Feasibility Analysis of RF Energy Harvesting for Internet of Things (IoT) Devices

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***Abstract*—Energy harvesting is a method to extend the useful life and to give autonomy to the Internet of Things' devices. This work focuses on the radiofrequency energy harvesting for wireless devices. A feasibility study was carried out to evaluate the amount of available energy in Palihue Campus in Universidad Nacional del Sur, together with the applicability of energy harvesting to a node's operation during a work cycle (sensing, processing and transmission). The results show that is possible to use 4G band 28 (mobile) and Wi-Fi bands (between 2.4 and 2.5 GHz) to power IoT nodes with elementary sensing and transmission tasks.**

***Index Terms*—Internet of Things, Energy harvesting, Wireless devices, Feasibility Study.**

I. INTRODUCTION

Internet of Things (IoT) is a network of devices connected to the Internet that can be monitored, detected and controlled. The objects are part of an IoT platform, which collects and processes data from the devices in order to detect patterns, make recommendations and predict problems.

IoT applications are almost endless, standing out its use in medicine, science, factories, agriculture, autonomous driving, wearables, logistic and smart homes. Given the variety of possible applications, the characteristics of IoT devices vary widely. There is, however, a shared topology among them. The main parts of an IoT node are the battery or power supply, the transceiver, the microprocessor and the sensors or actuators.

Many applications require a large number of IoT nodes, where the number of devices within the network can vary from a few to hundreds. At the same time, the access to the node is sometimes limited since they are often located in remote places, embedded in complex structures or even inside the human body. Additionally, some applications need solutions that involve mobile devices. Because of that, a wired connection is unfeasible in the majority of the cases and a wireless communication remains as the only option.

Although batteries are the most widespread power source for wireless devices, they have some limitations in the IoT scenario. First, battery recharge or replacement is a difficult task given the amount of devices and their inaccessibility. Second, high-capacity batteries are bulky in comparison with the rest of the components, which increases the size of the implementation. To overcome these limitations, energy harvesting techniques can be used to allow the operation of the nodes without maintenance [1].

Energy harvesting (EH) refers to the use of energy from the environment to power the devices, after converting it to a DC voltage. The main energy sources are solar, mechanical, thermoelectric, and electromagnetic radiation. The levels of harvested energy are strongly dependent on the source, varying from micro-Watts to milli-Watts. These alternative sources can be used alone or combined to feed the devices, replacing the batteries or at least increasing their durability. Moreover, as these methods use energy that otherwise would be wasted, they provide a green solution to the problem of powering a huge amount of devices, and lead to a reduction in the carbon footprint.

In EH, the available instantaneous power is usually less than the power consumption of the device in active mode, i.e. when it is sensing, processing, or transmitting. Therefore, IoT devices work in cycles, where the node is first in *sleep mode*, harvesting energy for typically a long period of time, and then it switches to *active mode*. When the task is completed or there is no more available energy, the node switches back to sleep mode. As a consequence, the harvested power determines the maximum allowable cycles per unit of time [2].

The energy from electromagnetic signals is obtained by rectifying the radiofrequency (RF) signals collected by the node antenna, where the combination of the antenna and the rectifier is known as *rectenna*. The RF sources can be divided in dedicated or ambient sources, where the first one refers to the transmission of an ad-hoc signal to power the device, and the second to the use of signals of other sources already present in the environment, such as: cellular, TV, and Wi-Fi signals. Given the ubiquitous presence of radio-frequency (RF) signals and that dedicated sources are not renewable, in this work we consider EH from ambient RF signals.

The main disadvantage of RF EH is the low level of available energy, being one of the weakest among all the energy sources. Additionally, contrary to what happens in urban zones, in rural areas the available energy is extremely low, becoming insignificant in some depopulated areas. Additionally, as the rectifier efficiency decreases with the increase in the antenna bandwidth, it is necessary to determine which bands are the best to harvest. Typical options include TV, Wi-Fi, and cellular providers, but as the activity on those services varies in the different countries and areas, a local measurement campaign is needed.

A feasibility study for the use of IoT devices powered by RF EH techniques in presented in this work. To this end, a measurement campaign was first carried out in a residential urban area of Bahía Blanca city, Argentina, to determine the best bands for RF EH in terms of power levels, regularity, and reliability. Cellular and Wi-Fi bands were considered in the measurements. Then, taking into account the available energy in the most suitable bands and the power consumption of commercial devices in a working cycle, we calculate the maximum achievable amount of cycles per hour.

In Section II we present the architecture of an IoT node, along with the energy consumption model. In Section III, the power spectral density and energy calculations are introduced. Section IV presents the measurement campaign and the analysis of the results, including the determination of the allowable working cycles per hour. Finally, Section V concludes the paper.

II. ENERGY CONSUMPTION MODEL

The architectures of an IoT node varies in sophistication, depending on the conditions of use, the topology of the network and of course the application. If the node has a built-in energy harvester, its topology becomes more complex, taking into account the necessary components according to the type of energy to be used. However, there are some common elements:

- Sensors and actuators, which often include signal conditioning circuits.
- Control unit or processors, typically microcontrollers, with memory and an integrated power manager. Its main task is to control the working cycle and the data processing.
- Communication unit (transceivers), refers to the circuit required for the node to transmit data to the local network or the cloud. Includes the antenna.
- Energy Harvester, depending on the source.
- Energy control unit. This in turn includes the storage of energy (either by supercapacitors or batteries) and the interface circuit that is a transducer of the harvested energy that ensures maximum efficiency. [1].

In the figure 1 there is the block diagram of the topology of an IoT node.

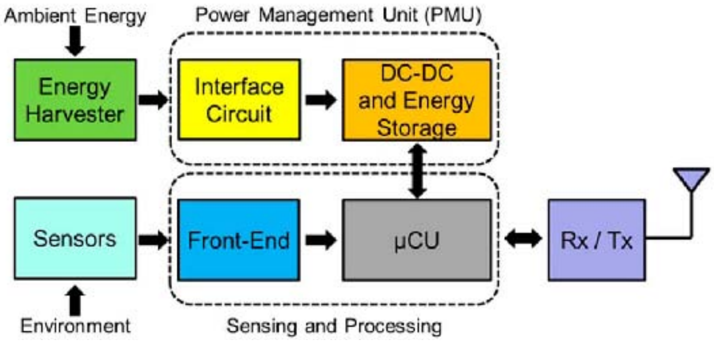

Fig. 1. Block diagram of an IoT node's topology [1].

Electromagnetic sources can be near- or far-field. The first one refers to methods used to supply energy to devices without a physical connection, using coupling mechanisms, over short distances. On the other hand, the second considers techniques that obtain the energy by rectifying the radiofrequency (RF) signals collected by the node antenna, allowing a longer distance between the source and the powered device.

There are two factors linked to the collected energy in far-field sources: the covered frequency bands and the location of the harvester. The first one is important because on one hand the available energy increases for a larger harvesting bandwidth, but on the other hand the efficiency of the rectenna decreases with the bandwidth. The second one, is related with the low density of RF signals in in rural or suburban areas. As a consequence, the determination of the harvesting bandwidth and the location of the device are critical.

The energy harvest circuit works as follows: first, the antenna captures the RF signal from the environment in the frequency bands where energy is available. In cases where it is required to collect energy from different services, multiband antennas can be used. This increases energy availability but makes the antenna design more complex and reduces its efficiency. The signal coming from the antenna adapts to the rectification circuit input to achieve maximum transfer. The energy obtained at the output of the rectification circuit is stored in a capacitor or a battery, for later use. Generally a voltage regulator is used to provide a stable DC voltage for the circuit to be powered [3] [4].

Because of the low level of available energy in RF EH, work cycles are used. In these, periods of activity (sensing, processing and transmission) with suspension periods (energy harvesting) alternate. The challenge is to determine the working cycles that allows the device to obtain the necessary amount of energy to perform the task [2]. However, given the low power available from EH, not all applications are suitable. The devices should be studied and chosen so that their consumption allows the use of the harvested energy. In some cases it is possible to lower the transmission rate as not to consume all the energy before the next recharge.

As mentioned above, one of the main characteristics of energy harvesting is its randomness. To soften this effect, it can be stored in a buffer, such as a supercapacitor or a battery, to balance the energy arrival profile and the energy consumption profile [5].

The mentioned energy consumption profiles varies widely depending whether the device is in active mode or sleep mode. The overall average energy consumption can be found using the following equation [6]

$$E_{avg} = \sum_{i=0}^{n} T_i P_i + \left(T_c - \sum_{i=0}^{n} T_i \right) P_{sleep} \tag{1}$$

where T_i is the time for which the device consumes average power P_i, T_c is the total time of the working cycle, and P_{sleep} is the power consumption in sleep mode.

III. ENERGY CALCULATION

The energy calculations are based on discrete measurements of the power spectral density per bin (measure resolution Δf). In the figure 2 are illustrated the bandwidth resolution Δt, Δf, measurement bandwidth AB and amount of samples n. The grey box represents a frequency bin per unit of time.

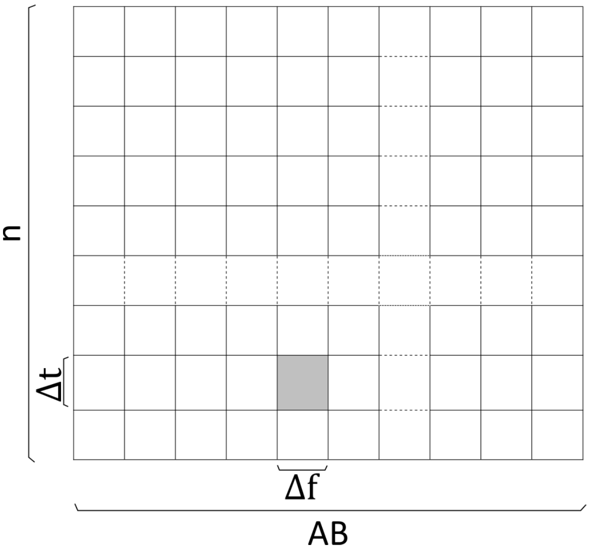

Fig. 2. Representation of Δt, Δf, bandwidth AB and amount of samples n.

The power spectral density in dBW/Hz is obtained from:

$$\frac{P}{\Delta f} = \frac{P_r}{\Delta f} - 30 - G_a + L_c, \tag{2}$$

where P_r is the received power in dBm, G_a is the antenna gain, L_c are the losses in the wire and Δf is defined as:

$$\Delta f = \frac{AB}{N_f}, \tag{3}$$

where AB is the measurement bandwidth and N_f the number of points in frequency taken by the analyzer.

The total energy per cell or bin in Watts-h/Hz is calculated as:

$$\frac{E}{\Delta f} = \sum_{1}^{n} 10^{\frac{P/\Delta f}{10}} \Delta t, \tag{4}$$

where n is the number of samples, and Δt is the time in hours between each sample.

The average energy per cell per hour is calculated as:

$$\frac{\bar{E_h}}{\Delta f} = N_t \frac{E}{n\Delta f} \tag{5}$$

where N_t is the number of samples per hour taken.

To obtain the total amount of energy the spectral density of energy is multiplied with the harvesting bandwidth.

IV. MEASUREMENT CAMPAIGN

The objective of the measurement campaign is the data collection for its further processing and study.

To determine the feasibility of the use of RF EH in IoT devices in urban and semi-urban zones is necessary to know the available energy levels in the main radiofrequency bands (cellular, Wi-Fi, TV).

The measurements were made in the Departamento de Ingeniería Eléctrica y de Computadoras's building in Palihue Campus (see Figure 3). It is located in a non-central urban area in the northern part of the city.

Fig. 3. Aerial View of Campus UNS Palihue (Google Maps). The red arrow indicates the measurement location.

The first campaign was carried out on 12th September with the directional antenna directed to the south-southeast and the second one on 1st October 2018 to the southeast. Figure 4 shows the connection and layout of the equipment used for the campaigns.

Fig. 4. Arrangement of the antenna and equipment used

The directional antenna (R&S HF907) connected to the signal analyser (R&S FSV30) with the wire (R&S HFU2-Z4) was used to perform the measurements.

The linearly polarized R&S HF907 double-ridged waveguide horn antenna is a broadband transmitting and receiving antenna for the frequency range from 800 MHz to 18 GHz. In Fig. 5 it is shown its typical gain.

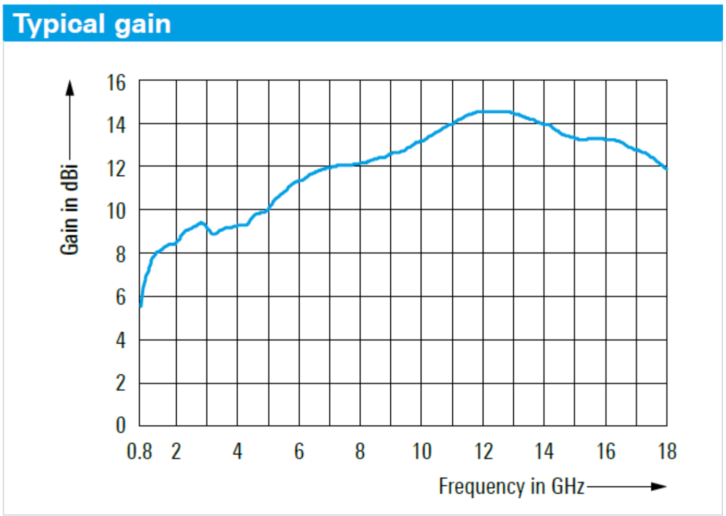

Fig. 5. Typical Gain of directional antenna Rohde & Schwarz HF907.

In the measurements $N_f = 625$ and $N_t = 120$, i.e a measurement every 30s. The analyser was also connected through the local network to a PC running a MATLAB script. From there, the measurements were started and stopped, the parameters were configured and the data was saved. The used software is listed below:

- NI VISA 17.5,
- Rohde & Schwarz VXIplug&play instrument driver (rsspecan 3.9.1),
- MinGW-w64.

In the following, we present the result of the measurement campaign in the range between 750 and 850 MHz, corresponding to band 28 of 4G (mobile telephony). In these frequencies, 127 measurements were made spaced every 30 seconds, equivalent to a time of 1h3'30". In Fig. 6 is plotted the power in dBm for each of the measurements in the frequency range between 750 and 850 MHz. In Fig. 7 the average energy available in the same range was plotted. The graph shows that around 830 MHz the highest energy is obtained, although this value is not regular. In the bands that turned out to be more persistent in time, between 755 and 780 MHz (corresponding to the 4G downlink of Movistar and Personal), 9.19 μWh is obtained

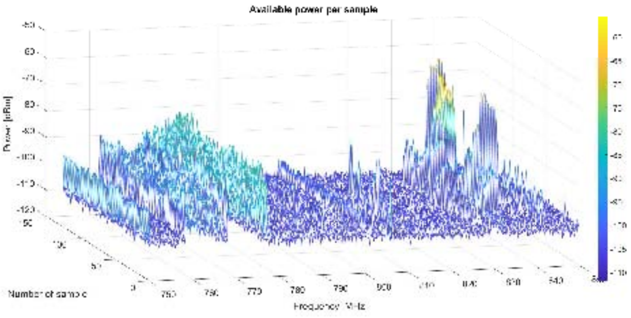

Fig. 6. Swept between 750 and 850 MHz.

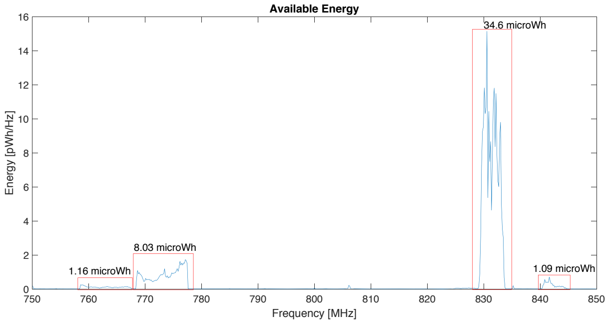

Fig. 7. Energy harvested between 750 y 850 MHz.

In the following, we present the result of the measurement campaign in the range between 1.85 and 1.95 GHz, corresponding to mobile telephony (2G, 3G and band 2 of 4G). In these frequencies, 137 measurements were made spaced every 30 seconds, equivalent to 1h8'30". In Fig. 8, the average available energy in the frequency range between 1.85 and 1.95 GHz was plotted. The power values up to 1.94 GHz are sporadic, from which two persistent bands are clearly differentiated in time.

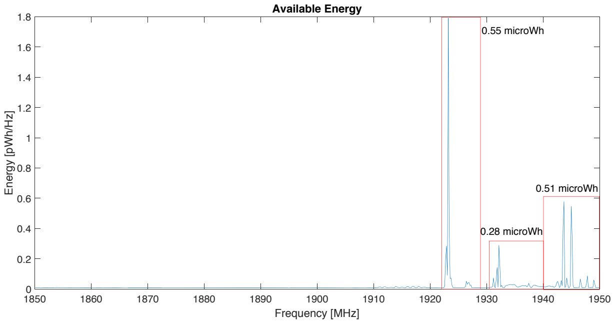

Fig. 8. Energy harvested between 1.85 y 1.95 GHz.

In the following, we present the result of the measurement campaign in the range between 2.4 and 2.5 GHz, corresponding to WiFi (channels 1 to 6 and 11 to 13). In these frequencies, 125 measurements were made spaced every 30 seconds, equivalent to 1h2'30". In Fig. 9 the average available energy in the frequency range between 2.4 and 2.5 GHz was plotted. In comparison with the previous graphs, in this case the power values reached are higher, however, they are more inconsistent, becoming sporadic in some cases.

In order to get a better coverage of the downlink of 4G band 28 (mobile telephony), a second measurement campaign was carried out, with an extended range between 700 and 850 MHz. We also changed the location of the antenna and slightly modified its direction. During this campaign, 627 measurements were made, spaced every 30 seconds, equivalent to a time of 5h13'30", in the range between 700 and 850 MHz. In Fig. 10 the average available energy in the frequency range between 700 and 850 MHz was plotted. It can be seen that between the 760 and 780 MHz the received power maintains its characteristics almost constant in time.

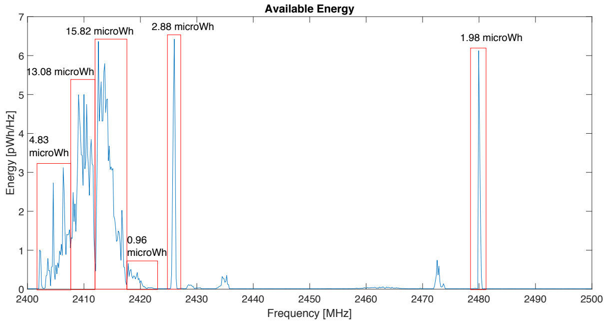

Fig. 9. Energy harvested between 2.4 y 2.5 GHz.

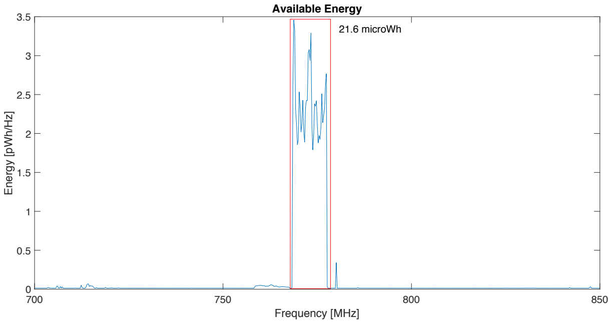

Fig. 10. Energy harvested between 700 y 850 GHz.

From equation 4, the available average energy is calculated. The Table I contains synthetically the energy available for each frequency band.

TABLE I
ENERGY HARVESTED IN EACH FREQUENCY BAND

Freq [MHz]	$E_h[\mu Wh]$
750-850	46.21
1850-1950	2.019
2400-2500	41.229
700-850	23.98

When evaluating EH feasibility to operate IoT devices, it is necessary to consider two important factors. The first one is the level of harvested energy under operating conditions and the second one is the power consumption of the device's components.

The power amplifier, local oscillators, the low noise amplifier, gain stages, and modulators and demodulators, consume a significant amount of energy in a conventional radio [7], where the wireless transceiver consumes the most power when all the blocks are active. In an ultra low power wireless system, all blocks must be specified and carefully designed to minimize the total power of the system [8].

For continuous transmission, all circuit blocks must be turned on for long periods of time to achieve reliable operation, consuming energy even when they are not actively communicating. For low data rate applications, where there is less information to communicate, the simplest way to save energy on a wireless link is to turn on the most energy hungry blocks (the power amplifier, the oscillator and the low noise amplifier / receiver) only when they are required. To do this effectively, the transmission and reception blocks must share certain information and coordinate when each one should speak and listen [7].

There are two modes of operation: the sleep mode and the active mode. In sleep mode, the device stops all operations and enters a low power mode consuming the minimum amount. In this mode, the device is exclusively and efficiently harvesting energy. With enough energy, it transitions to the active mode and the system reads the sensors, transmits data wirelessly to the user (base station), and then enters a state of low power (sleep state) [9]. This period can be of a few seconds or hours depending on how much energy is obtained from the harvest of energy to charge a capacitor to a certain level that allows the system to function again [10].

The Table II summarizes the energy consumed by some commercial devices during a work cycle, i.e. for sensing, processing and transmission. The TC77 is a digital temperature sensor, the MMA7361LC is a low power capacitive micromachined accelerometer, the MCP9700 are sensors whose output voltage is directly proportional to the measured temperature and the CC3120 Wi-Fi wireless network processor consists of a wireless network processor and power management subsystems.

TABLE II
CONSUMED ENERGY BY DEVICE [10]

Device	**Minimum active time**	**Consumed Energy**
TC77	$400[ms]$	$75 - 152.78[nWh]$
MMA7361LC	$0.5[ms]$	$0.12 - 0.2[nWh]$
MCP9700	$0.4[ms]$	$3.07 - 7.3[pWh]$
CC3120	$10[ms]$ transmission, $10[ms]$ reception and $50[ms]$ to wake up from suspension mode	$5.28 - 13.19[\mu Wh]$

The viability of energy harvesting is not only governed by the amount of harvested energy per hour, but also the consumption of IoT devices and the desired data rate. Using (1) the average energy consumed by the device is calculated and then the amount of work cycles per hour that can be completed with the available energy. The consumed energy of the device is multiplied by the minimum active time, whereas the energy consumed during the suspension mode is negligible [6].

Comparing the results of Tables I and II, using the CC3120 and the MCP9700 it is observed that in the band of 750 850 MHz 3.4 work cycles per hour can be completed, in the band of 1850 1950 MHz a work cycle every 6.7 hours can be performed, in the 2.4 2.5 GHz 3 work cycles per hour can be achieved and with the second location of the antenna between 700 850 MHz 1.7 cycles per hour can be completed.

V. CONCLUSION

In this paper we study the feasibility of EH techniques in a local scenario (UNS, Bahia Blanca). The best results are obtained in the bands of 750-850 MHz (4G) and 2.4-2.5 GHz (Wi-Fi), where 3.4 and 3 work cycles (sleep mode and active mode with sensing, processing and transmission) can be completed per hour respectively. With the obtained results, it can be concluded that 4G bands (750-850 MHz) and Wi-Fi bands (2.4-2.5 GHz) can be used to power IoT nodes with elementary tasks. Examples of these are temperature and humidity measurement, among others. For applications that require a higher data rate, other power sources should be sought. Bands between 1.85 and 1.95 GHz (cellular) are not viable to obtain the required energy considering the consumption of actual technology.

There are different alternatives to be studied in future work. The first one is to extend the measured area and time. The second one is to verify the results obtained in this work with a prototype of an IoT device with a built-in harvester.

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