Autonomous Sensor Node Powered over WiFi: A Use Case Study

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Abstract: This paper presents a new approach to the sizing of a radio frequency energy harvesting system. Starting from a sensor node to define our system constraints such as its energy requirement or its supply voltage, an energy budget analysis protocol is developed to validate whether it is possible to power such a system with a Radio Frequency to Direct Current (RF/DC) converter. We study a converter capable of harvesting RF signals in the Industrial, Scientific and Medical (ISM) band at 2.45 GHz whose ambient power has been previously characterized. Finally, the duty cycle is determined, i.e., how long would it take the converter to recover the required energy in order to power the sensor node.

1 INTRODUCTION

The Internet of Things (IoT) is gradually revolutionizing 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 electric energy for these objects. Batteries being a depletable source of energy and requiring regular maintenance, there is a need to find alternative energy sources that we can group together as the concept of Energy Harvesting.

Among the different harvestable energy sources, the most common one is the solar energy with the development of small organic solar panels. They have the advantage of making flexible panel and do not require rare-earth elements 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 on the source that we will focus on in this paper, which is the Radio Frequency (RF) signal. RF sources like WiFi, GSM, TV transmitters, ... emit electromagnetic waves and surround our environment. A lot of them are wasted and could be converted into Direct Current (DC) energy to power specific low consumption electronic devices like a sensor node, leading to a green IoT.

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 commonly used and powerful in the early 2010's, to more research in the Industrial, Scientific and Medical (ISM) 2.45 GHz and GSM 900 / 1800 bands (Ho et al., 2016) because of the emergence of WiFi, 3G, 4G systems...

To our knowledge, few works take into account the sizing of the harvester system for a dedicated application or a sensor node according to its energy requirements. A well-optimized "wake-up" principle allows the sensor to be powered for a short period to measure and send data, then turned off to allow the converter to charge a capacitor for energy storage. But we would like to go further and propose a new approach in the study of RF/DC converters by concretely characterizing the energy requirement of an application such as powering an IoT sensor node and thus discuss the feasibility of such a system.

We base this work on WiFi energy harvesting system in the 2.45 GHz band and we are focusing only on the necessary circuits after the antenna. This latter will not be discussed here because we can rely on other works such as (Kurvey and Kunte,), (Krakauskas et al.,) or (Shaker et al.,) if needed. We will contextualize our needs in Section 2 where we will present the energy requirement of a sensor node and the available ambient WiFi electromagnetic energy. Then, we will study the main issue of a RF/DC converter which is the low output voltage level in Section 3. Finally, a calculation model based on energy budget analysis will be defined in Section 4. It is ca-

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pable of determining the data transmission frequency based on ambient WiFi energy measurements.

2 CONSTRAINTS

Before taking an in-depth look at used RF/DC converter, we need to contextualize the study by defining the different requirements for the proper functioning of an IoT sensor node and a characterization of the electromagnetic environment around the 2.45 GHz 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 waves. Great progresses have been made in recent years on the architectures and power consumption of microcontrollers, Micro-Electro-Mechanical-System (MEMS) sensors and RF transceivers with the emergence of the term ”ultra low power”.

We will base our study on a platform developed by ON Semiconductor: RSL10-SOLARSENS-GEVK (Figure 1). This platform includes the BME280 environmental sensor from Bosch Sensortec and the RSL10SIP, a system in a package developed by ON Semiconductor and consisting of an ARM Cortex-M3 microcontroller and a Bluetooth Low Energy transceiver. A white paper (Bruno Damien, 2019) is dedicated to the feasibility of solar energy harvesting to power this sensor node. Therefore, we want to know if it is possible to operate this platform by replacing the solar panel with a RF/DC converter to obtain a sensor node powered from the WiFi 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 storing 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 reached in order to activate the energy management system.

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

- Boot, consuming 120 μJ

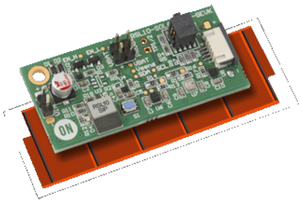

Figure 1: ON Semiconducor RSL10-SOLARSENS-GEVK sensor platform.

- Measurements, consuming 20 μJ
- Transmission, consuming 40 μJ

As described in the white paper, the required energy (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 (E_{cap}) in a capacitor is given by Equation (1) and is equal to 338 μJ in our case, which is enough given to the required energy.

$$E_{cap} = \frac{1}{2}.C.V^2 \tag{1}$$

We will consider an energy of 200 μJ instead of 180 μJ for the rest of the paper to simplify the calculations. We can now look at the required conditions for a proper functioning of the node:

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

Nevertheless, these conditions are obtained by ON Semiconductor using a solar panel. We now want to satisfy these conditions when harvesting ambient WiFi signal.

2.2 Ambient WiFi 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 estimate the ambient energy that could be recovered, i.e., the amount of energy that passes through the antenna. Hence, we did a measurement campaign on a WiFi router in a normal use. The measurements were performed using the spectrum analyzer Aaronia Spectran HF-2025E with the OmniLOG30800 antenna at a distance of 3 meters from the transmitting router. The device scans all the WiFi channels and Figure 2 shows the maximum power measured at each scan over a 7 hours period.

We notice a very heterogeneous result. We consider a received power threshold equal to -30 dBm (1 μW), value below which the received energy is considered to be negligible. Nearly 25% of the measurements show a power greater or equal to -30 dBm.

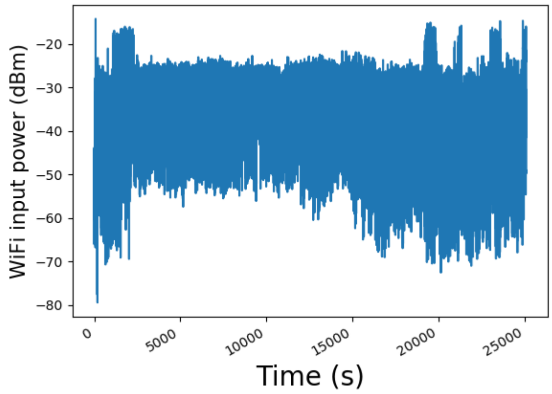

Figure 2: Received WiFi power.

By time integration, we can plot the energy accumulation as a function of time, as displayed by Figure 3.

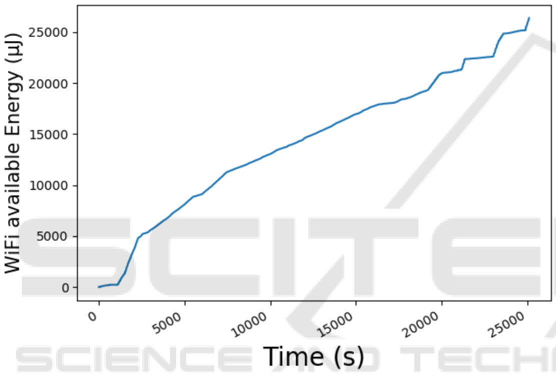

Figure 3: Accumulation of received WiFi energy.

Our spectrum analyzer received almost 25 mJ of WiFi energy during 7 hours of measurements. Knowing that we need 200 μJ to send data from our sensor node (see Section 2.1), we can be optimistic about the possibility to harvest WiFi signal to power our platform using a RF/DC converter that we will study in Section 3.

3 RF/DC CONVERTER VOLTAGE ISSUE

In order to provide the necessary DC power to our sensor node, we will consider a RF/DC converter (known also as rectifier) in the 2.45 GHz ISM band. We focus the study on the conversion circuit 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 development axes on which it is necessary to work. We will start with the simplest and well known RF/DC converter which is a basic crest detector, based of a single Skyworks SMS7630 Schottky diode as presented by Figure 4.

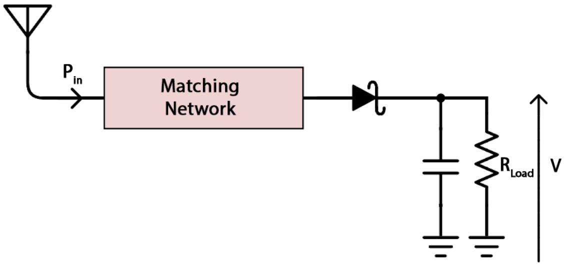

Figure 4: RF/DC converter.

For maximum power transfer from the antenna to the converter, an impedance matching network must be inserted in order to minimize signal reflexion and also harmonics created by the Schottky diode due to its non linearities, as presented on Figure 4. This matching network includes transmission lines and inductors as presented on Figure 5 and they are determined thanks to simulations performed with Keysight Advanced Design System software.

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 equivalent platform load resistance (R) to be about 1000 Ohm. Since the WiFi input power (P_{in}) will be converted into DC power (P_{DC}), we can be interested in the evolution of the efficiency (η) (Equation (2)) and of the DC output voltage (V) of our converter. Simulation results for different arbitrary WiFi input powers are presented in Table 1.

$$\eta = \frac{P_{DC}}{P_{in}} = \frac{V^2}{R.P_{in}} \qquad (2)$$

Table 1: Output voltage and efficiency of the RF/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 issue with a RF/DC converter is the DC output voltage, which can be very low given the RF input power levels. Indeed, with the reception power levels of WiFi signals, the diode sees its efficiency drops because of its lack of sensitivity. We can notice that we never obtain the needed 2.6 V output voltage since the

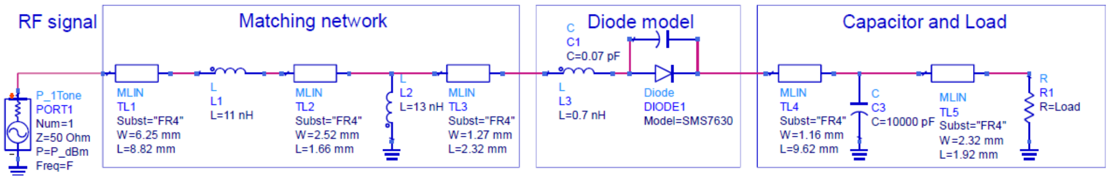

Figure 5: RF/DC converter schematic (Keysight ADS).

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 can be mounted in cascade to raise the voltage to our needs.

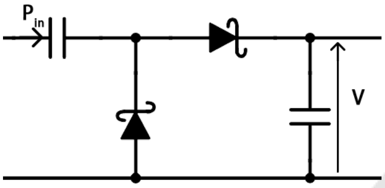

Figure 6: One stage Cockcroft Walton voltage doubler boost.

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 provide an output voltage of 3.3 V with the 300 mV input voltage provided by the converter. 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 us have a look on the energy. Having seen in Section 2.2 that it was possible to power our system given the amount of the received RF energy 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. Then, what would be the duty cycle (T), i.e., how long would it take the converter to store the required energy (E) of 200 μJ in the capacitor in order to power the sensor node to measure and send the data?

4.1 Theoretical Model

To answer to this question, we will define the duty cycle (T) according to Equation (3).

$$T = \frac{E}{P_{DC}} = \frac{E}{\eta . P_{in}} \qquad (3)$$

Firstly, we will start by considering an ideal converter with 100% efficiency ($\eta = 1$). Table 2 presents the duty cycle T for different P_{in}. So, for P_{in} equal to -30 dBm, T will be equal to 200 seconds. Consequently, we won't manage to get better than 200 seconds (3 minutes and 20 seconds) between two transmissions with a permanent harvested RF power of -30 dBm.

Table 2: Duty cycle (T) for different P_{in} with an ideal converter.

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

When considering our real converter, whose efficiency is given in Table 1, the estimated duty cycle (T) is presented in Table 3.

Table 3: Duty cycle (T) for different P_{in} 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 increasing from 200 seconds to 3509 seconds (around 58 minutes) for P_{in} equal to -30 dBm.

To get to the end of our approach, let's assume that we use the LTC3105 boost from Analog Devices as mentioned in Section 3. The component datasheet specifies 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. Then, let us compute the full efficiency ($\eta.\eta'$) to estimate the duty cycle (T) in this worst case, as presented in Table 4.

Table 4: Duty cycle (T) when taking into account the boost efficiency.

P_{in} (dBm)	$\eta.\eta'$ (%)	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 duty cycle of 5406 seconds (around 1 hours and 30 minutes) between two transmissions when using our RF converter associated to the DC boost.

The next step is to consider a non-constant harvested RF power to have a closer approach for a real conditions use case.

4.2 Application of the Model

In order to determine the obtained amount of DC energy harvested from a real WiFi signal, like one displayed on Figure 2, we have first to model the efficiency $\eta = F(P_{in})$ of our converter. We can apply a polynomial fitting on the data given in table 1 and then, use the obtained model to determine the converter efficiency associated to the measured WiFi input powers. The available DC energy could be obtained after time integration of P_{DC}, determined using Equation (2) and displayed on Figure 7. Vertical lines indicate each time the capacitor stores enough energy (200 μJ) to power the sensor node.

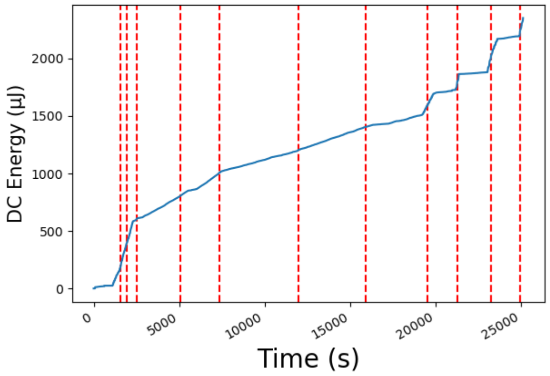

Figure 7: Amount of DC energy available to power the sensor node.

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

5 CONCLUSION

The objective of this work is to propose and study an energy budget analysis protocol to power an IoT sensor node by harvesting ambient electromagnetic WiFi waves. For that, a classical crest detector based on a Schottky diode is choosed as a RF/DC converter. After determining the sensor power requirements and characterizing the available ambient WiFi energy, the RF/DC converter is investigated in order to optimize its conversion efficiency through simulations.

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 converter efficiency of 3.7% with a RF input power of -30 dBm. According to the characteristics of our sensor node, it seems that it is possible to consider 11 data transmissions on a 7-hour harvesting of ambient WiFi signal.

However, this study does not allow us to operate the sensor node since an optimization work is necessary at the converter level to reach the 300 mV threshold. It will also be necessary to characterize the performance of the converter as a function of the distance to the nearest WiFi transmitting terminal. 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 to improve performances.

A study of the different sensors and microcontrollers (Mouapi and Hakem, 2016) 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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