AMBIENT RADIO FREQUENCY ENERGY HARVESTING – A LOAD OF HOT AIR?

Gavin T. Watkins

Toshiba Research Europe Limited, 32 Queen Square, Bristol, BS1 4ND, UK
Gavin.watkins@toshiba-trel.com

Ambient Radio Frequency (RF) Energy Harvesting is touted by some as a source of free energy for powering anything from Internet of Things (IoT) sensor nodes to charging mobile phones. Many start-ups have received significant funding pursuing this goal. To evaluate the feasibility of harvested RF power from radio transmissions, measurements were undertaken in Bristol, UK, in the spectrum between 500MHz and 6GHz, a band that includes TV broadcast, mobile phones, radar and Wi-Fi.

The first experiments involved measurements in Toshiba's office in central Bristol and in typical indoor domestic settings. To harvest enough energy to power a small calculator (2µW) for 1 second, an antenna array covering 1.7 to 2.5 GHz with an effective area of 1m^2 required 10 minutes of harvesting. A second experiment involved walking, driving and travelling by train around Bristol. As expected, outdoor ambient RF power densities were significantly higher than indoors. During the train journey between Bristol and Bath on average 17µJ energy could be collected, enough to power the calculator.

INTRODUCTION

As the power consumption of devices becomes more important, a means of supplementing the battery or completely replacing it with other sources becomes increasingly appealing. As a result, energy harvesting from ambient sources, such as solar, thermal, kinetic and RF energy has gathered a lot of attention over the past few years. Of particular interest is RF energy harvesting, as many believe it offers the potential of "free" energy for the taking [1]. In comparison to other source of ambient energy, RF has the advantage that it is available where others aren't, i.e. inside a darkened building.

Ambient RF energy is present in most urban and sub-urban environments from mobile phone base stations and digital television (DTV) transmitters. The density of these sources, and consequently ambient power densities, varies greatly between locations. Studies have been carried out to investigate the feasibility of harvesting such ambient energy [2], but do not always consider realistic scenarios and hence produces optimistic results. Similarly, many rectenna circuits (an antenna with integrated RF rectifier) have been published aimed at ambient RF energy harvesting, but typically require unrealistically large levels of RF power [3] [4]. They should more general be classed as wireless power transfer systems.

As any good RF engineer will know, the transmit power is relatively low and given the path loss equation, received signals powers tend to be miniscule. Modern mobile phones have sensitivities of around -100 dBm – 0.1 pW – and still frequently drop calls due to the low signal level. If a mobile phone cannot maintain a call, what is the chance of harvesting this power for "useful work"?

This paper aims to take a more realistic look at the RF ambient energy spectrum in and around the city of Bristol UK. The focus is on measuring the total amount of energy that can be harvest over a given timeframe for a number of different scenarios including an office, domestic residences, walking, driving and during a train journey. It is hoped that these results will go towards dispelling some of the myths that have been spread about what RF ambient energy harvesting is capable of. This paper summaries results which can be found in two previous publications [5] [6].

THE RADIO FREQUENCY SPECTRUM FIT FOR HARVESTING

The electromagnetic (EM) spectrum stretches from DC to light. Harvesting energy at the light end is common in the form of solar power. Harvesting infrared (700-1000nm) energy is also common with the Peltier-Seebeck effect, as used in thermocouples. Some recent research has tried to harvest energy from the low end of the spectrum by coupling to the fields that exist around overhead power cables (50 Hz) [7] and medium wave radio (540-1610 kHz) [8]. Both techniques require large impractical ferrite core antennas, although with a large enough ferrite core antenna an analogue wall clock can be powered if near to an AM transmitter [9].

Most RF energy harvesting work has focused on harvesting from TV transmitters, mobile phone base stations and Wi-Fi access points. These have the advantage that they radiate power 24 hours a day and there exists a high density of them in certain environments – definitely the case for mobile phone base stations and Wi-Fi access points. A summary of the ambient RF energy harvesting bands found in the UK – and covered in this paper – is listed in Table 1.

In addition to those shown in Table 1 other sources suitable harvested exist: emergency services, airport radio, short-range devices etc, however these are less consistent, so not considered here. The measurements presented here were taken in 2014 before rollout of 4G networks in UK. It would be interesting to repeat the measurements and see if 4G has increased the potential for RF ambient energy harvesting over the last five years. However, related historic measurements in Bristol from 2001 [10] do not show a great deal of difference to those recorded 13 years later, suggesting that this is unlikely to be the case.

Table 1. RF signals of interest

Band	Frequency (MHz)
TV	470-860
GSMR*	876-915, 921-960
GSM900	880-915, 925-960
GSM1800	1710-1785, 1805-1880
3G/UMTS2100	1920-1980, 2110-2170
Wi-Fi	2412-2472
Wi-Fi	5160-5865

*This is a dedicated GSM network for the railways

INITIAL MEASUREMENTS

The initial experiments focused on the RF spectrum between 500 MHz and 6 GHz took place in Toshiba's offices in Queen Square Bristol in February 2014. The spectrum was monitored over a number of weeks with a Keysight E4440 spectrum analyser controlled by a computer. This enabled it to take periodic sweeps and the resulting data saved to disk for later analysis. Long term measurements are important, because whereas the power detected from TV transmissions is fairly consistent over a 24 hour period, mobile phone and Wi-Fi signals are more sporadic. These may be significantly stronger, but generally last for a short period time resulting in low average power. To complete the measurement setup the broadband discone antenna shown in Fig 1 a) was developed. It had an S_{11} better than -10dB over the required band, as shown in Fig 1 b). Being a discone antenna, it is had an omni-directional response in the azimuth plane. Further antenna measurements can be found in [5].

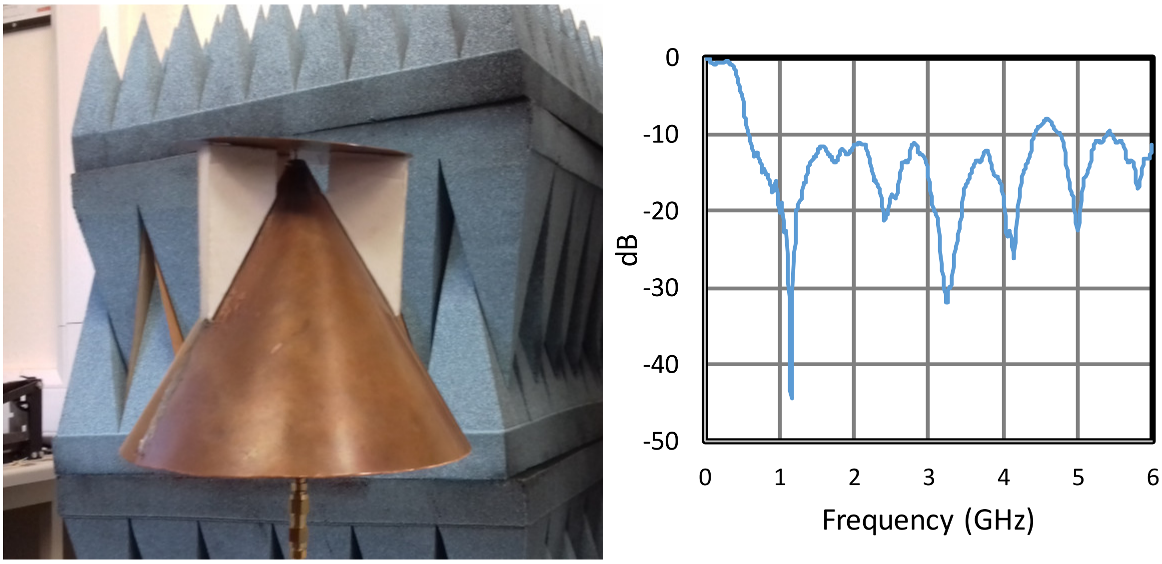
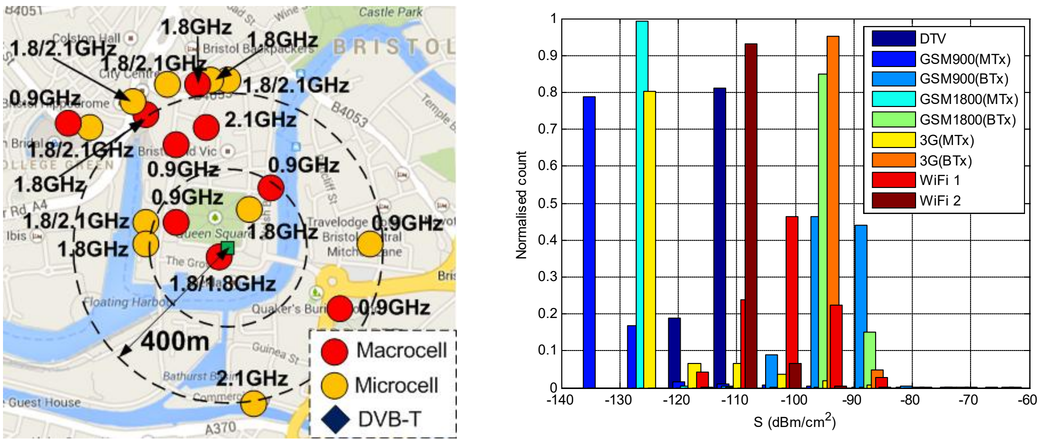


Fig 1. a) Photograph of discone antenna, and b) S_{11} response.

Toshiba's office is surrounded by a large number of mobile phone base stations as shown in Fig. 2 a). These were located using Ofcom's Sitefinder – which is sadly no longer available, although others are [11]. Measurements were conducted at the 30 kHz resolution bandwidth to provide a high dynamic range while not incurring an excessively too long sweep time.



(a) (b)

Fig 2. a) Location of office and surrounding transmitters, and b) measurement results.

The results of the experiement are presented in Fig. 2 b). The graph shows the frequency at which a power level was detected in a certain band. The power levels have been normalised to the antenna's effective area. It will be noted that a GSM1800 signal was detected virtually all the time, but only at a power level of -125 dBm/cm^2, (0.3fW). Wi-Fi seems like a more suitable source for harvesting. Almost 50% of the time -100 dBm/cm^2 (0.1 pW) was detected. 3% of the time this increased to -85 dBm/cm^2 signal (3 pW). Not that these two signals contain approximately the same amount of energy, since energy is the product of power and time.

These calculations do not consider the efficiency of an RF rectifier which is necessary to convert any RF power into useable DC power. Most published RF rectifiers are based on Schottky diodes with a threshold voltage around 0.2V. Sub-threshold rectification is possible, but at very low efficiency. The response of two published rectifiers is shown in Fig 3 from References [3] and [4].

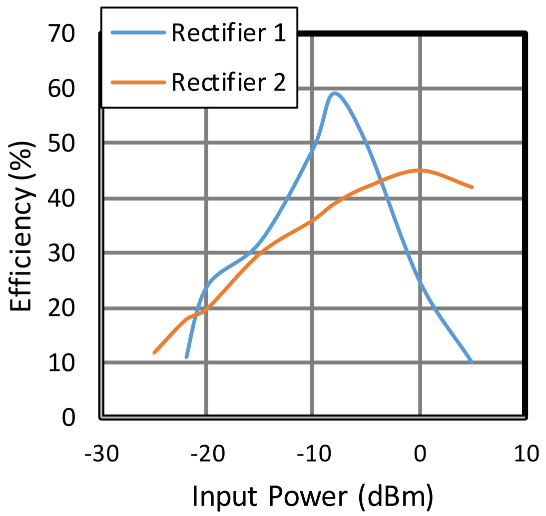
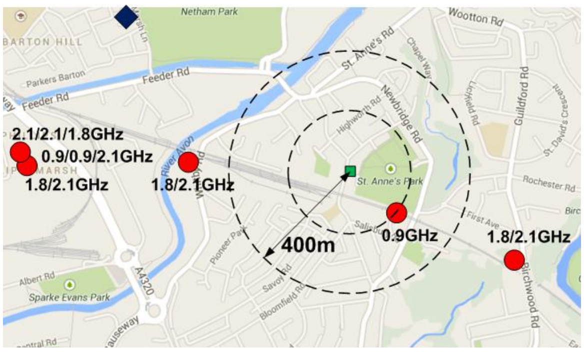


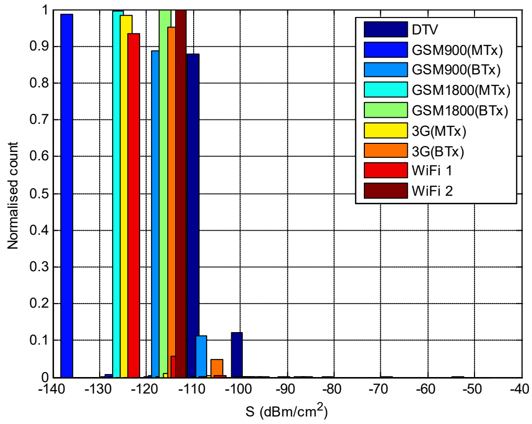
Fig 3. Performance of two published rectifiers.

Both rectifiers in Fig 3 require significant input power to achieve a useful efficiency. One obvious solution to harvest more energy would be to increase the antenna size. With regard to Fig 2, the best signal to harvest is the GSM900(BTX) – base station transmit signal. This has a recorded power of -90 dBm/cm^2. To achieve -10 dBm would require an antenna with an effective area of 10 km^2. This would produce 50μW of useable DC power, if an antenna 100 by 100 metres could be accommodated in any practical application.

WORKING FROM HOME

Similar measurements were repeated at the homes of the four researchers taking part in this work. The E4440 spectrum analyser is a large bench instrument, so a handheld R&S FSH8 spectrum analyser was leased. This also had the advantage that it could be set to take periodic measurements and store them to an SD card. Other than that, the same settings were used as for the measurements in the office. The location of residence number 1 and the recorded signal power recorded are shown in Fig 4.





a) b)

Fig 4. a) Location of residence 1, and b) measurement results.

Compared to the results presented in Fig 2, the signal strength measured in Fig 4 is significantly less. The TV (DTV) signal has a similar power, but the mobile phone signals are considerably weaker due to the lower density of base stations, as clear from the maps. Although there was a Wi-Fi router in the residence and neighbouring ones, the signal strength is lower, due to the brick walls separating the rooms, whereas the office was open-plan.

The other three locations produced similar results, with the only consistent signals being around the -110 dBm/cm^2 power level. The best recorded signal was a Wi-Fi one at -80 dBm/cm^2 (10 pW) 45% of the time, but this was because the Wi-Fi router was in the same room as the spectrum analyser.

WALKABOUT

The handheld spectrum analyser was leased for one calendar month. After the measurement campaigns at the four residences, there was time for some mobile measurements. Four scenarios were considered: walking in from residence number 4 to the office, driving from residence number 3 to the office, a long car drive around Bristol and a trip to Bath and back on the train. The parameters for the different scenarios are described in Table 2.

The route for scenario 4 (on foot and by train to Bath) is shown below in Fig. 5 as a dashed blue line. This route consists of five sections: the walk from the office to the train station, the train ride towards Bath, changing platforms at Bath station, the train ride back towards Bristol and finally the walk from the train station to the office. Over each section of the journey the available detected power was averaged and plotted with a blue circular marker. The size of the marker is proportional to the power density. The maximum and minimum average power density are also marked. The maximum was measured just before arriving at Bath railway station. Overall, the power densities measured in the train were higher than the other scenarios.

Table 2. Summary of parameters for different measurement scenarios.

Commuting Scenario	Measurement Time (h:m:s)	Distance Covered (km)
Walking	0:27:11	2.4
Car	0:25:28	12.9
Long car drive	1:33:43	39.1
Walking and by train to Bath	1:17:11	1 walking, 20 by train*

*One way

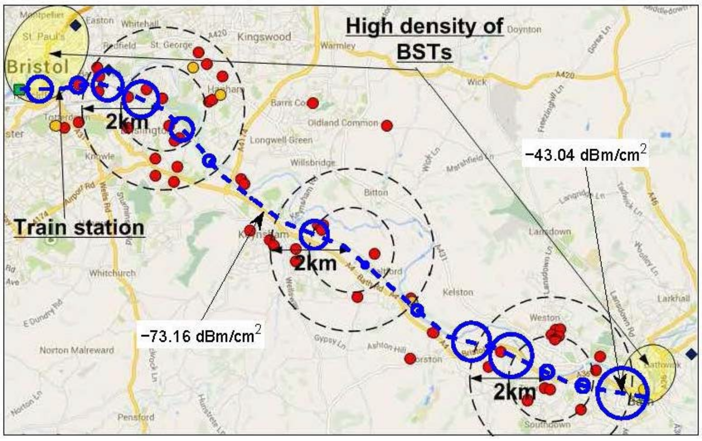


Fig 5. Commute by train from Bristol to Bath.

A summary of the recorded power densities for all considered scenarios is presented in Table 3. Frequency bands which are close together have been combined here, on the assumption that a realistic energy harvester would cover a large band [12].

Table 3. Summary of parameters for different measurement scenarios.

Scenario	Average Energy (μJ)		Total Collected Energy (mJ)	
	DTV/GSM900	GSM1800/3G	DTV/GSM900	GSM1800/3G
Walking	0.66	0.31	1.10	0.51
Car	0.12	0.20	0.18	0.32
Long Car Drive	1.91	0.84	8.90	0.36
Walking and by train	16.20	0.54	73.68	2.51

Table 3 indicates that the greatest ambient energy harvesting was when travelling on the train, even accounting for the longer journey time. This was particularly noticeable in the GSM900 band due to the high usage of mobile phones by commuters. There are also a significant number of base stations along the train route as shown in Fig 5. Further results in Reference [6] catalogue the power density during the train journey, where both the receive and transmit bands contain a lot of variation as mobile phones experience handover between base stations and the resulting power control operates. Although the dedicated GSMR network on the railway was detected, it's power was significantly less than that of mobiles phones.

ENERGY ENERGY EVERYWHERE, BUT…

To contextualise the results from the measurements, the power consumption of four low power electronic devices for domestic/office use were characterized. These are listed in Table 4 along with their consumption in μW. Assuming the antenna has a $1m^2$ effective area and 50% RF to DC efficiency conversion – generous given the results in Fig 3 – the expected harvesting time is determined for one second of operation.

Table 4. Power consumption of low-power devices and estimated harvesting time needed for one second of operation

Device	Power Consumption (μW)	Harvesting Time (hours:minutes:seconds)				
		Office	Res. 1	Res. 2	Res. 3	Res. 4
Small calculator	2	0:04:12	0:01:19	0:03:21	0:38:06	0:01:39
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	120	4:12:22	1:18:52	3:20:40	38:05:43	1:38:53

Table 4 suggests that energy harvesting from RF ambient sources is generally insufficient to power any of the devices, even the calculator – which was actually a solar powered one. These results assume the whole spectrum from 500 MHz to 6 GHz is received with a wideband antenna like the discone shown in Fig 1, which is impractical in most applications.

Compared to surveys performed in London in 2013 outside Tube stations, the levels reported in Bristol are much lower. In Reference [2], on average 44.8 μJ and 116.3 μJ were available in the DTV/GSM900 and GSM1800/3G bands. It should be noted that in those measurements the antenna was rotated in three axis and the spectrum analyser set to "max-hold". This recorded the peak power, not the average power as in the results presented in this paper.

For the mobile measurements, greater energy was harvested than the static ones, particularly during the long car drive and on the train. The greatest potential for RF ambient energy harvesting proved to be on the train from GSM900 sources. If the devices shown in Table 4 are considered, along with a 1 m^2 antenna and the two rectifiers discussed [3] [4] some meaningful use can be achieved as shown in Table 5.

Table 5: Estimated rectified energy over the considered scenarios from DTV and GSM900 bands.

Scenario	Duration (h:m:s)	Rectified Energy (mJ)		Useable time of calculator (minutes)	
		Rectifier 1	Rectifier 2	Rectifier 1	Rectifier 2
Walking	0:27:11	2.75	2.19	18	24
Car	0:25:28	2.64	2.12	18	21
Long car drive	1:33:43	3.35	2.71	24	30
Walking and by train	1:17:11	21.59	27.19	180	225

The results in Table 5 show that it is possible to harvest enough RF energy to power a calculator, even continuously while on a train. However, this relies on a suitably large antenna, which would be considerably larger than the calculator.

CONCLUSION

This paper takes a broad look at the topic of RF energy harvesting. This has recently been touted in the press and some academic journals as a viable way to power electronic devices. The measurements presented in this paper show that generally this is not the case. Only one considered scenario was actually able to achieve this, and this was with a 1 m^2 antenna, which would be impractical in that and all other scenarios.

Acknowledgement

This work was carried out as a team effort with Konstantinos Mimis, David R. Gibbins and Sema Dumanli.

REFERENCES

1. "Time for ambient energy harvesting from RF signals "*Electronics Weekly*", 23rd August 2018.

2. M. Pinuela, P. Mitcheson, S. Lucyszyn, 'Ambient RF energy harvesting in urban and semi-urban environments', *IEEE Transactions on Microwave Theory and Techniques*, 2013, Vol. 61, No. 7, pp. 2715-2726.

3. S. Hemour, Y. Zhao, C. H. P. Lorenz, D. Houssameddine, Y. Gui, C. Hu, K. Wu, "Towards Low-Power High-Efficiency RF and Microwave Energy Harvesting", *IEEE Transactions on Microwave Theory and Techniques*, 2014, Vol. 62, No. 4, pp. 965-976

4. T. Le, K. Mayaram, T. Fiez, "Efficient far-field radio frequency energy harvesting for passively powered sensor networks", *IEEE Journal of Solid-State Circuits*, 2008, Vol. 43, No. 5, pp. 1287-1302.

5. K. Mimis, D. Gibbins, S. Dumanli, G. T. Watkins, "Ambient RF energy harvesting trial in domestic settings", *IET Microwaves, Antennas & Propagation*, 2015, Vol. 9, No. 5, pp. 454-462.

6. K. Mimis, D. R. Gibbins, S. Dumanli, G. T. Watkins, "The ant and the elephant: ambient RF harvesting from the uplink" *IET Microwaves, Antennas & Propagation*, 2017, Vol. 11, No. 3, pp. 386-393.

7. Sheng Yuan, Yi Huang, Jiafeng Zhou, Qian Xu, Chaoyun Song, Pete Thompson, "Magnetic Field Energy Harvesting Under Overhead Power Lines", *IEEE Transactions on Power Electronics*, 2015, Vol. 30, No. 11, pp. 6191-6202.

8. Vladimir Dyo, Tahmina Ajmal, Ben Allen, David Jazani, Ivan Ivanov, "Design of a ferrite rod antenna for harvesting energy from medium wave broadcast signals", *The Journal of Engineering*, 2013, Vol. 2013, No. 12, pp. 89-96.

9. Centre of Wireless Research Bedfordshire University, https://www.youtube.com/watch?v=-POTonVcNBo

10. Watkins, G, "Potential interfering signals in software defined radio", *Sixth IEEE High Frequency Postgraduate Colloquium*, Cardiff, UK, Sep. 2001, pp. 41–46.

11. Mobile Phone Base Station Locator, www.coolsmartphone.com.

12. Z. Popovic, S. Korhummel, S. Dunbar, R. Scheeler, A. Dolgov, R. Zane, E. Falkenstein, J. Hagerty, "Scalable RF Energy Harvesting", *IEEE Transactions on Microwave Theory and Techniques*, 2014, Vol. 62, No. 4, pp. 1046-1056.