London RF Survey for Radiative Ambient RF Energy Harvesters and Efficient DC-load Inductive Power Transfer

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This paper presents experimental results of energy harvesters working from ambient RF sources and an efficient inductive power transfer (IPT) system. A city-wide RF spectral survey was undertaken outside all of the 270 London Underground stations. Results from this unique survey demonstrate that DTV, GSM900, GSM1800 and 3G are the highest contributors. As a result, single and multiband rectennas were fabricated for these frequencies. Based on the spectral survey and the harvesters' performance, it is expected that more than 220 of the surveyed locations are suitable for ambient RF energy harvesting. Finally, experimental results from a high frequency IPT system with a semi-resonant Class-E driver, capable of transmitting 105 W with a dc-to-load efficiency above 77% across a distance of 30 cm, are presented.

Index Terms— ambient RF; RF survey; inductive power transfer; semi-resonant; WPT

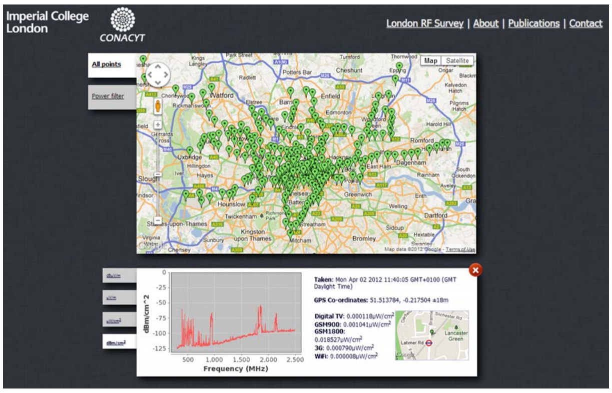
I. LONDON RF SURVEY

In order to assess the feasibility of deploying ambient RF energy harvesters, the available RF power needs to be measured in different locations. Such measurements, in conjunction with knowledge on harvester performance, can then be used to determine the locations at which RF harvester powered devices can be successfully deployed.

To identify the locations where RF harvesters could potentially work from non-dedicated sources, measurements from a detailed ambient RF spectral survey (from 0.3 to 2.5 GHz) covering 270 underground stations in London have been recorded and are available at www.londonrfsurvey.org. It is important to note that the spectral measurements were undertaken during the analogue-to-digital switchover period in the UK and so the measurements for DTV may represent an underestimate of present RF power levels that can now be measured now that switch over is complete. In addition, the first 4G network has just been switched on in the UK and is hence absent from the survey data.

Fig. 1 shows all locations where measurements were taken, together with their GPS coordinates and time stamps. As can be seen, once a point is selected from the map, its field strength or banded RF power density (S_{BA}) is displayed.

To establish a difference between urban and semi-urban environments, a boundary was defined by the line that separates zones 3 and 4 on the London Underground map [1].



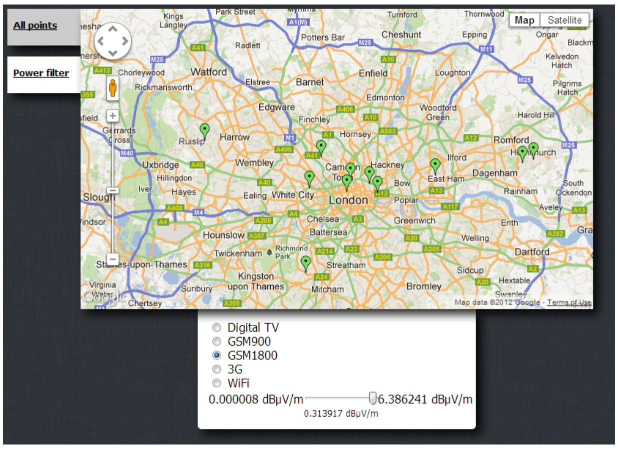
Taken: Mon Apr 02 2012 11:40:05 GMT+0100 (GMT Daylight Time)

GPS Co-ordinates: 51.513784, -0.217504 ±18m

Digital TV: 0.000118µW/cm²
GSM900: 0.001041µW/cm²
GSM1800: 0.018527µW/cm²
3G: 0.000790µW/cm²
WiFi: 0.000008µW/cm²

Figure 1. LondonRFSurvey.org snapshot with the Latimer Road underground station selected.

As one would expect, the central zones 1-3 host the highest density of base stations. With the use of an interactive filter on this website, the station exits with the highest field strengths can be easily selected and will appear on the map, as shown in Fig. 2.



○ Digital TV
○ GSM900
● GSM1800
○ 3G
○ WiFi
0.000008 dBµV/m — 6.386241 dBµV/m
0.313917 dBµV/m

Figure 2. Top ten highest GSM1800 field strength locations.

From our London RF survey, DTV, GSM900, GSM1800, 3G and WiFi were identified as potentially useful ambient RF energy harvesting sources, although DTV appears to be heavily dependent on atmospheric conditions and Wi-Fi is very dependent on user traffic.

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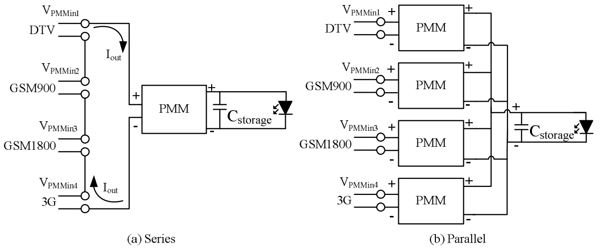
II. SINGLE AND MULTIBAND HARVESTERS

Based on a previously reported analysis [2] and the spectral survey results, the zero-bias SMS7630 diode (in a series configuration) was selected as the optimal solution for our ambient RF energy harvesters. Single band and multiband rectenna arrays, as shown in Fig. 3, were fabricated with scalable folded dipole omnidirectional antennas.



(a) Series

(b) Parallel

Figure 3. Multiband array architectures with four bands (a) voltage summing at the outputs of the single-band rectennas; and (b) current summing at the outputs of the single-band harvesters.

The aim of these multiband rectenna arrays is to reach the minimum input voltage 330 mV (cold-start) level of the BQ25504 power management module (PMM) from lower RF power levels, thus being able to operate in more locations than with the single band rectenna. The series architecture has a combined output current that prevents each rectenna to reach its maximum power point. This means that although all the rectennas are contributing to reach the minimum start-up voltage, only the rectenna with the highest RF power provides enough power to the PMM for it to operate.

With the parallel architecture, the issue of shared current with the series architecture is avoided by having a PMM for each rectenna. Although the cold-start voltage is not reached as fast as with the series architecture, the fact that each rectenna can reach its maximum power point operation is reflected in a more efficient system than with the previous multiband architecture. Furthermore, having independent PMMs allows all harvesters to start as soon as one of the harvesters reaches the minimum start-up voltage, since all of them share the same storage capacitor.

Fig. 4 shows the end-to-end efficiency for all prototypes with input power levels as low as -25 dBm, as shown in [3], and efficiencies as high as 40%. The multiband series and parallel rectenna arrays were able to cold-start at power levels as low as -29 dBm.

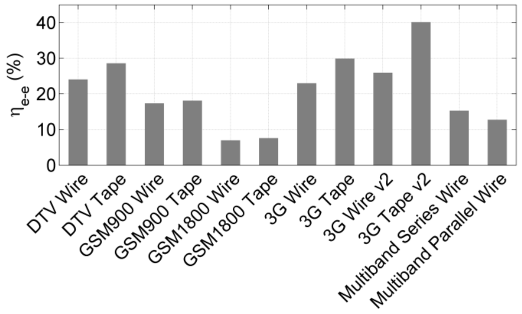


Figure 4. End-to-end efficiencies for ambient RF energy harvesting at Imperial College London (ICL)

Using the harvester's performance and the survey results, Table 1 shows the number of locations where the harvesters would work if deployed in London.

TABLE I. NUMBER OF LOCATIONS FROM THE LONDON RF SURVEY WHERE SINGLE AND MULTIBAND HARVESTERS FROM THIS WORK WOULD OPERATE.

	DTV	**GSM900 (BTx)**	**GSM1800 (BTx)**	**3G (BTx)**
Stations with higher S_{BA}	2	28	68	122

These results demonstrate how, by using input power levels from a spectral survey as a starting point for designing ambient RF energy harvesters, can drive the design of more efficient and versatile radiative ambient RF energy harvesters. Furthermore, the London RF Survey results can be reliably used to identify the locations where existing and future harvesters can be placed in London, depending on the harvester's cold-start specifications.

III. IPT COIL DESIGN AND DRIVER

An alternative to the far field or radiative-WPT technology described in Section II (for ambient RF energy harvesting) is near field or inductive-WPT, more commonly known as inductive power transfer (IPT) . Here, radiation is kept low to increase the overall system efficiency.

In this section, we point out key figures of merit for an IPT system and will show measurement results for an IPT link driven by a tuned semi-resonant Class-E driver, across different vertical offsets and misalignment conditions having a coil separation of 30 cm. The optimization process of the IPT system is focused on increasing the dc-load efficiency ($\eta_{dc\text{-}load}$), as shown in Fig. 5 and determined as follows:

$$\eta_{dc-load} = \frac{P_{load}}{P_{dc}} \tag{1}$$

where P_{load} is the power dissipated in the load and P_{dc} is the total dc power coming from the power supply units at the input.

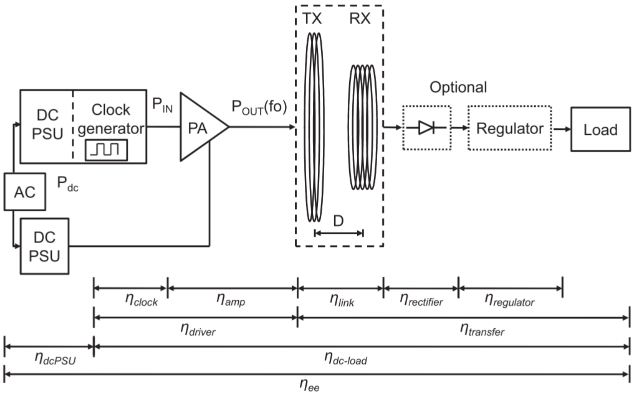


Figure 5. IPT system architecture [10].

It is important to emphasize that the link efficiency η_{link} does not describe the overall system's efficiency. Concentrating only on the link becomes a limitation to the system performance, since the driver efficiency η_{driver} is a major part of the system and can drop the system's efficiency considerably. An example of this can be seen in [4], where the system's efficiency was 15% even with a link efficiency of 50%, due to the use of an inefficient Coplitts oscillator.

This can be overcome by designing an efficient driver that maximises the link efficiency of a specific coil set design. By designing a bespoke amplifier, the unloaded Q of the transmitting TX and receiving RX coils can be maximised by setting the operating frequency just below the point at which the radiation resistance of the largest coil starts to dominate, as explained in [5], [6].

To achieve this high Q operation, the driver is designed to achieve the high frequency required to maximize the Q of the coils (15 cm diameter three turn TX copper pipe coil and a 10 cm diameter five turn RX copper pipe coil). The semi-resonant Class-E amplifier is an ideal solution, since zero-voltage and zero-current switching can be achieved with the appropriate choice of components. Furthermore, efficiency can be increased by avoiding the use of 50 Ω terminations, as used in [7]–[9].

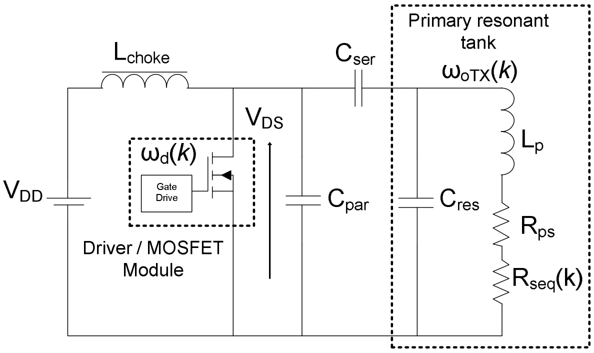


Figure 6. Semi-resonant Class-E topology [10].

By avoiding the impedance matching network required by the latter termination, and using the coil's equivalent lumped components, the TX coil and the reflected load can be integrated into the Class-E design, as shown in the previous figure.

In a semi-resonant Class-E topology, the effective load resistance (composed of the transmitter coil series resistance R_{ps} and the effective receiver resistance $R_{seq}(k)$) and transmitter coil inductance L_p, appear to be larger, thus helping to increase both driver and link efficiencies. This is achieved by tuning the loaded transmitter resonant tank to a higher driven resonant frequency $\omega_{oTX}(k)$ than the receiver resonant tank driven resonant frequency $\omega_{oRX}(k)$, at which the MOSFET gate driver switches at an operating frequency $\omega_d(k) = 1/T$, as shown below:

$$\omega_{oTX}(k) > \omega_{oRX}(k) \equiv \omega_d(k) \tag{2}$$

IV. VERSATILITY ANALYSIS

Dc-load experiments were performed with perfect alignment of the coils and with various misalignments scenarios to test the versatility of the system. Efficiencies of 66% were achieved at an operating frequency of 6 MHz and a distance of 30 cm with a received power of 68 W [10]. This efficiency was demonstrated by a finely tuned Class-E driver for perfectly aligned coils, as shown in Fig. 7, with transmitting and receiving coil unloaded Q-factors of 1270 and 1100, respectively.

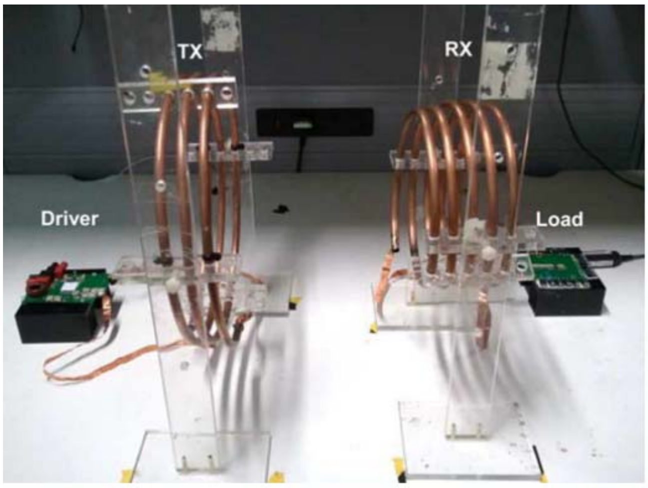


Figure 7. IPT prototype with semi-resonant Class-E driver [10].

To demonstrate the versatility of the system, dc-load efficiency measurements were performed while varying vertical offset (h) and the receiver coil angular misalignment (θ_{RX}), as shown below.

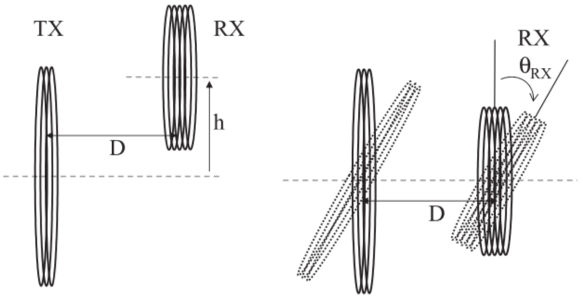


Figure 8. Vertical offset (h) and RX angle misalignment (θ_{RX}) [10].

Figure 9 shows the measurement results for variable vertical offset when the driver was only tuned to the initial condition $h = 0$ cm. Even though no tuning was performed throughout the experiment, efficiencies higher than 25% were achieved with an offset of 20 cm. It is important to note that this was achieved without any field shaping enhancement techniques.

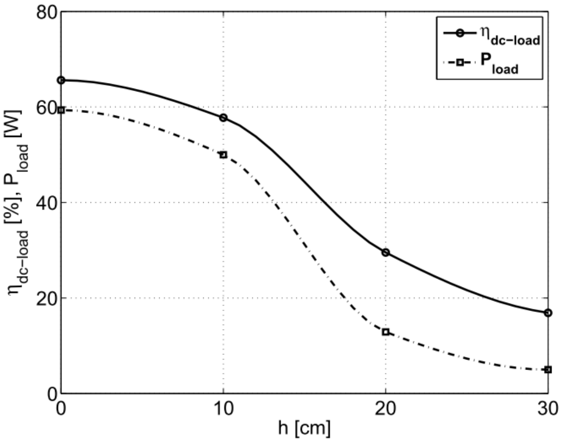


Figure 9. Measurement of the dc-to-load efficiency against vertical offset [10].

The dc-load efficiency can be optimized by varying the clock frequency until the zero-voltage, zero-current switching is achieved. Although this is not the best optimization technique, since the maximum dc-load efficiency should be reached by modifying the load which would result in a completely different selection of Class-E amplifier components, a noticeable efficiency improvement can be seen in the following figure after performing frequency tuning.

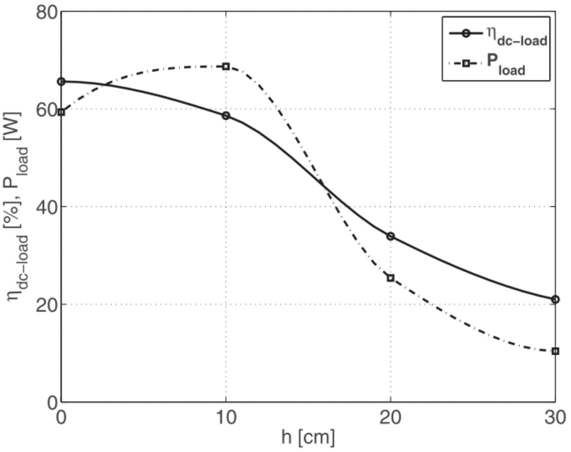


Figure 10. Measurement of dc-load efficiency against vertical offset with frequency tuning [10].

Efficiencies above 10% for an offset of 30 cm were achieved compared to an efficiency of 6% with no frequency tuning. A small variation of less than 1% in the clock frequency achieved a 4% efficiency increase in efficiency.

To quantify the capabilities of the system to transfer energy to a skewed receiver, with and without frequency tuning, experiments were undertaken by varying the receiver angle from 0 to 90º, as shown in Figures 11 and 12.

Applying the clock frequency technique yielded an almost flat efficiency above 50% for offset angles up to 52º. These results show the dramatic effect that a small variation on the frequency can have by increasing by more than 12% the efficiency of the system without physically changing components or adjusting the load.

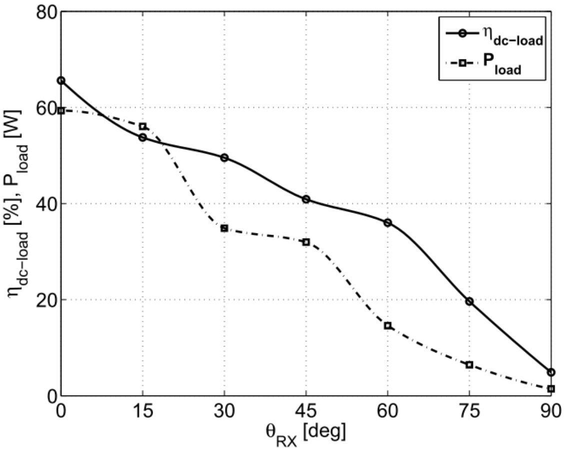


Figure 11. Measurement of the dc-load efficiency against receiver coil angular missalignement [10].

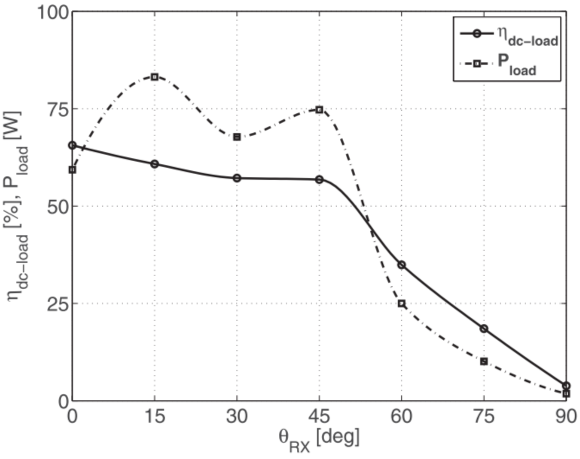


Figure 12. Measurement of the dc-load efficiency against receiver coil angular missalignement with frequency tuning [10].

V. CONCLUSIONS

Results of a city-wide RF survey in London have been presented and used to design radiative ambient RF energy harvesters, single and multi-band, capable of operating in more than 50% of the underground exit stations with efficiencies of up to 40%. Moreover, an alternative wireless power transfer technology, using IPT without coupling factor enhancement techniques, was capable of transmitting more than 105 W with an efficiency of 77%. This efficiency was achieved when transmitted power was increased after performing the versatility analysis presented in this work. This system is capable of achieving efficiencies of more than 50% for an offset of *h* = 14 cm and for RX coil angular misalignments of up to 52º. This was achieved with adjusting the clock frequency for different coupling factors, presenting a relatively simple optimization solution for inductive power transfer links.

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