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Autonomous sensor node powered over WiFi: A use case study

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Abstract: This paper presents a new approach to the development of a radio frequency energy harvesting system. Starting from a sensor node to define the constraints of our system such as its energy requirement or its supply voltage, we develop a protocol. It allows us to validate whether it is possible to power such a system with an RF/DC converter. First we study a RF/DC converter capable of converting signals in the ISM band at 2.45 GHz whose ambient power has been previously characterized.

1 INTRODUCTION

The Internet of Things (IoT) is gradually revolutionizing our lives in our daily lives as well as in the industrial, medical, connected city projects and electricity distribution with smart grids. But the explosion in the number of connected objects also implies the explosion in the production of batteries, the main source of energy used for these objects. Batteries being a depletable source of energy, requiring regular maintenance, there is a need to find alternative energy sources that we group together under the concept of Energy Harvesting.

Among the different energy sources, the most commonly harvested one is the solar energy with the development of small organic solar panels, which have the advantage of making the panel flexible and do not require rare-earth element in its design. Also, mechanical energy is well suited for products such as connected switches. We can also find research teams working on thermoelectric energy sources based on the Seebeck effect or the source we will focus on in this paper: Radio Frequency (RF) signal. RF sources like WiFi, GSM, TV... emit electromagnetic waves and surround our environment. A lot of them are wasted and could be converted into DC energy to power specific devices.

During the last 10 years, RF energy harvesting state of the art has evolved from a converter system using TV signals (Parks et al., 2013), which was still very present and powerful in the early 2010's, to more research in the ISM 2.45 GHz band and GSM 900 /

1800 (Ho et al., 2016) with the emergence of WiFi, 3G, 4G... To our knowledge, the different converter developments are made and characterized for theoretical purposes, i.e. they do not take into account the final application in which the converter could be useful. This is why we wish to follow a new approach in the study of RF/DC (direct current) converters by concretely characterizing the energy requirement of an application and thus discuss the feasibility of such a system.

We base this work on WiFi energy harvesting in the 2.45 GHz ISM (Industrial, Scientific and Medical) band, focusing on the part after the antenna that we will not discuss here because we can rely on work such as (Kurvey and Kunte,), (Krakauskas et al.,) or (Shaker et al.,) if needed. We will contextualize our need in Sec.2 where we will present the energy requirement of our sensor and the available ambient WiFi energy. Then, we will study the main problem of an RF/DC converter which is the voltage level obtained in Sec.3. Finally, a calculation model capable of determining the data transmission frequency from an application based on measurement of the received ambient signal power is defined Sec.4.

2 CONSTRAINTS

Before taking an in-depth look at our RF/DC converter on which we will base our work, we need to put some context by defining the different requirements for the proper functioning of an IoT (Internet

of Things) sensor node and an inventory of our electromagnetic environment around 2.45 GHz ISM band.

2.1 Sensor node

Let us consider here a sensor node as a platform capable of measuring physical quantities and transmitting its data by radio wave. Great progress has been made in recent years on the architectures and power consumption of microcontrollers, MEMS sensors and RF transceivers with the emergence of the term "ultra low power".

We will base our study which is reported here on a platform developed by ON Semiconductor: RSL10-SOLARSENS-GEVK (Fig.1). This is a platform containing the BME280 environmental sensor from Bosch Sensortec and the RSL10SIP, a system in a package developed by ON Semiconductor consisting of an ARM Cortex-M3 microcontroller and a Bluetooth Low Energy transceiver. A white paper (Bruno Damien, 2019) is dedicated to it on the feasibility of solar energy harvesting. We therefore want to know if it is possible to operate this platform by replacing the solar panel with an RF/DC converter to obtain a sensor node powered from the 2.45 GHz ISM band harvested electromagnetic energy.

The first thing to note is the supply voltage. Indeed, the solar panel already provides a voltage in the operating range of the platform which therefore charges a capacitor that stores the energy necessary for one cycle of data sending. Once a threshold voltage ($V = 2.6 V$) is reached, a voltage regulator is activated so that the capacitor can power the sensor node. Therefore, a voltage higher than 2.6 V must be achieved in order to activate the energy management system.

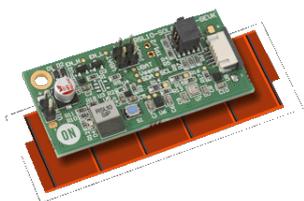


Figure 1: ON Semiconductor RSL10-SOLARSENS-GEVK sensor platform.

Next, we need to quantify the energy required. Because the platform is not permanently powered, ON Semiconductor explains that there are three phases in the software process, each of which has its own energy consumption:

- Boot consuming 120 μJ
- Measurements consuming 20 μJ

- Transmission consuming 40 μJ

As described in the white paper, the energy required (E) for the three phases above is about 180 μJ . To store this energy, a very common 100 μF capacitor (C) can be used. Indeed, the accumulated energy is given by Equ.(1) and is equal to E_{cap} , i.e. 338 μJ in our case which is enough compare to the energy required.

$$E_{cap} = \frac{1}{2} \cdot C \cdot V^2 \quad (1)$$

We will consider an energy of 200 μJ instead of 180 μJ for the rest of the paper to simplify the calculations. We will therefore now look at the possibilities for fulfilling the two conditions for the proper functioning of the node:

- Have a DC voltage of 2.6 V.
- Recover an energy of 200 μJ .

Nevertheless, these conditions are obtained at ON-Semiconductor using a solar panel. We now want to meet these conditions using RF waves in the ISM band.

2.2 Ambient power

In France, the legislation limits the transmission power on all channels in the 2.45 GHz ISM band to 100 mW (20 dBm) (leg, 2018). We want to define here the ambient energy that we can hope to recover, i.e. the amount of energy that passes through the antenna. We have done a measurement campaign on a WiFi router in normal use in order to get an idea of the ambient powers that can be expected to be received.

The measurements were performed using the Aaronia Spectran HF-2025E with the OmniLOG30800 antenna at a distance of 3 m from the transmitting router. The device scanned all the WiFi channels and Fig.2 shows the maximum power measured at each scan over a period of 7 hours.

We notice a very heterogeneous result. Our power in reception pivot being -30 dBm (1 μW), value below which we consider the energy received to be negligible, nearly 25% of the measurements show a power greater than or equal to -30 dBm. By time integration we can plot the energy accumulation as a function of time at reception as displayed by Fig.3.

So, our spectrum analyzer received almost 25 mJ in 7 hours of measurements in ISM band. Knowing that we need 200 μJ to send data from a sensor according to section 2.1, we can be optimistic about the possibility of powering our platform with an RF/DC converter that we will study in section 3.

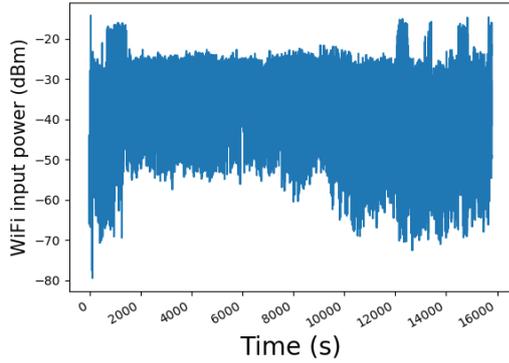


Figure 2: Maximum channel received power in the 2.45 GHz ISM band

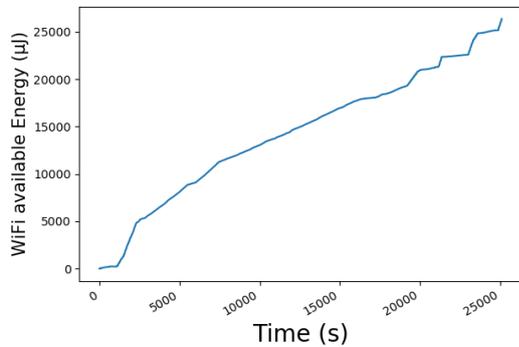


Figure 3: Accumulation of received WiFi energy

3 RF/DC converter voltage issue

In order to provide the necessary power to our sensor node, we will consider an RF/DC converter (known also as rectifier) in the 2.45 GHz ISM band. We focus here on the conversion part and not on the antenna. Let us first of all establish an inventory of the evolution of the DC output voltage (V) and of the conversion efficiency (η) in order to be able to define the axes of development on which it is necessary to work. We will start with the simplest RF/DC converter which is basic crest detector, based of a single Skyworks SMS7630 Schottky diode as presented on Fig.4.

Matching network includes transmission lines and inductors and are determined thanks to simulations performed with Keysight Advanced Design System software in order to optimize impedance matching for maximum power transfer by minimizing signal reflexion between the antenna and the converter and also harmonics created by the Schottky diode due to its non linearities (Fig.5).

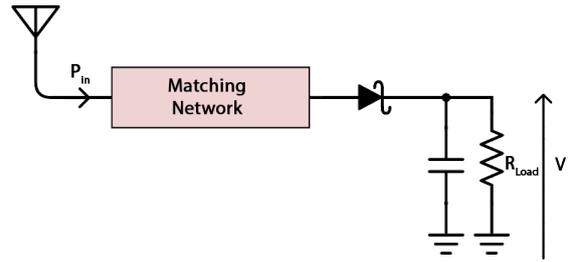


Figure 4: Rectifier schematic

We will therefore optimize the circuit parameters to maximize the DC output voltage for our load. Based on ON Semiconductor's white papers, we can estimate the load resistance of the platform at about 1000 Ohm. Since the WiFi input power (P_{in}) will be converted into DC power (P_{DC}), we can then look at the evolution of the efficiency (η) (Equ.(2)) and the DC output voltage (V) for different arbitrary P_{in} on table 1.

$$\eta = \frac{P_{DC}}{P_{in}} \quad (2)$$

Table 1: Output voltage and efficiency of the simple RD/DC converter

P_{in} (dBm)	η (%)	V (mV)
-30	5.7	8
-25	12	19
-20	20	45
-15	28	94
-10	34.6	186
0	42	648

The main problem with the RF/DC converter is the DC output voltage, which can be very low given the RF input power levels. Indeed, on current reception power levels for WiFi signal, the diode sees its efficiency drop because it is not sensitive enough. We can notice that we never obtain the needed 2.6 V voltage since the maximum obtained is 648 mV at 0 dBm. It is therefore necessary to work on a more elaborate conversion system to reach acceptable voltage levels. The state of the art on the subject mainly uses Cockcroft-Walton voltage doubler assemblies (Kee et al., 2018) which have the advantage of being able to be mounted in cascade to raise the voltage to our needs.

To limit the number of Cockcroft-Walton stages required, we can consider adding a boost like the BQ25504 from Texas Instruments or the LTC3105 from Analog Devices. We thus lower our target voltage at the converter output down to about 300 mV instead of 2.6 V which relaxes our constraints. Indeed, the boost will thus provide an output voltage of 3.3 V with the 300 mV input voltage provided by the recti-

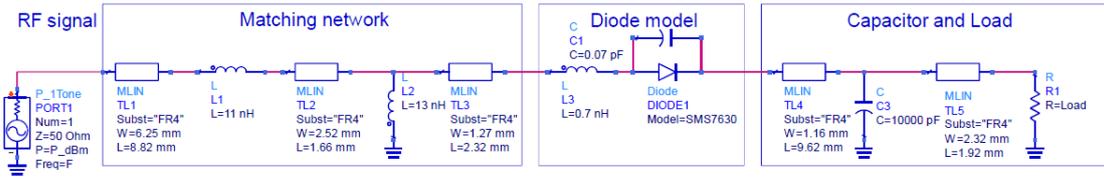


Figure 5: Keysight ADS schematic

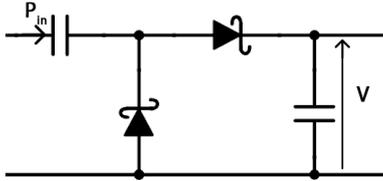


Figure 6: One stage Cockcroft Walton voltage doubler

fier. It will then allow us to charge a capacitor up to our threshold voltage of 2.6 V.

Now that we have some answers about our voltage constraint, let's look at the question of energy. Having seen in section 2.2 that it was possible to power our system given the amount of energy received at the antenna, is it still energetically viable after conversion?

4 Energy harvesting duty cycle

Let's assume for this part that we have solved our voltage concerns, so we can store energy using a capacitor. How often can we expect to measure and send our data, i.e. store the 200 μJ needed to operate the sensor node?

4.1 Theoretical model

Firstly, we will start with a ideal converter with 100% efficiency ($\eta = 1$), what would then be the duty cycle (T), i.e. how long would it take the converter to store the required 200 μJ in the capacitor in order to power the sensor node once the storage is reached? To answer this, we will use the Equ.(3).

$$T = \frac{E}{P_{DC}} = \frac{E}{\eta \cdot P_{in}} \quad (3)$$

So, for a P_{in} equal to -30 dBm, the duty cycle T will be equal to 200 seconds. Table 2 displays the duty cycle (T) for different P_{in} .

Thus, we won't manage to get better than 200 seconds (3 minutes and 20 seconds) between two transmissions with a permanent harvested power of -30 dBm. Because of the efficiency of our rectifier that is not ideal (table 1), we have to correct the estimated duty cycle (table 3) according to Equ.(3).

Table 2: Duty cycle with a perfect converter

P_{in} (dBm)	T (s)
-30	200
-20	20
-10	2
0	0.2

Table 3: Duty cycle with a real converter

P_{in} (dBm)	η (%)	T (s)
-30	5.7	3509
-20	20	100
-10	34.6	6
0	42	0.48

We therefore notice a drastic drop in performance with a duty cycle from 200 seconds to 3509 seconds (around 58 minutes) at -30 dBm.

To get to the end of our approach, let's suppose that to work we use the LTC3105 boost from Analog Devices that we mentioned in section 3. The datasheet of the component announces a minimum efficiency (η') of 65% for an input voltage lower than 1 V which should be the case in the light of the study carried out in section 3. Let's then consider the compute efficiency ($\eta \cdot \eta'$) to have an idea about the duty cycle in this worst case (table 4).

Table 4: Duty cycle by taking into account the boost efficiency

P_{in} (dBm)	$\eta \cdot \eta'$ (%)	T (s)
-30	3.7	5406
-20	13	154
-10	22.5	9
0	27.3	0.73

For a constant RF input power of -30 dBm, the result indicates a period of 5406 seconds (around 1 hours and 30 minutes) between two transmissions when using our RF converter associated to the DC boost.

So next step will be to consider a non-constant harvested power to have a closer approach for real conditions use case.

4.2 Application of the model

In order to determine the obtained amount of DC energy harvested from real WiFi signal as displayed on Figure 2, we have first to model the efficiency η from the arbitrary RF input power P_{in} given by table 1 using a polynomial function. Then, apply the obtained model to determine the converter efficiency $\eta(t)$ associated to the available WiFi signal $P_{in}(t)$ measured (Fig.2). The available DC energy could be obtained after time integration of $P_{DC}(t)$ determined using Equ.(2) and is displayed Fig.7. Vertical lines indicate each time the capacitor store enough energy (200 μ J) to power the sensor node and the duration between two vertical lines are displayed table 5.

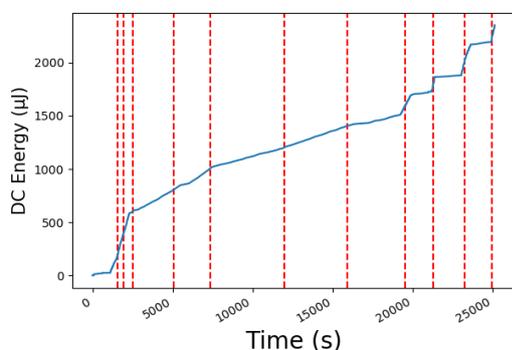


Figure 7: Amount of energy available to power the sensor node labelled

We can consider 11 transmissions on a 7-hour measurement of ambient WiFi signal. We can therefore expect one data transmission every 38 minutes and 11 seconds on average.

5 Conclusion

We thus realized a measurement and simulation bench allowing to define, from P_{in} , the frequency at which the system can send the data of its sensors. Even if the availability of electromagnetic energy is non constant, our work shows that powering such a system with ambient WiFi signals is energetically viable despite a low efficiency of 3.7% with a P_{in} of -30 dBm.

However, there is a optimization work to be done on the converter to overcome the low output voltage and reach the 300 mV threshold required, still for a P_{in} around -30 dBm, to operate the voltage booster. of the latter and to allow data to be sent at more regular intervals in order to diversify the possible applications. The use of a converter that extends over several

frequency ranges, such as for example combining the 2.45 GHz ISM band with GSM 1800 (Bergès et al., 2015) can be a way of improving performance.

A study of the different sensors and microcontrollers in the industry will also have to be carried out to compare and ensure that we have an optimal software layer with regard to power consumption.

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