Radio Frequency Harvesting in domestic and office settings: State of the art and perspectives

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ABSTRACT |

Radio Frequency (RF) energy harvesting is the method where the least amount of energy can be harvested compared to solar, vibration and thermal harvesting. There are more and more RF emissions on different frequencies and much of this energy is wasted because it is often emitted omni-directionally. By harvesting this energy, low-power devices could be continuously powered. In this context, we present a study based on two development boards from E-peas for energy harvesting at 2.45 GHz, corresponding to the Wi-Fi band that is deployed worldwide, and at 868 MHz which is an open band (in Belgium) where we find home automation, etc. This article aims to show as much information as possible about energy harvesting with different input powers, and the possible consumption of the output power depending on the storage capacity.

I. Introduction

Nowadays, there are more and more radio frequency emissions all over the world. These emissions are used for many different applications and are also at different frequencies. The frequency plan changes depending on the country but remains mostly in the same frequencies for major radio frequency applications, there are Wi-Fi bands operating at 2.45 GHz / 5 GHz, GSM bands operating at 900 MHz / 1800 MHz, FM bands operating between 87 MHz and 108 MHz, and many more. Most of these sources are emitted omni-directionally, so there is a lot of energy wasted due to non-reception by any device. That's why it would be nice to be able to harvest this energy for low-power applications [1].

Some low-power applications that currently run on batteries, however, may only run on energy harvesting. One of the main advantages is that the RF energy received continuously due to a very large number of radio frequency transmitters. Depending on where you are, outside or inside, the powers that can be received are different. It is therefore important to know where the application should be located. In a domestic environment, there are often one or more Wi-Fi routers that emit in general 100 mW (20 dBm) in all directions.

This paper aims to provide a study on the reliability of RF Harvesting in a domestic environment. Several tests were carried out on development boards of the supplier E-peas operating at 2.45 GHz and 868 MHz in order to show the efficiency of these with different loads and different energy storage capacities.

II. Different Types of Energy Harvesting

There are several types of energy harvesting where each of them works under certain conditions and with different efficiency. It is possible to harvest energy from the environment using vibration/motion energy, thermal energy, light or RF radiation. Table 1, summarizes the power output that could be obtained from its various environmental sources using optimized devices.

Source	Source power	Harvested power
Ambient light		
Indoor	0.1 mW/cm²	10 µW/cm²
Outdoor	100 mW/cm²	10 mW/cm²
Vibration/motion		
Human	0.5 m @ 1 Hz 1 m/s² @ 50 Hz	4 µW/cm²
Industrial	1m @ 5 Hz 10 m/s² @ 1 kHz	100 µW/cm²
Thermal energy		
Human	20 mW/cm²	30 µW/cm²
Industrial	100 mW/cm²	1 - 10 mW/cm²
RF		
Cell phone	0.3 µW/cm²	0.1 µW/cm²

Table 1: Characteristics of different ambient energy sources and power harvesting. [2]

Depending on the environment, some solutions are more suitable than others. The outdoor light outperforms all other energy sources. However, the harvesting energy studied in this article, that is RF energy, is the weakest source and the smallest amount of energy that can be harvested. The RF sources depend on the types of radio frequencies one wishes to harvest. Table 1 shows us for a cell phone source, but many other sources are available at different power levels, so Wi-Fi will be strongly emphasized in our tests.

As far as other sources are concerned, indoor light is comparable to thermal energy and vibrations, and the industrial environment is more favorable in relation to the energy around the body.

III. Radio Frequency energy harvesting

To harvest RF energy, as shown in Figure 1, a specific circuit consisting of one or more antennas, a matching circuit, an RF rectifier and optionally an energy storage element must be implemented. Then we find a voltage regulation in order to supply a low power application and if necessary, a management of the energy storage charging. [3]

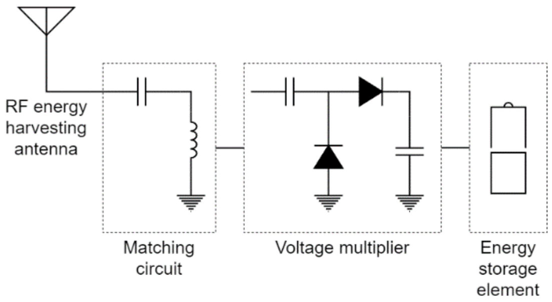

Figure 1: A general architecture of an RF energy harvester. [4]

The following are the main elements:

- The first stage is the antenna, which collects the RF signals. Depending on its type, the antenna is designed to operate at a certain frequency, in broadband or in multiple frequency bands. However, to recover energy at different frequencies, several antennas with different matching circuits will offer better results.
- The second step is impedance matching, which is a resonant circuit operating at the intended frequency to maximise power transfer. This circuit is designed to stay close to the characteristic impedance (often 50 Ohms) in order to have the best SWR.
- The third stage is the voltage multiplier, which consists of rectifier circuit diodes that convert RF signals (AC signals) into DC voltage. This type of circuit is often a Greinacher circuit.
- The last stage, which may be optional, is the storage of the received energy. Ideally, if the application always consumes less than the energy received, there is no need to use storage. However, the storage system is rarely removed due to power peaks during transmission, sensor use, or other consumption, as shown in Figure 2. In addition, energy harvesting may be absent at certain times. The storage system can be a battery, a capacitor, a supercapacitor, etc.

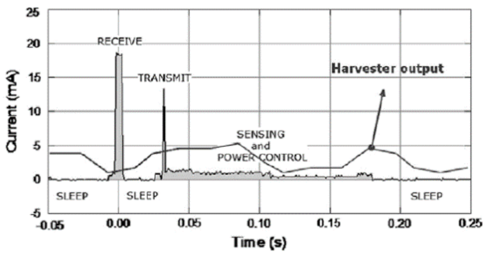

Figure 2: A typical scenario for the power consumption of a sensor node. [2]

Depending on the frequency on which we work, between transmission and reception there is a loss of power in the air. The harvested RF power of a transmitter in free space can be calculated on the basis of the Friis equation (without reflection, interference, etc.) as follows:

$$P_r = G_r . G_t . P_t . \left(\frac{\lambda}{4.\pi.d}\right)^2$$

Where P_r is the received power, P_t is the transmitting power, G_t is the linear transmitting antenna gain, G_r is the linear receiving antenna gain, λ is the wavelength emitted and d is the distance between the transmit antenna and the receiver antenna.

This equation can also be put into a logarithmic form which is as follows:

$$P_r = P_t + G_r + G_t - 20\log(f) - 20\log(d) + 147.5$$

Where P_r is the received power in dBm, P_t is the transmitting power in dBm, G_t is the linear transmitting antenna gain in dBi, G_r is the linear receiving antenna gain in dBi, f is the emitted signal frequency and d is the distance between the transmit antenna and the receiver antenna.

Table 2 shows the application of the Friis equation at different frequencies for a constant transmission of 0dBm with a 2dBi transmitting and receiving antenna at a distance of 1 metre.

Transmitting power: 0 dBm - Antennas: 2 dBi - Distance: 1m				
Frequency	868 MHz	915 MHz	2,45 GHz	5 GHz
Received power	-27.22 dBm	-27.67 dBm	-36.23 dBm	-42.43 dBm

Table 2: Application of the Friis equation, with different frequencies

This result shows that the higher the frequency, the higher the power loss in the air. Low frequencies are more efficient than high frequencies in RF harvesting. Furthermore, the higher the frequency, the harder it is to create circuits and antennas to receive the energy, and therefore the lower the efficiency.

IV. E-peas solutions test

To evaluate the efficiency of energy harvesting, we decided to experiment with the development boards from E-peas [5]. The choice to take boards from E-peas, is explained by the fact that he offered development boards for standardized frequency.

The tests started with the 2.45 GHz board, because we wanted to know if a source like Wireless

Fidelity (Wi-Fi) was able to run the development board (both boards just have different antenna matchers). By putting on two Wi-Fi routers and on the E-peas board antennas, with 5 dBi gain, placed at less than 5 cm, the losses are so big that it was not possible to activate the output voltage (in less than 4H).

To verify that the Wi-Fi routers are working properly, an ambient emission level test has been performed. This test was done with a Wi-Fi analyzer such as "Acrylic Wi-Fi Analyzer". As you can see in the Figure 3 both routers are generally to -15 to -20 dBm and the other ambient Wi-Fi range from -50 to -88 dBm.

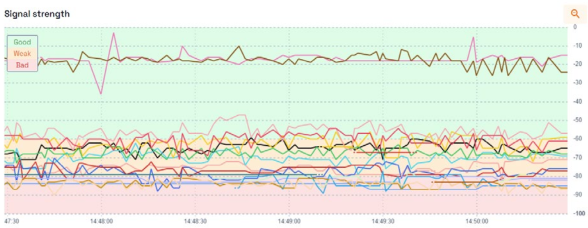

Figure 3: Graph of Wi-Fi power

Based on its first results, but also on the characteristics of the cards from E-peas (minimum input power of -20 dBm), the possibilities of using as a source of energy the Wi-Fi of a company or domestic will not be viable with these cards, since the sources and receiver must be too close.

The purpose of the research is to be able to characterize the boards and see the possibilities of it. The second test was to know the time it takes to charge a 1000 µF capacitor with different powers received at the input of the 2.45 GHz board. The results represented on the Figure 4 show how the capacitor charges according to different powers and according to the inputs[1]. The signals sent are continuous and not in bursts, like Wi-Fi. The results obtained are linear[2], no matter the power received.

NB: The tests for signals above 0 dBm have not been performed because the equipment for this study did not allow it.

Another important parameter is to know the time of use when the capacitor has been changed completely before. The Figure 5 shows the result time that the user can expect according to the current required (output voltage chosen was 1.8 V, but can be from 1.2 V to 3.3 V).

The last test describes, with the Table 3, the maximum current that can be used to make the system work permanently and not to have active and sleep phases for the system supplied by the board from E-peas.

Minimum input power (dBm)	Permanent current of (µA)
-12.87	0.21
-11.91	1.8
...	...
-2.86	81.81
-1.41	90

Table 3: Stability limit for permanent operation

Moreover, the fact of putting a capacitor twice as big (2000 µF) will allow them to use twice as much energy, but will take twice as long to charge the capacitor. The E-peas boards are also linear on this point.

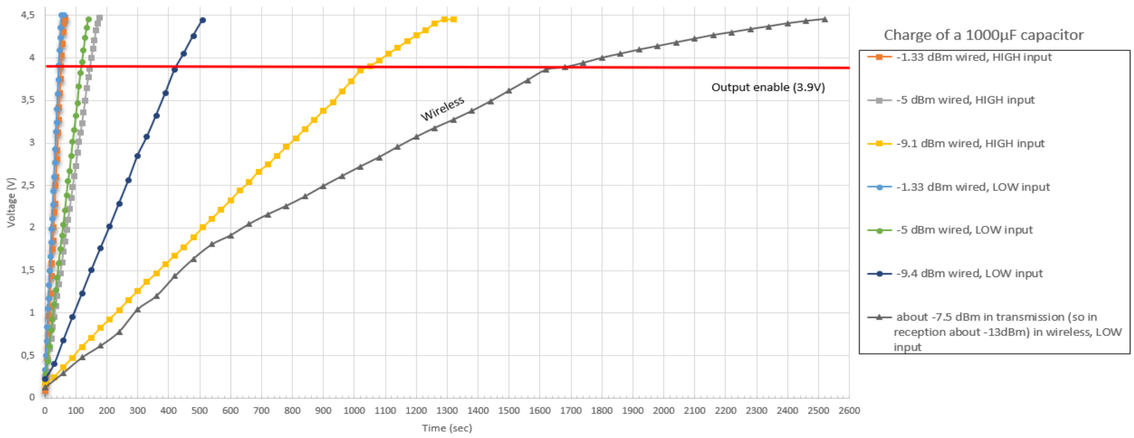

Figure 4: Charge of a 1000 µF capacitor (2.45 GHz)

[1] The high input is designed for signals from -10 to 10 dBm and the low input for signals from -20 to 0 dBm.

[2] The output was activated only from 3,9 V, continues to charge the capacitor until 4,5 V and disables the output if it is below 3,5 V.

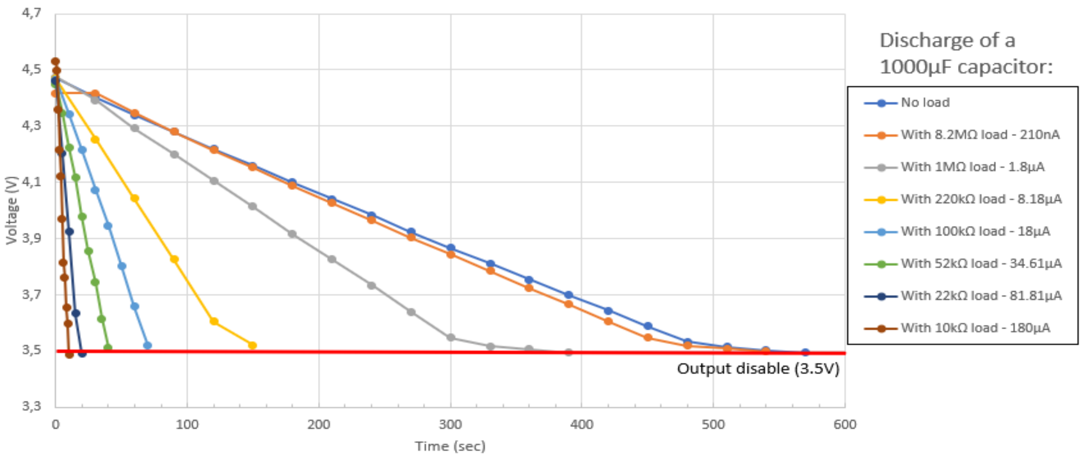

Figure 5: Discharge of a 1000 µF capacitor (2.45 GHz)

There was no other test on the 2.45 GHz board, but as mentioned in point 4 of this article and by Mr. Damien B. [6], the lower the frequency of use, the lower the power required to transmit. That's why it was important to test the 868 MHz board. The test of the charging time of a 1000 µF capacitor is shown in the Figure 6 and, as stated in the E-peas documents, the efficiency of the 868 MHz board is greater, as it can reach 65% compared to 55% for the 2.45 GHz.

As for the capacitor discharge test and the test with the change to a capacitor twice as big for the 868 MHz board, they are not relevant, because the difference between the boards is just in the matching circuit and not in the voltage multiplier and the energy storage circuit.

In addition to the same finding from E-peas [6], other problems on the use of ambient Wi-Fi for an IoT project were highlighted by E-peas, such as:

- The Wi-Fi does not work continuously but sends data in a burst.
- The more we increase the frequency of use, the more the source must emit a strong power if we want to recover the same power at the receiver.
- "Classic" Wi-Fi routers are designed to emit 100 mW (20 dBm), whereas it would take 1 W (30 dBm) to be viable with the receiver at 1m distance. Because, to be higher than the threshold of -20 dBm required by the board to be activated.

V. Important points for the use of RF harvesting

Like the ambient Wi-Fi network supplies not sufficient power, the RF harvesting technique could work if we control the source.

If the source allows to receive sufficient power, there are different important points to consider to have a viable application:

- Having a coherent storage system according to the charge/discharge time and the capacity to store energy is essential! Based on the Figure 7, which represents a Ragone diagram [7], the super/ultracapacitor is a good compromise to have a dynamic charging system, with sufficient available energy for the IoT.
- Having a system that consumes as little as possible is important to increase the time that the IoT can operate without having to set up wake-up and sleep phases [8].
- A low-power data storage system reduces its impact on system efficiency. A data storage system, with an RFID system to read data and receive power, that can accept another power supply when the data is ready, regardless of whether the energy storage system is recharged, is an important consideration. An example is the ST25DV64KC system [9].

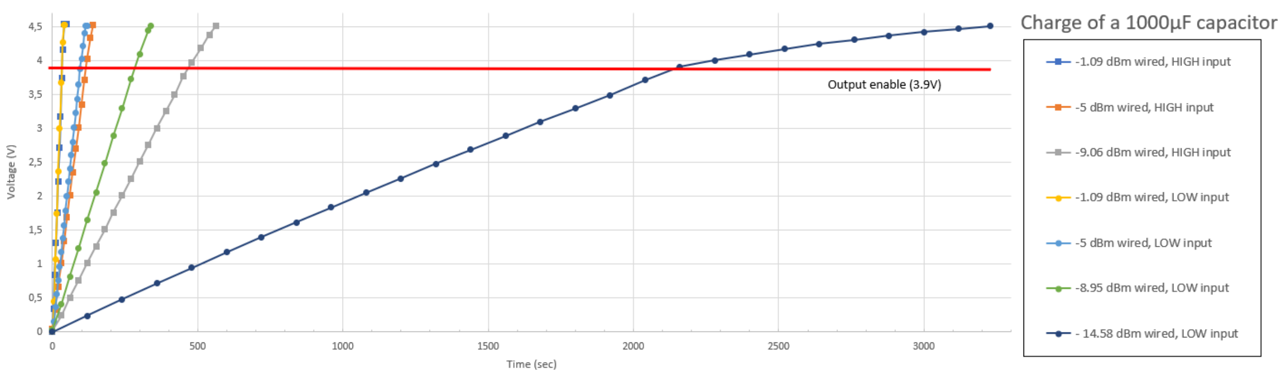

Figure 6: Charge of a 1000 µF capacitor (868 MHz)

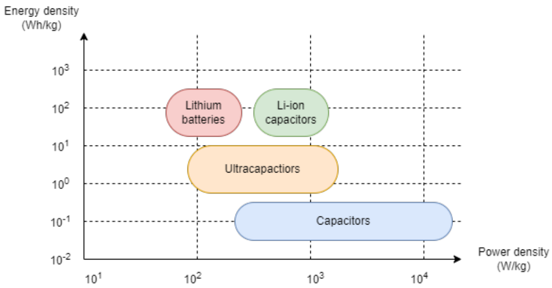

Figure 7: Ragone diagram

VI. Conclusion

This article explored if RF harvesting could be used without source control and in which case the E-peas boards could be efficient. The first tests on the possibility to use the ambient 2.45 GHz Wi-Fi waves, which can be found in a house, in an office,... were not conclusive since the power levels collected by the boards, at a distance close to the transmitter (less than 5 cm), are not sufficient to activate the RF harvesting boards from E-peas. This implies that the implementation of a RF harvesting system must require a very specific attention on the power levels. Moreover, this power level must be in accordance with the regulations of your country. Regarding the comparison of the two E-peas boards (2.45 GHz and 868 MHz), the 868 MHz board has a better yield since there is more received power for the same transmission power. This energy harvesting is due to lower losses in the environment when the operating frequency is reduced.

Finally, if the power levels are sufficient to operate systems of this kind, it is always necessary to think about the overall yield of the installation, and to see if another energy harvesting technique is not more interesting from a yield point of view, but also about the ease of implementation.

VII. Acknowledgment

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