RF Energy Harvesting for the Low Energy Internet of Things

Abstract: *RF energy harvesting has been under development for many years but it has so far been limited in its application and commercial deployment. One of the main limiting factors has been the ability to design an RF energy-harvesting system that can operate at a high enough efficiency to harvest ambient RF energy from the very low power densities that are present in most city, home and office locations. As a result, current commercial systems require the use of a dedicated transmitter to boost RF power density levels to provide sufficient harvested power to undertake useful work. This white paper considers recent technical advances in RF Energy Harvesting at Drayson Technologies and the potential impact on the deployment of Low Energy Internet of Things devices and applications powered exclusively by harvesting of ambient RF energy.*

Key words: *Ambient RF energy; RF Energy Harvesting; Freevolt™; Harvesting Efficiency; Internet of Things; IoT; Low Energy IoT; LE-IoT; Battery Lifetime; RF Power Density; Battery Swap; WiFi; Cellular; Broadcast; Frequency Bands; RF-DC*

I. INTRODUCTION

Radio frequency (RF) energy harvesting circuits have been under development for over 50 years, however these systems have primarily been based on dedicated RF transmitting sources and directional or beam forming antennas[1]. This inflexibility and high system cost has therefore resulted in limited commercial success.

An alternative energy harvesting approach is needed if ambient RF energy harvesting is to be considered a widely applicable power source for the 26 billion Internet of Things (IoT) devices and the anticipated $300 billion industry being predicted by 2020[2]. Photovoltaic, thermoelectric, and piezoelectric energy harvesting systems have been developed as technologies that can power Low Energy Internet of Things devices (LE-IoT). These technologies have their own inherent limitations, such as moving parts, fragility, and most importantly the constant presence of the energy source: solar energy harvesting only being available during daylight hours for example.

Harvesting ambient RF energy, from WiFi, cellular networks and broadcast masts, offers an alternative solution to powering LE-IoT devices and could provide enough energy to extend the lifetime of these devices.

This white paper explores and proposes an RF energy harvesting technology called Freevolt™ based on research initially carried out at Imperial College London and further developed by Drayson Technologies Ltd.

II. RF ENERGY HARVESTING HISTORY

There continues to be strong growth in the number of companies and research institutions working in the field of energy harvesting. In 2014, the UK Technology Strategies Board (TSB) – now renamed Innovate UK – identified 29 UK universities, 74 principal investigators and 130 companies working in the energy harvesting supply chain[3], an increase from the 10 UK universities identified in 2010. This clearly demonstrates a strong interest in energy harvesting across multiple industries. The TSB report also highlighted that although there was a strong and increasing energy harvesting research base and the early identification of industrial sectors with potential, this had not yet translated into significant sales revenues.

Drayson Technologies has been investing for a number of years to further develop ambient RF energy harvesting PhD research originally carried out by Dr. Manuel Pinuela (now CTO of Drayson Technologies)[4] and its evolution throughout the last three years with Dr. Bruno Franciscatto[5] and the R&D team at the company. The result is an RF energy harvesting technology that overcomes many of the challenging technical issues that have limited the use of RF energy harvesting in the past. The first commercial application of this new RF energy harvesting technology, branded Freevolt, is now being commercially deployed. This work has also evolved into multiple patent applications covering all aspects of the RF energy harvesting technology owned by Drayson Technologies.

III. HARVESTING FROM RF SIGNALS

Energy harvesting (EH) may be defined as the process of transforming ambient energy into electrical energy. Radiant (solar, infrared, radiofrequency), thermal, mechanical and biochemical are examples of the different forms of ambient energy. The energy harvesting efficiency can be defined as the ratio between the converted DC power and the available source of energy.

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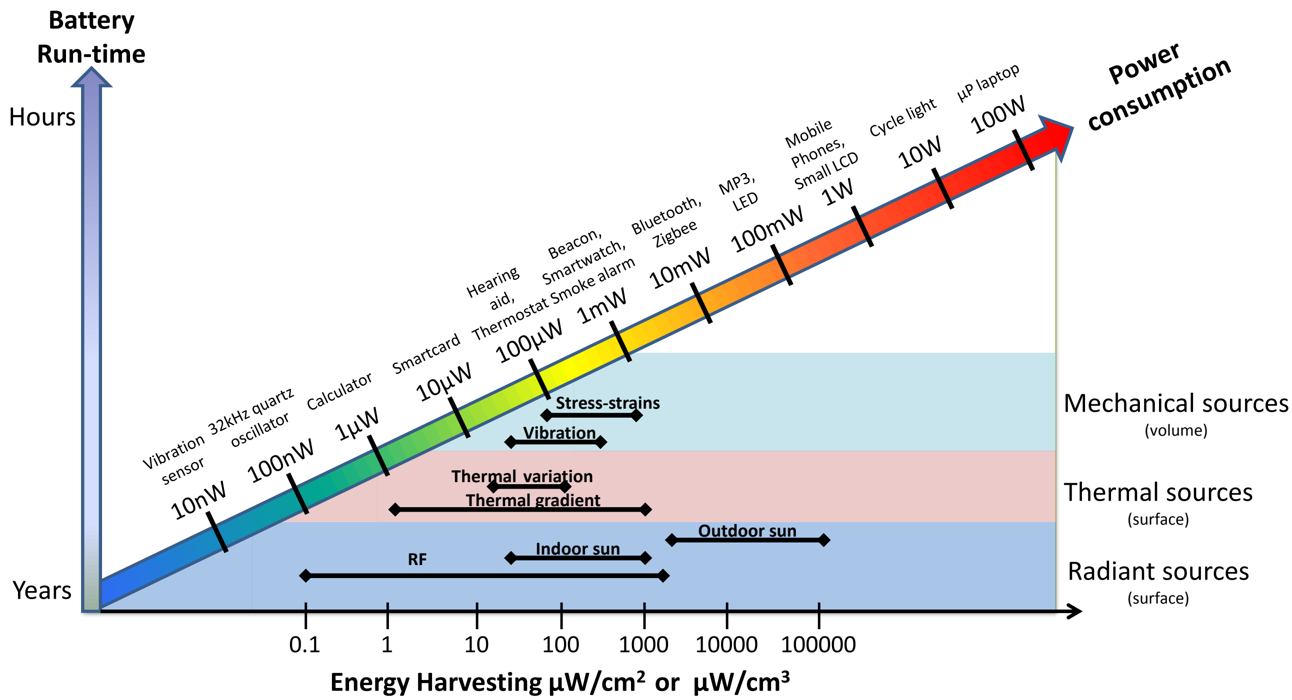

Fig. 1. Overview of the power densities from various energy sources and average power consumption of electronic devices and systems[5].

Among the different energy sources available around us, outdoor photovoltaic energy is the most powerful source of ambient energy, as shown in Fig. 1, but the conversion efficiency presents very low values of energy harvesting, (around 10%[6]). Moreover, the photovoltaic panels will only be able to provide this efficiency during a few hours per day depending on solar incidence.

Thermoelectric energy harvesting needs a constant temperature gradient to achieve the peak of efficiency. For a temperature gradient of 10˚C, the efficiency would typically be 3% and even for a 100˚C temperature gradient, an efficiency of 20% is expected[7].

Piezoelectric energy harvesting requires a specific and constant vibration frequency to have medium-high conversion efficiency[8,9,10].

Radio frequency (RF) energy harvesting requires sufficient levels of ambient RF energy density to be effective. In contrast to many other energy sources, RF signals are purposely generated and regulated[11]. Due to the development of new radio technologies, the radio spectrum is becoming heavily populated: television, radio, cellular, GPS, WiFi, satellite and radar, among many others. Each of these frequency bands has an associated standard, which stipulates how it is used and the amount of RF authorised power to be transmitted[12]. Depending on the location the RF power, energy densities can vary from 0.01 µW/cm^2 to 100 µW/cm^2, and in some cases, where a dedicated RF transmitter is available, the RF power density can reach 300 µW/cm^2.

Mobile network growth continues to expand exponentially, driven by mobile broadband access, smartphones, tablets and applications such as mobile video and social networking[13]. A broad range of frequency bands are used by mobile operators, from 450 MHz up to 3.5 GHz[14]. It is noted that the International Telecommunication Union will be debating additional spectrum allocation as part of the World Radio Communication Conference (WRC) process and WRC19 agenda[15]. Combined with the continued growth of WiFi enabled equipment[16], RF energy density will continue to increase year on year, expanding the possibilities of deploying devices powered by Freevolt ambient RF energy harvesting.

IV. Freevolt Concept

Freevolt is a patented[17] technology that harvests ambient RF energy from existing wireless data and broadcast networks. It does not require a dedicated transmitter or any modifications to existing RF energy sources such as WiFi routers. The Freevolt harvester consists of an antenna and associated circuitry (Rectifier + Power Management Module) that harvests radio frequency energy mainly from the carrier waveform of wireless network and broadcast transmissions, as described in Fig. 2. When a low energy device is fitted with a Freevolt harvester, RF signals are converted into direct current (DC) power. This power can then operate low energy devices or trickle charge energy storage devices, such as batteries or super-capacitors.

Ambient RF energy harvesting can reduce the installation and maintenance costs of having to change batteries integrated within billions[18] of devices. Most importantly, it

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enables the cable free installation of connected devices in hard to reach or dangerous locations.

By providing an “always on” source of energy for low power devices, ambient RF energy harvesting reduces the dependency on battery swapping or plug in charging, while unlocking the full potential of the Internet of Things.

A. *How does it work?*

Freevolt’s high-efficient harvester is composed of an antenna, an impedance matching network, followed by a non-linear component, ending with an RF filter and Power Management Module (PMM) Fig. 2[19, 20].

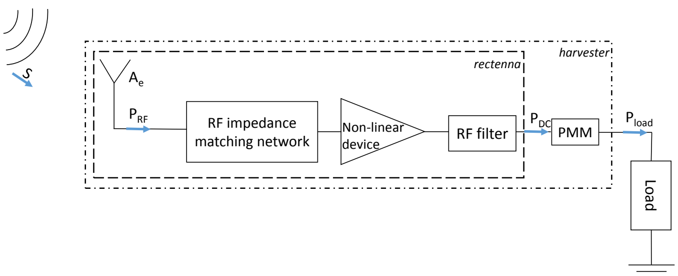

Fig. 2. Freevolt harvester block diagram.

To integrate Freevolt into different devices Drayson Technologies has developed standard harvesters but can also provide different antenna and rectifier designs, depending on the application requirements. It is important to note that a harvesting antenna can have different and unique characteristics depending on the application. For example, if the application is for a device placed on a wall, the antenna can be optimised to cover a broad angle and have the appropriate polarisation and frequency bands to take advantage of the maximum number of existing RF sources. Drayson Technologies has performed extensive RF surveys in different environments to ensure that the correct antenna and rectifier designs and form factors are achieved to maximise Freevolt’s operation depending on the use case. In some situations, to reduce the size and increase the efficiency of the harvester, the antenna can be conjugately matched to the rectifier. This will enable a standardised design for specific applications to simplify product manufacturing and speed time to market.

Flexible conformal rectennas are suitable for applications like smart bands or smart watchstraps. Classical microstrip rectennas can be easily integrated into the already existent PCB designs in various applications.

B. *Energy Harvested*

The amount of DC power that a Freevolt harvester can deliver to the load (P_{load}) depends on the RF power density available (S), effective aperture area of the antenna (A_e), RF-DC conversion efficiency ($\eta_{RF/DC}$) and finally the PMM efficiency ($\eta_{DC/DC}$), as described in Eq. I.

$$P_{load} = SA_e\eta_{RF/DC}\eta_{DC/DC} \qquad \text{I}$$ [5]

The amount of the power delivered to the load (P_{load}) depends on the efficiency of the various system blocks throughout the harvesting process and most importantly on the available RF power density. In this case, RF power density can be defined as a function of the RF input power (P_{RF}):

$$S = \frac{P_{RF}}{A_e} \qquad \text{II}$$ [5]

where the effective aperture area of the antenna is given by:

$$A_e = \eta_{ant} D_{ant} \frac{\lambda^2}{4\pi} \qquad \text{III}$$ [21]

η_{ant} is the antenna efficiency, D_{ant} is the antenna directivity and λ is the wavelength in the air.

The RF-DC conversion efficiency ($\eta_{RF/DC}$) is directly proportional to the DC power (P_{DC}), divided by the RF input power (P_{RF}):

$$\eta_{RF/DC} = \frac{P_{DC}}{P_{RF}} \qquad \text{IV}$$ [5]

The Freevolt PMM is responsible for efficiently charging the storage element (e.g.: battery, super capacitor, etc.) and ensuring that a usable DC voltage is provided even in low power density situations.

Finally, the Freevolt end-to-end efficiency is defined by:

$$\eta_{end-to-end} = \frac{P_{load}}{P_{RF}} \qquad \text{V}$$

As it will be described in section VI, the ambient RF power densities are very low. Fig. 3 illustrates how much DC power one of the Freevolt harvesters with different antenna types is able to harvest depending on the available RF power density in the 2.4 GHz ISM band. As described in Fig. 3 depending on the application, Freevolt harvesters could be designed to extract energy even from a very-low RF power density.

C. *Freevolt advantages*

Freevolt has a unique and proprietary design where wireless RF energy is harvested to power low energy devices. Without adding any major complexity to the device, Freevolt technology can be added to the electronic circuitry, enabling the device energy storage source to be constantly trickle charged, extending the lifetime of the device.

An example of this is a wireless sensor, a wireless sensor node or a retail beacon. These devices generally need to have their batteries changed regularly, which requires manpower and the associated battery cost. For example, retail beacons are usually located in difficult to reach locations to reduce the occurrence of device or battery theft, further increasing the cost of battery replacement due to additional manpower costs.

When considering low energy devices like wearables, sensors and some smart home devices like a smoke detector, thermostat or security or monitoring camera, the value of ambient RF energy harvesting comes from the knowledge that the device may never need a battery replacement during its lifetime.

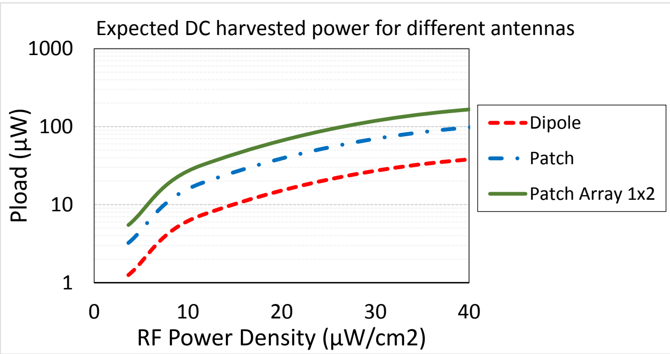

Fig. 3. Freevolt harvested power (DC) depending on the available power density in the ISM 2.4 GHz band.

Freevolt enabled devices can also be hermetically sealed if required, making it possible to deploy a fully weatherproofed device in harsh environments.

V. Freevolt Application – CleanSpace™ Tag

Freevolt RF energy harvesting technology has been first demonstrated in the CleanSpace Tag, a personal air quality sensor that measures carbon monoxide and links to an application on the user's smartphone. A Freevolt harvester with dual band 1800 MHz – 2.45 GHz band antennas, as shown in Fig. 4, harvests enough energy to perpetually power the Tag for the lifetime of the sensor.

VI. Freevolt™ RF Energy Harvesting

Drayson has developed its Freevolt RF energy harvesting technology to address the power and battery lifetime needs of the LE-IoT industry. Freevolt has been designed to extend the battery life of LE-IoT devices indefinitely, for many applications, or to vastly extend the time between battery swaps, therefore reducing the economic cost and environmental impact of batteries being changed out multiple times during the lifetime of billions of devices.

A. Technical Challenges

The technical challenge of harvesting RF energy in office, retail and city environments originates mainly from the variation in RF energy density in different locations. The increase in office and city WiFi and denser mobile phone coverage has, however, improved the viability of RF harvesting for multiple applications.

To determine the level of RF energy density in different locations, Drayson Technologies carried out a broad power density study in multiple locations around London. A summary of the results is presented in this white paper.

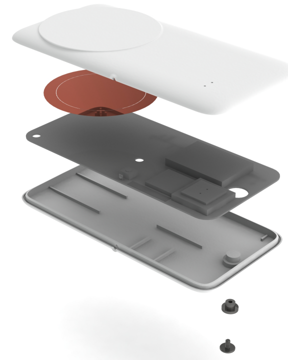

Fig. 4. CleanSpace™ Tag personal air quality sensor powered by Freevolt technology.

B. Power density study

Various locations around London were selected to carry out RF energy measurements. These included an office in a central city area, tube and train stations, retail shops, high streets, as well as larger retail establishments.

An SRM-3006[22] (**S**elective **R**adiation **M**eter), frequency selective measuring system from NARDA Safety Test Solutions was used for the environmental measurement of the high frequency electromagnetic fields.

The RF bands measured in the study are shown in Table 1. For each location, a set of measurements was taken in numerous sections/zones in order to best understand the variations of each frequency band throughout the area. This provided a range of expected power densities and after data post-processing an estimation of the energy that could be harvested in each environment. Over 50,000 samples were taken throughout London during July and August 2015.

Band	Frequencies (MHz)
DTV	470-610
GSM/4G LTE 900	791-960
GSM/4G LTE 1800	1710-1876
3G (MTx)	1920-1980
3G (BTx)	2110-2170
ISM WiFi 2.4 GHz	2400-2495
4G LTE 2600	2500-2690
ISM WiFi 5 GHz	5150-5725

Table 1: Radio Frequency bands measured in the energy density study

C. Office coverage

Variations of power density were measured in a four-story London office block. Measurements were taken across different rooms and floors in the building as well as numerous discrete locations in the offices.

Upper and lower WiFi frequencies had the highest average power densities while the 3G (2100 MHz) and LTE (2600 MHz) average power densities were the lowest. The highest peaks recorded were in the sub-micro-Watt per square centimetre range for both WiFi frequencies as well as the GSM/4G LTE 900 band, which were around 600-700 nW/cm^2.

D. Other locations

Similar measurements were taken for the power densities in outdoor environments around London. Measurements were taken in areas such as Oxford Circus, Piccadilly Circus, Canary Wharf, as well as various other streets throughout the city.

The highest average power densities measured in outdoor areas around London, were predictably in the GSM, 3G, and 4G bands. Peak power densities measured were in the micro-Watts per square centimetre range for these cellular bands, the highest being 6.7 uW/cm^2 in the 3G band. In comparison to office measurements, significantly lower power densities have been measured for the WiFi bands overall, with some peaks measured near tube stations. Measured Digital Television (DTV) levels were relatively low for both indoor and outdoor environments around London.

VII. Energy Budget

In order to assess the feasibility and application areas for Freevolt, an energy budget study was conducted on various low energy Internet of Things (LE-IoT) devices. As previously mentioned, Freevolt is not intended to replace the battery but to extend the life of the device and reduce the economic and environmental cost of battery replacement.

The first step is to assess a device's average power consumption. Performing this analysis, a Year in the Life (YiL) model has been developed that matches the different environments that a device will be exposed to with the RF power densities available in each environment (office, retail, home, etc.). This model then provides an indication of the device's extended battery life using Freevolt ambient RF energy harvesting.

A typical CR2032 battery has 240 mAh capacity[23]. A connected device with a 6 month battery life, yields an average current consumption of 0.055 mA. There will be periods of higher current demand by the device, such as when the wireless radio is transmitting. Equally, there will be periods when the current consumption is lower than 0.055 mA, for example when the device is in sleep mode. Multiplying the average current by the battery voltage, the estimated average power consumption of the device is obtained, in Watts (W). For the connected device above, the average power consumption is approximately 165 μW.

Once the average consumption of the device is calculated, a Year in the Life model can be created. At this point, the expected application of the device needs to be determined, *i.e.* will the device be in a fixed location, such as on a wall, or will it be portable, carried around in a bag, or pocket. For example, a portable device will be exposed to different RF environments, each with varying power densities across different frequency bands (WiFi, GSM 1800, etc.). On the other hand, a fixed device will be in a static location, whereby the RF power densities around the device will be relatively consistent, with some variations due to multi-path effects [24 25].

Regardless of the fixed/portable nature of the device, many of the principles and assumptions for the YiL model calculations remain the same. The device's energy consumption, in Joules, is calculated using the average power consumption over the period of one year. The energy harvested, depending on whether the device is fixed or portable, is also calculated over the period of one year.

For the fixed location device, the energy harvested in the anticipated environment is calculated using the results from the Power Density Survey. The power density measured in the designated environment, an office for example, is coupled with the rectenna performance to determine the expected output power obtained from the harvester. With the expected output power, the estimated harvested energy over a period of one year is determined.

For the portable device scenario, certain assumptions are made on the different periods for which the device will be exposed to varying RF sources. For example, during the week, a person carrying a device may spend around 8 hours at the office. From the Power Density Study, the largest contributor in an office is generally 2.4 GHz WiFi, and therefore the energy harvested over the 8 hour period is calculated.

A study conducted in the UK found that the average person sleeps 6 hours 35 minutes per night[26]. Using this period, as well as taking the power density measured in a typical bedroom/home environment, the harvested energy while sleeping can be added to the model. Another similar study found that the average person in the UK spends approximately 3.3 hours on their mobile phones – a multi-band source which is carried around similarly to how a portable sensor or wearable might be used[27]. Similar data can be obtained for when the person and, therefore, device is at home, exercising, or whilst commuting – each time using the largest RF contributor for each environment. The expected harvested energy over the course of a year can be calculated by aggregating all of these harvested energy fragments to map out a typical day, week, and month for a device, and the associated RF environments they will encounter.

With this data an estimation is made using the device's energy consumption as well as the energy harvested over a year to calculate the energy budget. Assuming that the device, now with ambient RF energy harvesting, would use a battery with the same capacity, the new extended battery life can be calculated.

As an example, a low power commercially available temperature and humidity sensor requires approximately 3.2 μJ to take a reading. Using the Power Density Survey data, the average RF density measured in an office or external environment ranges from 20 to 35 nW/cm^2. This power density yields an estimated harvested energy between 5.5 and 10 Joules over a one-year period. As a result, placing the sensor in either environment would allow for over 1.5 million readings – this is equivalent to over 4,000 per day.

Looking at comprehensive wireless sensor packages, a wireless tracking node that has a battery capacity of 230 mAh and life of 12 months, can now reach up to 58 months autonomy using Freevolt, when exposed to various RF sources on a daily basis. Another example is a wireless thermostat node, powered by a rechargeable coin cell battery, which can extend its battery life from 9 months to 24 months with Freevolt ambient RF energy harvesting.

VIII. Conclusion

Harvesting low levels of ambient RF energy from various energy sources has been proven to be suitable for powering low energy devices and can extend the battery lifetime in such devices. Depending on the energy budget of the device it is possible, in some cases, to perpetually power the device so that the battery or energy storage unit never needs to be swapped or charged via a cable.

Although the RF energy is very low - RF power densities up to 300 uW/cm^2 have been measured - power density does vary by location. Overall, the energy that can be harvested with a Freevolt ambient RF energy harvester has been validated as sufficient to trickle charge an energy storage device.

By calculating a year in the life of a device, either in a fixed location or as a portable device, it is possible to calculate an energy usage and harvesting budget to ascertain the overall lifetime of the device – before it needs to have the energy storage device changed or charged by cable.

Finally the value proposition of ambient RF energy harvesting comes from extending the battery life of IoT devices, in some cases perpetually, which can vastly reduce the installation and maintenance costs for devices such as beacons or industrial sensors. For consumer devices like wearables – or smart home IoT devices – Freevolt technology creates a far better user experience due to the extended time between battery changes or the knowledge the battery may never need changing or charging via a cable.

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About Drayson Technologies

Drayson Technologies Ltd is a development stage electronics and software company headquartered in London with offices in Silicon Valley focused in the field of wireless energy transfer. Drayson Technologies is exploiting a new patented technology, called Freevolt™ that "harvests" energy from ambient wireless radio frequency networks, (WiFi, Cellular, Broadcast TV) to power low-energy electrical devices and eliminate the need for cable charging or changing batteries. The initial implementation of Freevolt RF energy harvesting is in the CleanSpace™ Tag, a personal air pollution sensor that is totally portable.

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