urban environment is shown in Fig. 4. In these measurements, the discone antenna was kept inside the car. It is seen that the power densities measured in the DTV and GSM900 bands do not vary significantly along the route. The minimum measured power density was around −100 dBm/cm^2 and corresponds to the end of the commute.

Another measurement campaign was done over a long car drive of about an hour and a half (Fig. 5). The measurements commenced at the city centre where the power density levels were steadily high. It was followed by a sub-urban drive where the lowest levels were consistently measured, before a 5 km drive along the M5 motorway in which the power density was high. The route returned towards the city centre through a radial route (A roads) where the power density was consistently high. The route ended at the city centre.

The low power density recorded in the sub-urban part of the route can be explained by the absence of a sufficiently large number of transmitters. Along the motorway the density of transmitters is large and probably in line-of-sight. At the final part, along the sub-urban environment (A roads), although line-of-sight is less probable, the density of transmitters increases towards the city centre.

The fourth and final campaign was a commute by train to the city of Bath, 20 km from Bristol (Fig. 6). The commute from Bristol to Bath consisted of five sections: the walk from the city centre to the train station, the train ride towards Bath, the change of platforms and travel direction at Bath, the train ride towards Bristol and finally the walk from the train station to the city centre. A large variation of power density is observed during the train ride, with lower levels recorded while the train is in fast motion. The peak level was measured just before arriving at Bath railway station.

Overall, the power densities measured in the train are higher than the other scenarios. Even the minimum level recorded was 16 dB higher than measurements performed outdoors while walking (second to best case). This scenario seems the most interesting due to the higher levels of available energy and will be analysed in more detail (Fig. 7).

A summary of the recorded power densities for all considered scenarios is given in Table 3, distinguishing between different operating bands and also between the uplink (MTx) and the downlink (BTx) where appropriate. Also, in the table the available power density in combinations of bands is given. The bands are clustered as low frequency (0.5–1 GHz) and high frequency (1.7–2.5 GHz) bands with the rational that it is possible to cover each with a single broadband rectenna [18].

It is clear that the most promising case for ambient energy harvesting is that of the train. On average there is more than 9 dB (about eight times) higher power density than in driving and 13.8 dB (almost 24 times) more than in the case of walking outdoors. By investigating further into the distinct bands and their contributions, in Table 3, it can be observed that between the various scenarios the GSM900 band shows significantly higher levels than all the other cases, both in peak and average recorded values. The GSM-R signals, as expected, were only measured during the train commute, but the levels are non-significant.

This could be justified by the fact that in the train – as in any other means of public transport – during peak hours there is a large number of people situated in a small space. It is very common to

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there are a larger number of DTV repeaters than in Bath they were not in line-of-sight, whereas in Bath the position of the repeater is favourable. In the case of GSM900, GSM1800 and 3G in Figs. 7*b*–*d*, respectively, it is clear that the uplink and downlink ‘complement’ each other. When the downlink signal is strong a good propagation environment exists between the UE and BST and the handsets transmit in lower powers and vice versa, as expected. Fig. 7*e* shows the results for the GSM-R case, where the downlink shows some available power density while the train is in motion. Overall, the energy available through the GSM-R especially in the uplink is very low. In outdoors environments such as the measurements in Fig. 7, before point **a** and after point **h** – that is walking to and from the train station – the downlink is much stronger and the UE density is very low, as is their transmit power. The same is true for the walking measurement scenario. On the other hand, the measurements taken inside the train (points **a**–**c** and **e**–**g**) and especially going towards Bath (points **a**–**c**) – because the train had more passengers – the downlink signal strength is clearly lower and the density of UE and the fact that they boost their transmit powers leads to significant power densities present within the train. This was not observed in any other scenario, as the downlink was steadily the dominant signal. In the period between points **a** and **c** in Fig. 7*b* (while in the train) there are 17 times the mean power density and 45 times the peak power density in the uplink, compared with the downlink.

This highlights the importance of the uplink in certain cases, where the number of transmitters (ants) and their proximity to the rectenna is more important than the strength of the transmission

Fig. 5 *Driving around Bristol*

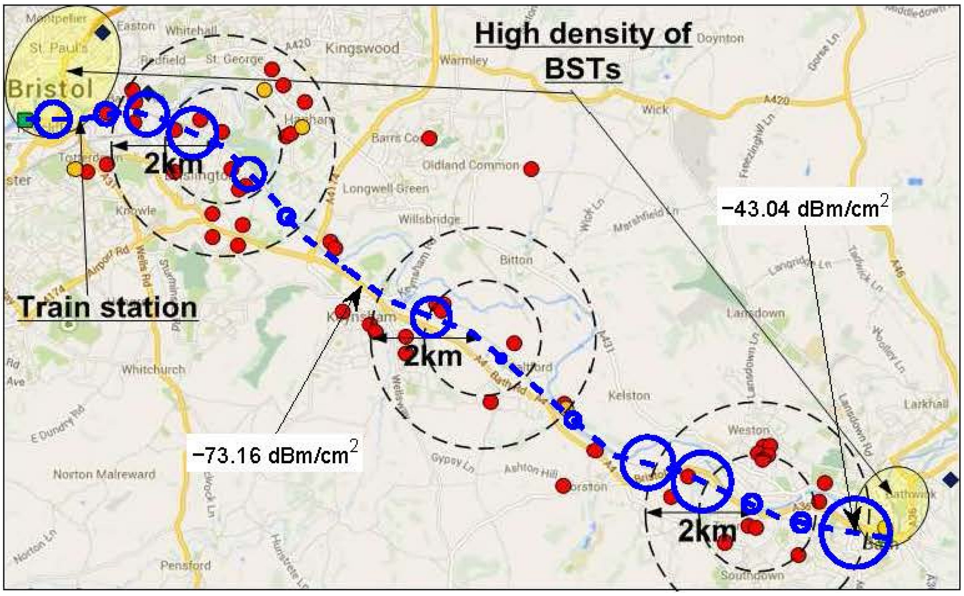

Fig. 6 *Commute by train from Bristol to Bath*

(elephant). So the rectifier could collect sufficient energy from the uplink to power a device, relying on the large number of UE rather than the powerful distant transmitters, similar to the hordes of ants that are able to carry an elephant [19].

use UE (laptops or mobile phones) while on the train, thus the density of UE in use is large. As was seen in Section 1 significant power can be transmitted from a phone while performing calls and even higher when browsing the internet. To further investigate this, an analysis over time of the individual bands and uplink/downlink channels is performed for the train scenario.

3.2 Analysis of the train commute

To investigate further the reasons for the elevated power density levels, the measurements for the train commute data are examined in more detail. The different bands for uplink and downlink are shown in Fig. 7. The measurement positions are annotated on the figures. Also, as mentioned in Table 2, one measurement was taken every 20 s, but in the plots the average of each three samples is plotted to increase readability. Thus, each plotted point in Fig. 7 corresponds to the averaged power density over a 1 min period.

Fig. 7*a* shows power density in the DTV band. There is no significant power density recorded except for the slightly higher levels in the train station platform in Bath. Even though in Bristol

4 Discussion

From the measurement results, it was seen that areas with line-of-sight, and with high density of transmitters have much higher power densities, e.g. while driving on the motorway or riding a train compared to walking or driving in sub-urban and urban environments. This was evident from the data sub-sets of car commute and drive loop measurements. Moreover, as already discussed, in situations where there is a large density of UE used there is significant energy for harvesting due to the uplink, even though the downlink has been considered the dominant source. Table 4 shows the average energy available in the corresponding bands and also the total energy that would be collected with an antenna having a 1.2 m^2 effective area in each scenario.

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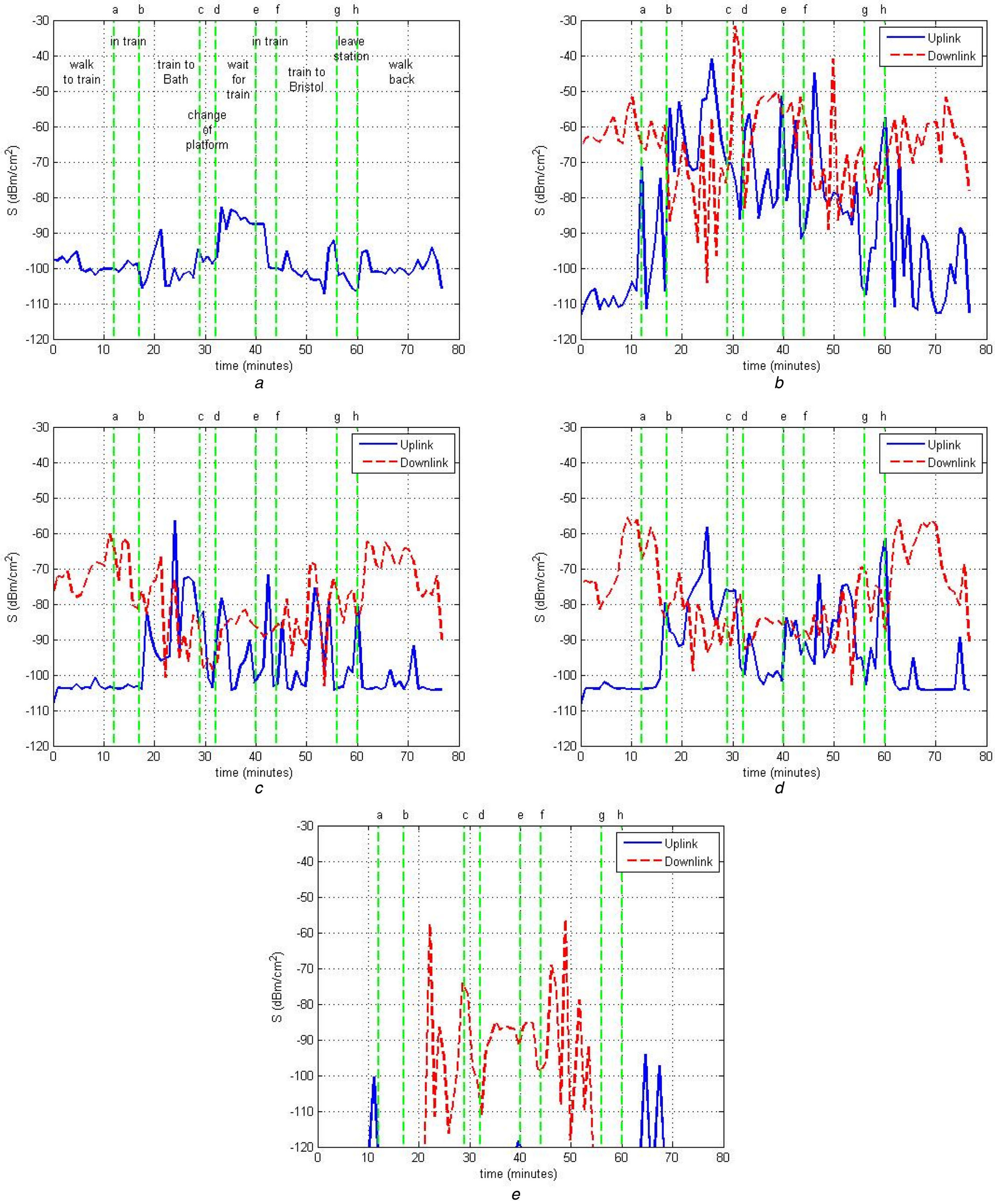

Fig. 7 *Measured power densities over time for train commute*
(a) DTV band, ***(b)*** GSM 900 band, ***(c)*** GSM 1800 band, ***(d)*** 3G band, ***(e)*** GSM-R band

The 1.2 m^2 effective area antenna would, in practice, be implement as an antenna array. Assuming that typical rectangular microstrip patch antennas (with directivity of 7 dB) on a low cost FR4 substrate ($\varepsilon_r = 4.5$) are used, an array of 5 × 5 and 12 × 12 elements would be required to get an effective area of 1.2 m^2 at 800 MHz and 2 GHz, respectively. That would translate to an approximate physical size of 45 × 45 cm^2 and 42 × 42 cm^2 in each case.

In comparison with previous measurements performed in the same area (Bristol, UK), but in indoor [4] domestic and office environments, the results reported here are significantly higher. Those measurements in four domestic settings in urban and sub-urban areas and one office situated in the city centre found an average of 31 nJ by harvesting either DTV/GSM900 or GSM1800/3G/WiFi. In the measurements reported here, orders of magnitude higher energy were available for harvesting.

Compared with a recent thorough survey performed in London outside 270 London Underground station, the levels reported here are much lower. In [5], on average, 44.8 and 116.3 μJ are available if an antenna array of the same effective area is used for the DTV/GSM900 and GSM1800/3G bands, respectively. One reason for the higher levels is the measurement procedure. In those measurements, three, 1 min long measurements were performed with the antenna rotated in three orthogonal axes with the spectrum analyser set to ‘max-hold’, so the final reading was the maximum amplitude per frequency points over the measurement time and over the three axes. This method is intended for measuring exposure limits and can lead to overestimation of the available energy for the applications considered here.

4.1 Estimated energy harvested

The highest energy collection potential is seen to be in the train commute by harvesting the DTV and GSM900 bands. In the rest of the cases useful energy could be collected for powering up low-power on-body sensors by using fabric antennas with large

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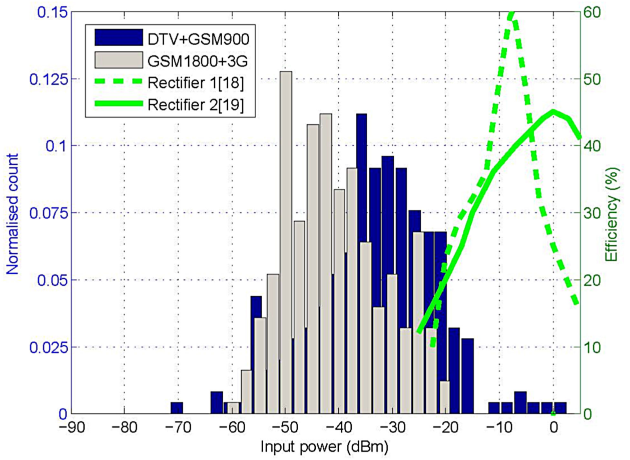

Fig. 8 *Distribution of incident power to the rectifier for the train commute scenario and rectifier efficiencies from the literature*

effective areas. Care should be taken when designing such systems so that their placement will not affect the link between the UE and the base stations or gateways. In order to get a more realistic figure for the energy that could be harvested during the train commute, the 1.2 m^2 effective antenna array is assumed again.

The distribution of incident power from an antenna of such size is plotted in Fig. 8 for the train commute scenario. Based on the summarised results for state-of-the-art microwave rectifying circuits found in [20] and the available power from the antenna, two rectifying elements were chosen as appropriate. Their efficiencies [21, 22] are also plotted in Fig. 8 and were assumed for the calculations.

For the given power distributions and corresponding rectifier efficiencies at each power level, the rectified energy is calculated for all the measured scenarios assuming two broadband rectifiers covering the DTV/GSM900 and GSM1800/3G bands. The input power levels that fall below the turn-on power for the assumed rectifiers are ignored in the calculations as no conversion would occur. The estimated energy rectified for each scenario is summarised in Table 5.

The energy collected in the DTV/GSM900 bands from both rectifiers is quite similar. In the GSM1800/3G as the power levels are very low the rectenna is not able to rectify any power. To give a feeling of the energy levels, we chose an on-body sensing wearable device, used in an ambient assisted living system reported in [23] which has a power consumption of about 60 μW.

Clearly, the energy scavenged with the assumed rectenna during the considered scenarios is not enough to keep the wearable operable throughout the day, but could possible complement the battery to either reduce the required battery size or to prolong its lifetime. During the different commuting scenarios the harvest time to operation time ratio ranges from 45 to 1 for the walking case to about 10 to 1 for the train case. It has to be noted that the rectenna will not only harvest during the considered times of the day, but continuously.

5 Conclusions

Measurements in four, dynamic, outdoors, commuting related scenarios were performed and presented. The measurements were performed around Bristol, UK while walking, travelling in a car and on a train. A comparison with previously conducted indoors measurements revealed significantly higher power density levels, as expected. Moreover, it was found that in certain scenarios significant energy was available in the uplink, due to the high density of active EU. This shows that in certain settings such as means of public transport, the cellular uplink could be a stable and strong source of RF energy. By accounting for the rectification efficiency, a total of 27.2 mJ of energy would be collected during the train commute between Bristol and Bath using a $40 \times 30\ cm^2$ effective area antenna array. This energy level was the highest of all the considered scenarios mainly due to the contribution of the uplink.

Table 3 Summary of average and peak power (in brackets) densities measured in the different scenarios

Available power density (dBm/cm²) per band and scenario										
DTV	GSM-R		GSM900		GSM1800		3G		DTV/ GSM900	GSM1800/3G
	MTx	BTx	MTx	BTx	MTx	BTx	MTx	BTx		
Commuting by foot										
−94.7 (−85.4)	−119.3 (−105.6)	−115.9 (−97.8)	−97.1 (−82.4)	−62.6 (−51.1)	−110.7 (−93.2)	−69.4 (−57.9)	−90.6 (−72.5)	−68.4 (−58.9)	−62.6	−65.9
Driving around Bristol										
−83.1 (−65.7)	−121.8 (−103.2)	−103.4 (−82.9)	−105.9 (−87.2)	−59.0 (−39.4)	−108.7 (−86.9)	−79.9 (−65.9)	−93.9 (−73.9)	−72.7 (−58.1)	−58.0	−71.9
Commuting by car										
−95.0 (−81.2)	−126.8 (−112.1)	−95.2 (−81.0)	−109.0 (−98.0)	−70.5 (−59.5)	−104.2 (−88.8)	−75.7 (−64.7)	−110.9 (−97.0)	−68.5 (−54.6)	−70.2	−67.7
Commuting by foot/train										
−93.5 (−80.8)	−110.7 (−89.4)	−72.9 (−51.5)	−57.3 (−36.2)	−49.4 (−28.6)	−75.0 (−51.6)	−70.3 (−56.3)	−74.7 (−54.9)	−65.4 (−53.4)	−48.7	−63.5

Table 4 Total energy collected with a 1.2 m^2 effective area antenna in the different scenarios

Scenario	Duration (h:mins:s)	Average energy, μJ		Total collected energy, mJ	
		DTV/GSM900	GSM1800/3G	DTV/GSM900	GSM1800/3G
walking	0:27:11	0.66	0.31	1.10	0.51
car	0:25:28	0.12	0.20	0.18	0.32
drive loop	1:33:43	1.91	0.84	8.90	0.36
train	1:17:11	16.20	0.54	73.68	2.51

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Table 5 Estimated rectified energy over the considered scenarios

Bands	Duration (h:mins:s)	Rectified energy, mJ Rectifier 1 [21]	Rectified energy, mJ Rectifier 2 [22]	Wearable time of operation, min
Walking				
DTV/GSM900	0:27:11	2.75	2.19	0.6–0.8
GSM1800/3G		0	0	0
Driving				
DTV/GSM900	0:25:28	2.64	2.12	0.6–0.7
GSM1800/3G		0	0	0
Drive loop				
DTV/GSM900	1:33:43	3.35	2.71	0.8–1
GSM1800/3G		0	0	0
Train				
DTV/GSM900	1:17:11	21.59	27.19	6–7.5
GSM1800/3G		0.07	0.14	0.03

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