COTS-Based Modules for Far-Field Radio Frequency Energy Harvesting at 900MHz and 2.4GHz

Taris Thierry, Fadel Ludivine, Oyhenart Laurent, Vigneras Valérie

► To cite this version:

Taris Thierry, Fadel Ludivine, Oyhenart Laurent, Vigneras Valérie. COTS-Based Modules for Far-Field Radio Frequency Energy Harvesting at 900MHz and 2.4GHz. IEEE 11th International New Circuit and System, Jun 2013, PARIS, France. hal-01717667

HAL Id: hal-01717667

<https://hal.science/hal-01717667>

Submitted on 26 Feb 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

COTS-Based Modules for Far-Field Radio Frequency Energy Harvesting at 900MHz and 2.4GHz

TARIS Thierry, FADEL Ludivine, OYHENART Laurent, VIGNERAS Valérie
IMS lab, University of Bordeaux
33405 Talence Cedex, France

Abstract —This paper presents a guideline to design a microwaves energy harvester optimized to convert far-field RF energy to DC voltage at very low received power. Implemented on a standard FR4 board with commercially off-the-shelf devices, the modules are dedicated to 900 MHz and 2.4 GHz ISM bands. The 900 MHz 2-stage harvester exhibits the best sensitivity with a rectified voltage of 200 mV at - 25 dBm of input power. The 900 MHz 4-stage module provides the best overall voltage gain above - 15 dBm with a DC output voltage of 2.2 V at - 10 dBm. At 2.4 GHz the 4-stage harvester yields a rectified voltage of 400 mV and 3.5 V respectively at - 20 dBm and - 5 dBm.

I. INTRODUCTION

With the growing popularity and applications of large-scale sensor-based wireless networks, the need to adopt inexpensive, green communications strategies is of paramount importance. To address such purpose the top most challenge concerns the supply and management of the energy required to operate the system. One approach is to deploy a network comprising self-powered nodes extracting their power from a variety of natural (sunlight, thermal...) and/or man-made (propagating radio waves, mechanical vibration...) sources for sustained network operation [1], [2]. Thus there is a strong motivation to enable off-the-shelf wireless sensor network (WSN) with energy harvesting capability that would allow sensor nodes to fill part or all of its energy costs.

The propagating radiofrequency (RF) waves allow low cost, compact and adaptable solutions in energy harvesting [3]. Among the most popular frequency allocations are the 900 MHz and 2.4 GHz ISM bands. Since the attenuation of the RF waves is inversely proportional to the frequency, the 900 MHz band yields lower loss in the power transmission. On the other hand the higher the frequency the smaller is the antenna, so the 2.4 GHz band allows more compact solutions.

This work investigates the design and implementation of RF energy harvesters in the unlicensed ISM Bands at 900 MHz and 2.4 GHz on FR4 printed circuit boards (PCB) with off-the-shelf devices. The optimization of a RF harvester including a rectifier, a matching network and a storage capacitor is first investigated through the close form expression of the overall voltage gain. As case of study the measurement results of four demonstrators are presented and

discussed with respect to the theoretical results proposed in section II. A scenario of wireless power transmission with standard dipole antenna finalizes the characterization of the harvesting modules.

II. RF HARVESTER BASICS AND BUILDING BLOCK DESIGN

Figure 1. Building blocks of the RF harvesting module

The basic architecture of an RF energy harvester is presented in Fig. 1. The antenna performs the transduction of an electromagnetic energy into an electrical signal. To transfer a maximum of the signal to the rectifier a matching network is introduced. The rectifier converts the AC signal into a DC voltage charging a storage capacitor.

In RFID applications the rectifier supplies the tag on time [4]. The design is usually led by the minimum load current and rectified voltage required to operate the tag properly. In such a case the power efficiency of the rectifier is of major importance [4]. In the context of RF harvesting the energy collected is first stored in a capacitor, or a battery, to be further released to the system. The available energy is defined by the storage element once its charge is completed. In this case the design of the rectifier focuses on maximizing the rectified voltage for a fixed input power. This purpose is investigated in this section with the modeling of a RF harvester including a N stage voltage doubler, a L type matching network, a resistive antenna, and coupled to a chemical storage capacitor.

A. Rectifier

Since the level of collected power, P_{rf} , is low, the AC to DC converter, namely the rectifier, is based on a voltage multiplier to deliver an acceptable output DC voltage. A Cockcroft-Walton Voltage Doubler [4], Fig. 2, composes the elementary stage of the rectifier where C_1 (100 pF) and D_1 form the negative clamp, C_2 (100 nF) and D_2 achieves peak

rectification. The diode skills are critical for the overall performances of the module. Schottky diodes, offering a low threshold voltage and a high switching speed are well suited for RF energy harvesting. For this design the Avago HSMS-2852 zero biased diode is used.

Figure 2. Schematic of a Greinacher Voltage Doubler

The single stage doubler of Fig. 2 serves as a basic building block for the multi-stage rectifier. The leakage current, $I_{leakage}$, comes from the dielectric losses in the storage capacitor C_2 . At a fixed temperature this current is almost constant over a wide range of the rectified voltage. At low power, the AC input voltage v_{in} operates the diodes close to the threshold voltage. In this region of conduction the voltage drop across the diode is strongly dependent of the current. According [5] in the steady-state conditions the peak of diode drop voltage, V_{Dpeak} , is:

$$V_{Dpeak} \approx n V_T \ln \left(\frac{\chi \cdot I_{leakage}}{I_s} \right) \quad (1)$$

With V_T , the thermal voltage, n the diode non-ideality factor, I_s , the saturation current of the diode, and χ an empirical term representing the ratio of peak diode current to leakage current. If we assume that the parasitic capacitor of D_1 is negligible compared to C_1 , and C_2 is larger than C_1 , the rectified voltage, V_{REC} , of a N stage doubler in steady-state conditions can be derived as follows :

$$V_{REC} = 2N \left[|v_{in}|_{peak} - V_{Dpeak} \right] = 2N \left[|v_{in}|_{peak} - n V_T \ln \left(\frac{\chi \cdot I_{leakage}}{I_s} \right) \right] \quad (2)$$

Fig. 3(a) represents the AC model of a HSMS-2852 diode including the parasitic elements L_p and C_p for a SOT 23 packaging. This model leads to the equivalent input admittance of a single stage doubler, Fig. 3(b), with series to parallel network transformations at 900 MHz and 2.4 GHz.

Figure 3. AC model of a HSMS-2852 diode (a) equivalent impedance of a HSMS2852 single stage doubler at 900 MHz and 2.4 GHz (b)

At a fixed frequency f_0 the input admittance Y_{REC} of a N stage rectifier is:

$$Y_{REC}|_{@f_0} = \frac{1}{Z_{REC}|_{@f_0}} = N \cdot Y_{dbl}|_{@f_0} = \frac{N}{R_{dbl}|_{@f_0}} + j\omega(N \times C_{dbl}|_{@f_0}) \quad (3)$$

The expression (3) highlights that the real part of the input impedance decreases with the number of cascaded stage where as the input equivalent capacitor increases.

B. Matching Network

A schematic of the harvesters developed in this work is proposed in Fig. 4. To transfer a maximum of the available power delivered by the antenna, P_{rf} , to the rectifier, the matching block is expected to present an input impedance $Z_{in/match}$ equals to Z_{ant}^* at the operating frequency f_0 . To reduce the losses a minimum of devices should be embedded in its synthesis. It is completed by the L-matching configuration depicted in Fig. 4, which only needs a capacitive and an inductive section to perform a narrow band matching.

Figure 4. Schematic of the RF Energy harvesting module

The impedance of the dipole antenna is real at the operating frequency and is noted R_{ant} . Under matching conditions – i.e. $Z_{in/match} = R_{ant}$ – the voltage v_{rf} delivered by the antenna to the L-matching network can be written as:

$$v_{rf} = \sqrt{8 \cdot R_{ant} \cdot P_{rf}} \quad (4)$$

At f_0 , the L-section yields an impedance transformation and a voltage boosting, referenced as Q_{match} , between the input voltage v_{rf} and the output voltage v_{in} . Q_{match} depends on the input resistance of the rectifier according (5).

$$Q_{match} = \frac{v_{in}}{v_{rf}} = \sqrt{\frac{R_{REC}}{R_{ant}} - 1} = \sqrt{\frac{R_{dbl}}{N \cdot R_{ant}} - 1} \quad (5)$$

Combining (1) to (5) we can derive the rectified voltage V_{REC} as a function of the input available power, P_{rf} :

$$V_{REC} = 2N \left[\sqrt{8 \cdot P_{rf} \cdot \left(\frac{R_{dbl}}{N} - R_{ant} \right)} - n V_T \ln \left(\frac{\chi \cdot I_{leakage}}{I_s} \right) \right] \quad (6)$$

V_{REC} is drawn in Fig. 5 for various number of stage at 900 MHz. The leakage current is fixed to 1,5 μA , the parameters of HSMS-2852 diodes are extracted from the data sheet and the antenna impedance is 50 Ohm.

When P_{in} is lower than -20 dBm, a limited number of cascaded stages, typically one or two, yields a larger rectified voltage. Indeed most of the voltage gain comes from Q_{match} which decreases with N in (4). Above -20 dBm increasing the number of stages significantly improves the rectified voltage as illustrated by the 4-stage and 6-stage topologies in Fig. 5.

Figure 5. Rectified voltage at 900 MHz versus input power of a N -stage rectifier – $R_{ant}=50 \Omega$, $n=1.06$, $V_T=26 \text{ mV}@25^\circ\text{C}$, $I_S=3 \mu\text{A}$, $\chi=9.7$, $I_{leakage}=1.5 \mu\text{A}$ and $R_{dbl}=3250 @900 \text{ MHz}$

Unlike tags in RFID applications, a RF harvester is not supposed to be in line of sight of the RF source. As consequences we assume that the collected power ranges from -25 dBm to -10 dBm in the best case. The harvesting module is so expected to have a good sensitivity, high Q_{match} , to operate in very low power conditions, and also enough voltage gain in case of a larger collected power. Referring to Fig. 5, a single stage doubler clearly provides the best sensitivity but not enough voltage gain above -20 dBm. At the opposite a 6-stage rectifier starts to be really efficient above -13 dBm. To investigate this tradeoff we developed a 2-stage and a 4-stage harvester at 900 MHz and at 2.4 GHz.

III. CHARACTERISATION OF THE RF ENERGY HARVESTERS

The four harvesters are implemented with the same design, on a standard 1.5 mm FR4 printed circuit board (PCB), a sample is presented in Fig. 6. For a fixed number of stage, the rectifier part is the same at 900 MHz and 2.4 GHz, only the input matching, length of the stub and C_{match} , located on the left side of the PCB in Fig. 6 are resized.

Figure 6. 900 MHz 4-stage RF harvester on 1.5 m FR4 PCB

A. Input matching and rectifier performances

The harvesters have been first characterized without the antenna with a HP 8720 network analyzer. The input matching of each module is represented in Fig. 7 for an input power of -30 dBm. The 900 MHz demonstrators, Fig. 7(a), are centered at 904 MHz with a very low return loss ($S_{11} < -17 \text{ dB}$).

In the 2.4 GHz band, Fig. 7(b), the 4-stage module yields the best input matching ($S_{11} < -20 \text{ dB}$) at 2.38 GHz. The 2 stage version is centered at 2.46 GHz with a return loss of -14 dB.

Figure 7. Measured return loss S_{11} of the 900 MHz 4-stages and 2-stages harvesters (a) the 2400 MHz 4-stages and 2-stages harvesters (b)

The Fig. 8 reports on the S_{11} for various input power. We observe that the centered frequency shifts up with the input power. This phenomenon comes from the current dependency of the junction resistance of the diode. Indeed a larger input power induces an increase in diode current which reduces R_v and C_{dbl} in the equivalent model proposed in Fig. 3(a). The amplitude of the shift is weakly dependent to the number of stages but it increases with the frequency. As illustrated in Fig. 8(a), the frequency variation is 7 MHz, from 904 MHz to 911 MHz. At 2.4 GHz it is 40 MHz, Fig. 8(b), from 2.38 GHz to 2.42 GHz.

Figure 8. Measured S_{11} for various P_{in} of the 900 MHz 2-stage harvester (a) 2400 MHz 4-stages harvester (b)

Fig. 9 represents the rectified voltage at 900 MHz for the 2-stage and 4-stage modules. Below -20 dBm, Fig. 9(a), the 2-stage harvester provides a slightly larger rectified voltage than the 4-stage module. According the study of section II, most of the voltage amplification comes from the Q_{match} of the input matching network for such range of power. Above -15 dBm the 4-stage is better and would be preferred as depicted in Fig. 9(b).

Figure 9. Rectified DC voltage of the 900 MHz 2-stage and 4-stage harvesters from -30 to -20 dBm (a) from -20 to -5 dBm (b)

At 2.4 GHz, the low value of R_{dbl} , 1250 Ω in Fig. 3(b), limits Q_{match} and most of the voltage amplification is performed by the doubler stages of the rectifier. For this reason the 4 stages harvester exhibits a larger rectified voltage V_{REC} even at very low input power in Fig. 10.

Figure 10. Rectified voltage at 2.4 GHz for the 2 stages and 4 stages harvesters

To sum up the small difference, in favor of the 2-stage topology, between the two 900 MHz demonstrators below -20 dBm is negligible. Above this power, the 4-stage topology provides more voltage gain. At 2.4 GHz the 4-stage harvester exhibits better performances than the 2-stage over the entire power range.

IV. POWER HARVESTING TEST

A scenario of RF power harvesting has been set up in a testing room of the lab. A schematic of the test bench is proposed in Fig. 11. The RF source is a HP 8720 network analyzer connected. A 50 Ω dipole antenna is used to transmit the power at the RF source in Fig. 12. The voltage delivered by the harvester is measured with a Lecroy Wave pro 960 oscilloscope. To perform the measurement, the network analyzer is in Continuous Wave (CW) mode delivering a power of 14 dBm. The overall radiated power is estimated to 16.8 dBm including the cable loss, 0.2 dB, and the antenna gain, 3 dBi.

Figure 11. Model of the WPT scene

Fig. 12 represents the rectified voltage, V_{REC} , with respect to the distance at 900 MHz and 2.4 GHz. In agreement with the study proposed in this work the 4-stage harvester provides a larger V_{REC} than the 2-stage module up to 1.2 meter. The comparison between the 900 MHz and 2.4 GHz 4-stage demonstrators highlights the impact of the frequency on the transmission efficiency. To reach a 1V rectified voltage, a standard supply in modern low power applications, the distance is 0.95 m at 900 MHz and 0.65 m at 2.4 GHz.

Figure 12. V_{REC} versus distance at 900 MHz and 2.4 GHz for a 2-stage and a 4-stage harvester and 16.8 dBm radiated power

V. CONCLUSION

The optimization of the overall voltage gain of a RF energy harvesting module is investigated through the complete modeling of a harvester which includes an antenna, a matching network, a rectifier and a storage capacitor. Four demonstrators implemented on a FR4 board with COTS devices operating at 900 MHz or 2.4 GHz are presented and characterized. At 900 MHz the measurement results figures out the 2-stage and the 4-stage topologies yield almost the same sensitivity, a roughly 450 mV at -20 dBm of input power. Above this power the 4-stage module, 2.2V@-10 dBm, is better suited. At 2.4 GHz the 4-stage exhibits higher performance over the entire power range with a rectified voltage of 400 mV@-20 dBm up to 1.9 V@-10 dBm.

REFERENCES

- [1] K. Lin, J. Yu, J. Hsu, S. Zahedi, D. Lee, J. Friedman, A. Kansal, V. Raghunathan, and M. Srivastava, "Helimote: Enabling long-lived sensor networks through solar energy harvesting," in 3rd Int. Conf. Embedded Networked Sensor Syst, pp.309, Nov 2005.
- [2] J.A. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," IEEE Pervasive Computing, Vol. 4, Issue: 1, pp. 18-27, March 2005.
- [3] K. Finkenzeller, RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification, 2nd ed. Chichester, Sussex, U.K.: Wiley, 2003.
- [4] T. Le, K. Mayaram and T. Fiez, "Efficient far-field Radio-Frequency Energy Harvesting for Passively Powered Sensor Networks" IEEE J. of Solid State Circuit, vol.43, N°5, pp. 1287-1301, May 2008.
- [5] R. Batnett, J. Liu and S. Lazar "A RF to DC voltage conversion model for multi-stage rectifiers in UHF RFID transponders" IEEE J. of Solid State Circuit, vol.44, N°2, pp. 354-370, February 2009.