RF Energy Harvesting System with RFID-Enabled Charge Storage Monitoring

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***Abstract*—Radio frequency (RF) energy scavenging is a compelling approach to energize the low-power wireless devices. We present an energy harvesting system consists of a low-power RF switch circuitry and a passive UHF RFID tag. When the voltage at the storage capacitor terminals exceeds 0.58 V, RF switch connects the UHF RFID microchip to a dipole-type tag antenna. This way, an RFID reader can detect the charge storage level wirelessly with minimal power consumption at the harvester. In this paper, we detail the development of the system and present results from both simulations and measurement. Overall, we were able to achieve 0.58 V at the storage capacitor and detect the storage level indicator tag at the distance of 5.1 m in an experiment where regular 8.7 dBi patch antennas were connected to the harvester input and output of an RFID reader emitting 2.5 W EIRP.**

Keywords—RF energy harvesting; UHF RFID tag; RF rectifier; RF switch; impedance matching network; dipole antenna; PIN diode

I. Introduction

In today's modern technologies, one of the most remarkable challenges is enhancing the lifetime of required batteries along with reducing their size in low power wireless technologies and any portable electronic devices [1]. A growing interest technique to provide the required power for operating wireless devices continuously without degrading their performance is energy harvesting. Scavenging ambient energy from electromagnetic wave known as the RF energy harvesting. It is becoming a promising solution to power the battery-less electronics devices and passive RFID tags over very long periods. Due to widespread deployment of various types of wireless technologies including cellular, TV, radio, satellites, and Wi-Fi signals in urban environment, this power extracting method can provide a sustainable power supply for any wireless applications particularly in HF and UHF frequencies. Therefore, RF energy harvesting has recently attracted the most significant attention in studying systems, which partially/fully provide the required power for low power devices including Wireless Body Networks (WBN), wireless sensor network (WSN), RFID, medical implantable devices, and internet of things (IOT) [2-5].

In general, an RF energy harvesting system converts the RF input signal to the DC voltage and charges a storage for future use. This system comprises of an RF power source, an impedance matching network, a single/multi stage rectifier as a major element and an energy storage unit. Different topologies have been studied for converting the RF signal to DC voltage at UHF bands containing the Villard/Dickson charge pump [2-4], Schottky diode with low threshold voltage [5] and CMOS compatible MOSFET with zero threshold voltage. Hence, the passive devices are able to gain adequate DC power extracted from the incoming RF power and operate at the desired frequency [2-4].

In our previous work, we have proposed an RF energy harvester using two stage Dickson charge pump topology to convert RF power to DC voltage and an RF switch monitors the charge storage to activate the passive RFID IC. We have analyzed the proposed RF energy harvesting system at operating frequency of the European UHF RFID spectrum from 865.7 MHz to 867.7 MHz. The experimental results demonstrate that 0.633 V at the capacitor terminals can be attained with −5.5 dBm of incoming RF power to the energy harvesting unit and we can get RFID IC response at the distance of the 39.7 cm [2]. This paper advances upon our previous approach and overcomes the read range limitation of reading RFID IC by presenting a new configuration for the RF switch circuitry made up of two PIN diodes.

II. Overview of the System and Simulation Results

Our RF energy harvesting system is composed of two main units; an energy harvesting unit and the proposed RF switch unit. Fig. 1 shows the block diagram of the system.

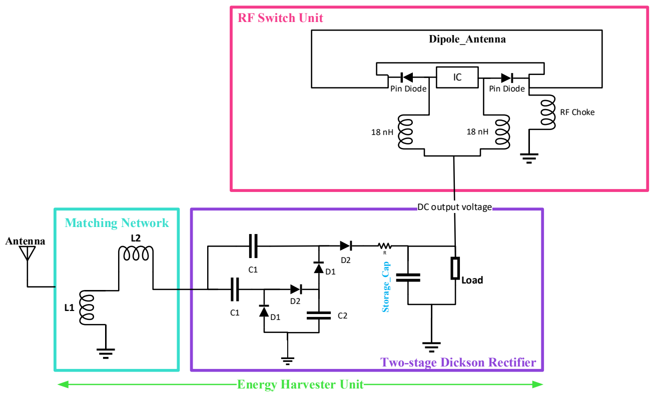

Fig. 1. The block diagram of the proposed RF energy harvesting system integrating an RF switch.

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In the energy harvesting unit, a receiving antenna captures the incoming RF signal, an L-network impedance matching maximizes the transferred power through the chain, and a multi stage charge pump rectifies the incident RF signal into an output DC voltage followed by a battery or a capacitor to store the produced energy. The RF switch unit consists of two pin diodes, RFID IC, RF chokes, and a dipole antenna. When the energy harvesting unit picks up the RF signal, storage capacitor starts charging. If the voltage at the capacitor terminals approaches 0.58 V, the two pin diodes will be turned ON and the dipole antenna is connected to RFID IC. In this state, signal can be transmitted to the RFID reader.

A. Energy Harvesing Unit

As illustrated in Fig. 1, a receiving antenna referred as an RF power source, L- network impedance matching, and two-stage Dickson rectifier comprise the energy harvesting unit. The receiving antenna picks up electromagnetic waves from various sources including UHF signals, mobile phones (900-950 MHz), or Local Area Network (LAN) for 2.45GHz/5.8 GHz [6].

The most significant challenges in the development of the energy harvesting unit are related to the impedance matching network and the rectifier. Indeed, the key circuit block in this unit is the rectifier and the main electrical component to perform RF to DC conversion at UHF bands, is a diode. In this context, junction capacitance, saturation current and conduction resistance of the diode have considerable effect on the rectification performance. Hence, silicon Schottky barrier diode is considered as the most attractive candidate for rectifier circuitry due to its low forward voltage, lower junction capacitance than PN junction diode and operating as very fast switches at high frequencies. Truly, the low threshold voltage results in higher efficiency at low powers, and the low junction capacitance allows for improving the maximum operating frequency of the diode [7-8].

Over and above that, choosing the architecture of the rectification circuit is dependent on the received RF power level, the input frequency and the desired output DC voltage level. One of the most common topologies is a charge pump, which includes a number of diodes connected in series to rectify the incoming RF signal and provide the higher output DC voltage. The simplest configuration of the charge pump, known as a voltage doubler, consists of two diodes and two capacitors [9]. Therefore, we used two stages of the voltage doubler connected in parallel that is called the two-stage Dickson charge pump. Considering the two voltage-doubling stages ensures the sufficient DC output voltage to turn ON the PIN diodes located in the RF switch unit [2].

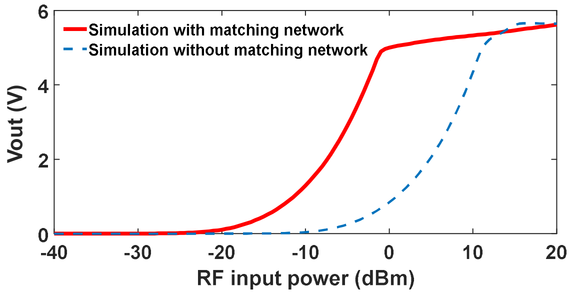

Fig. 2. Simulated output DC voltage of the RF rectifier with and without impedance matching network.

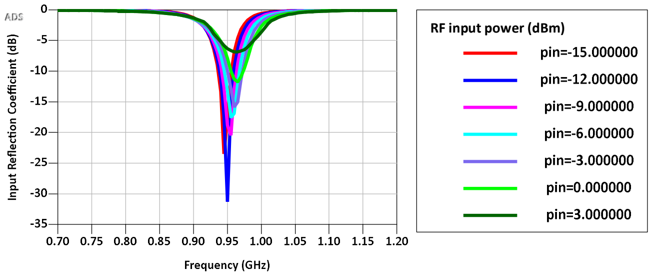

Fig. 3. Simulated input reflection coefficient versus frequency with different input power levels.

In this study, we employed the zero-bias detector Schottky diodes SMS7621-005LF with two capacitors, as shown in Fig. 1, in each stage. Each SOT-23 package of SMS7621-005LF possesses two diodes connected in series, hence, to fabricate the circuit and save the circuit size two packages were enough. Eventually, the storage capacitor connected to 56 kΩ load and RF switch charges through the harvested power.

On the other hand, the matching network stage plays a crucial role to reduce the transmission loss, enhance the output DC voltage and improve the performance of the whole system. If the impedance of the load (energy harvesting system) is not equal to the complex conjugate impedance of the RF source (antenna), Impedance mismatch power loss will occur. Therefore, the RF rectifier will reflect a part of incoming power back, which leads to decreasing the available power for rectification and degrading the power conversion efficiency (PCE) [3][7-8].

Since Schottky diodes employed as the most common rectifying elements have a non-linear voltage-current relationship, the input impedance of the rectifier will change as a function of both incoming power and frequency [8]. Therefore, we utilized an L-network matching containing two reactive components with regard to the various input power levels and operating frequencies. To optimize the matching components, the PSPICE model of Schottky diode was used in Agilent ADS simulator. Fig. 2 demonstrates the effect of the impedance matching and mismatch on the output DC voltage. For an instance, by tuning the impedance match properly between the antenna and the rectifier for the input power of −14 dBm, the rectifier provides the 0.58 V across the load resistance of 56 kΩ, while this voltage can be provided almost at the input power of −1.5 dBm without matching network. Finally, after optimizing this unit, the return loss was simulated at the operating frequency of 950 MHz, while RF input power swept, as displayed in Fig. 3.

B. RF Switch Unit

At the last step, as can be seen in Fig.1, the proposed RF switch circuitry, which is responsible for activating the IC tag, was created. For this purpose, a series Single Pole Double Throw (SPDT) switch structure including low insertion loss level in the RF frequency range was employed in the RF switch. We utilized two SMP1340-079LF of plastic packaged PIN diodes with a low capacitance at RF frequencies in this configuration. It is an appropriate component for fast switching speed. Due to possessing the low ON resistance of 0.85 Ω in this diode model, the insertion loss and power dissipation will be declined.

In this approach, when the output DC voltage of the rectifier charges up the storage capacitor and reaches to the threshold voltage of PIN diodes, both Pin diodes will be turned ON. In this state, the ON resistance of the diodes are exhibited between the output of the RF rectifier and load in both sides symmetrically and all incoming power can be passed. Hence, the provided DC voltage is able to control the DC bias through the pin diode and RF choke. The dipole-type tag antenna, which we modelled in ANSYS HFSS (full-wave electromagnetic field solver based on the finite element) V15 simulator, is a widely utilized antenna structure for passive UHF RFID tags that has been studied for instance in [10]. In order to use this dipole antenna, it was required to modify the basic designed geometrical parameters of the antenna for matching the antenna impedance to the rest of the circuit impedance. In addition, two 18 nH inductors are employed as RF chokes. Then, the signal can take out through the IC. Consequently, the RFID reader enables to get response from the RFID IC.

The simulation results of the output DC voltage of the whole energy harvesting system are shown in Fig. 4. As is obvious, although the level of the output DC voltage declines compared to the output voltage of the system without the RF switch circuitry, the required voltage for turning ON the PIN diodes still can be produced at low power. Fig. 5 depicts the reflection coefficient of the whole system for different RF input power. As shown by the results, the energy harvester is matched optimally at low input power levels, i.e. when the conversion efficiency is most crucial, but also pertains appropriate matching at higher power levels.

III. Measurement Results and Disscussion

We fabricated the proposed RF energy harvesting system on FR4 substrate and connected it to a 50 Ω patch antenna as a receiving antenna via an SMA connector. In addition, we attached the 1×1 mm^2 pads of the tag IC fixture between two PIN diodes placed in the RF switch with conductive epoxy. Fig. 6 shows the fabricated circuit board.

First, it is necessary to measure the input reflection coefficient of the RF energy harvesting system through a Vector Network Analyzer (VNA). According to this measurement, the peak value of the input reflection coefficient shifted frequency from 950 MHz. Hence, the acquired components values of matching network in simulation should be tuned on the PCB board to transmit the maximum available power to the RF rectifier. As a result, the optimum values of L-network matching at 950 MHz in practice include L=6.8 nH for the series inductor and L=5.6 nH for the parallel inductor.

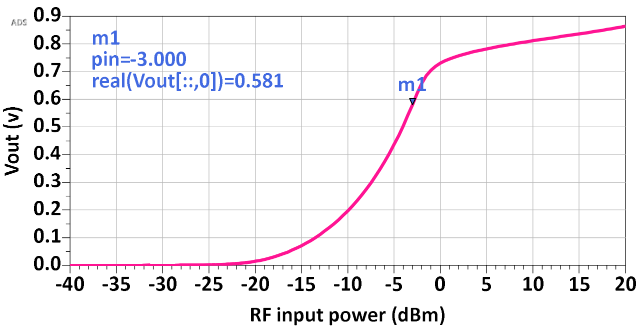

Fig. 4. Simulated output DC voltage of the whole energy harvesting system.

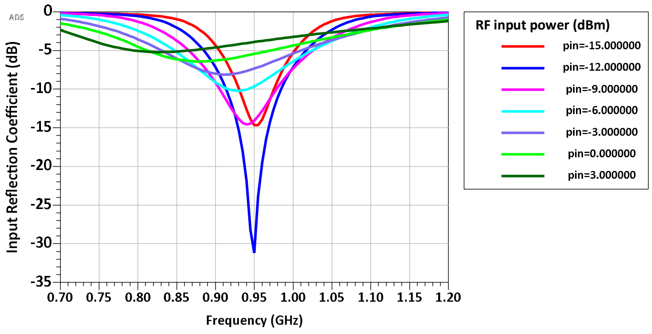

Fig. 5. Simulated input reflection coefficient of the whole energy harvesting system.

In addition, the effect of the input power variation on the input impedance of the rectifier should be considered. In this context, the circuit was matched in all ranges of RF input power. According to the measurement results, the circuit is perfectly matched at the desired UHF range with a sufficient power to wake-up the RFID IC. Fig. 7 displays the measured input reflection coefficient for different input power level.

Afterward, in order to use the information stored in the IC tag by reader at the target frequency, the maximum distance of the tag from the reader should be determined. For this purpose, a UHF RFID measurement system, Voyantic Tagformance lite, was utilized to analyse the tag behaviour. Hence, the circuit board was placed in the Voyantic anechoic chamber that is coated by absorbers to avoid any reflections.

Then, to supply the rectifier, an RF signal generator was used as an equivalent device of the receiving antenna, which can generate the stable continuous-wave (CW) and accurate input signal at 950 MHz. Besides, to follow the capacitor charging, we connected the Voltage Multimeter to the output of the rectifier. Fig. 8 shows this measurement setup, where the fabricated board was located at the distance of 30 cm from the RFID reader.

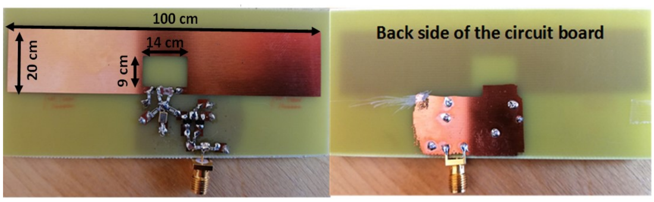

Fig. 6. Fabricated RF energy harvesting system.

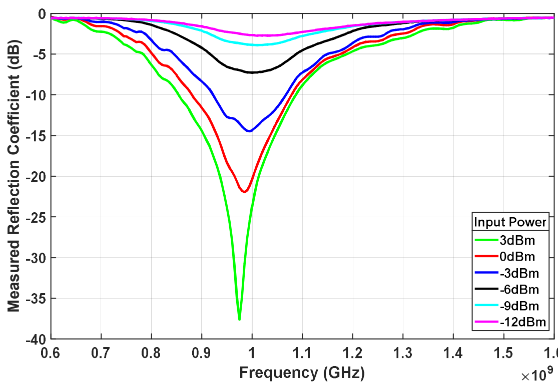

Fig. 7. The measured input reflection coefficient of the whole energy harvesting circuit.

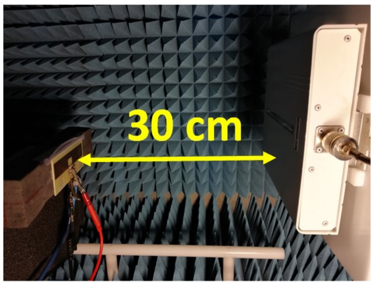

Fig. 8. Measurement setup in the anechoic chamber.

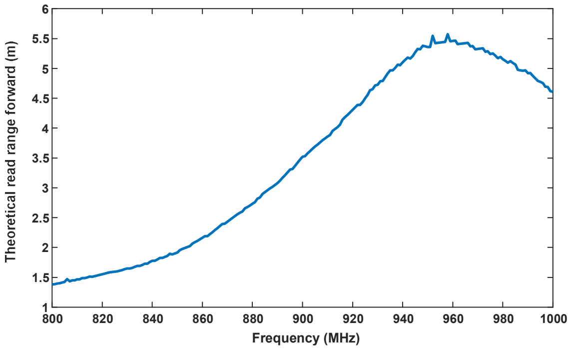

Fig. 9. Measured read range in the anechoic chamber measuremnt.

According to measured reflection coefficient magnitude for various input power levels, the output power of the generator set at −6 dBm as the optimum power, which can energize the IC tag successfully to get a response. The sweep of measurement frequency set from 800 MHz to 1 GHz with the step of 1 MHz. The transmitted power of the reader enhanced from 5 dBm to the maximum of 30 dBm with a step of 0.1 dB at each frequency point. Then, the minimum transmitted power at which the IC tag can be powered on was recorded. Hence, the read range was provided by referring to the calibration value with a reference tag. As seen in Fig. 9, the corresponding attainable read range is about 5.36 m at the desired frequency of 950 for the minimum transmitted power of 4.8 dBm.

At the next step, we tested the energy harvesting system in the real environment. To this end, a 50 Ω patch antenna with the gain of 8.7 dBi, which supplies the rectifier, was used to harvest RF signals energy and an identical antenna was connected to the RFID reader for transmission and reception. Indeed, the RFID reader of the Voyantic Tagformance Pro was used as a single antenna for both energy harvesting and RFID operation. According to the read range measurement, we expected that the RFID reader gets response at the achieved distance in the real environment. Fig. 10 demonstrates the measurement setup outside of the anechoic chamber, where the energy harvesting patch antenna and circuit board containing the harvester and the RFID tag were placed at the distance of 5.1 m and 6.37 m from the reader, respectively. The distances were set to the maximum at which we were able to charge the energy storage and energize the microchip from the RFID reader.

We did the measurements in two phases at the desired operating frequency of 950 MHz and in each phase; we observed getting response from RFID IC when the proposed RF switch was turned ON or OFF. At the charging phase, whenever, the patch antenna does not receive any RF signal to feed the rectifier, the IC does not have any response. Once

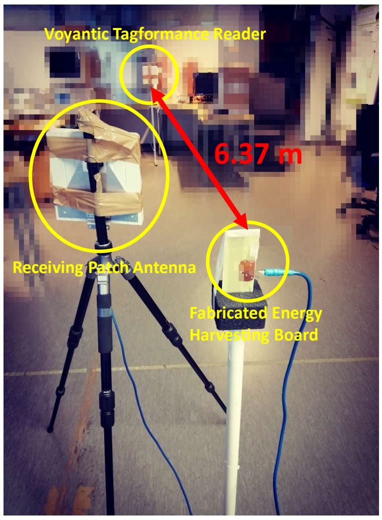

Fig. 10. Measurement setup.

the patch antenna enables to harvest RF signals, the rectifier is able to convert the RF signal to DC voltage and charges up the 11mF capacitor. As soon as, the DC output voltage of the capacitor approaches 0.58 V, the PIN diodes are turned ON and activates the RFID tag to get a response.

At the discharging phase, when the receiving antenna does not harvest any RF signal for applying to the input of rectifier, the storage capacitor starts discharging quickly through the load of 56 kΩ and, hence, reading the IC is stopped. Fig. 11 illustrates the storage level indicator tag's response at the input of the RFID reader during the experiment. In the measurement setup illustrated in Fig. 10, the RFID reader's output power was set to maximum available power of 27.5 dBm. Given the transmitting antenna gain of 8.7 dBi and the cable loss of 2.14 dB, this corresponds to an equivalent isotropic radiated power (EIRP) of 2.55 W. In practice, for instance, in European countries, the regulation would allow up to 3.28 W EIRP. In free space environment, this means 13% (or 1.1 m).

In conclusion, according to this achievement, two PIN diodes can be activated by sufficient transmitted power about 27.5 dBm for connecting the RFID microchip to the dipole antenna at the distance of the 6.37 m from reader at the desired frequency. Therefore, this is a successful demonstration of the RFID enabled wireless charge storage monitoring

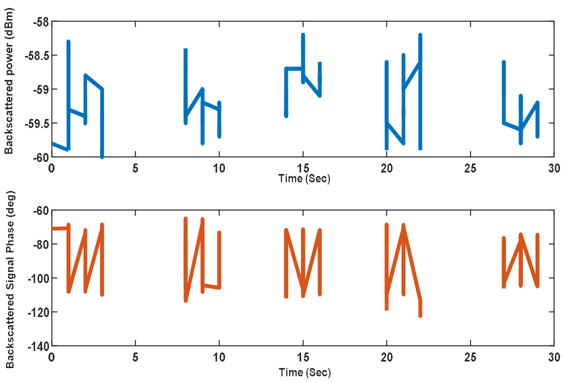

Fig. 11. Storage level indicator tag's response at the RFID reader's input during the experiment.

REFERENCES

[1] Z. Khonsari, T. Björninen, Manos M. Tentzeris, L.Sydänheimo and L. Ukkonen, “Inkjet-printed monopole antenna and voltage doubler on cardboard for RF energy harvesting,” in IEEE APS/URSI, pp. 1312–1313, 19-24 July 2015, Vancouver, BC, Canada.

[2] Nikta Pournoori, M. Waqas. A. Khan, Leena Ukkonen, and Toni Björninen, “RF energy harvesting system integrating a passive UHF RFID tag as a charge storage indicator,” accepted in IEEE International Symposium on Antennas and Propagation, Boston, Massachusetts, USA, July 2018.

[3] Z. Hameed and K. Moez, “Design of impedance matching circuits for RF energy harvesting systems,” Microelectronics J., vol. 62, pp. 49–56, April 2017.

[4] H. Dai, Y. Lu, M.-K. Law, S.-W. Sin, U. Seng-Pan, and R. P. Martins, “A review and design of the on-chip rectifier for RF energy harvesting,” in IEEE International Wireless Symposium, pp. 1–4, 30 Mar.-1 Apr. 2015, Shenzhen, China.

[5] A. Nimo, D. Gric, and L. M. Reindl, “Optimization of passive low power wireless electromagnetic energy harvesters,” Sensors, vol. 12, no. 10 pp. 13636–13663, Oct. 2012.

[6] M. P. Aparicio, A. Bakkali, J. Pelegri-Sebastia, T. Sogorb, V. Llario, A. Bou. Radio frequency energy harvesting-sources and techniques. InRenewable Energy-Utilisation and System Integration 2016. InTech.

[7] X. Lu, P. Wang, D. Niyato , D. I. Kim, Z. Han, “Wireless networks with RF energy harvesting: A contemporary survey,” IEEE Communications Surveys & Tutorials, vol. 17, no. 2, pp.757–789, May 2015.

[8] C. R. Valenta, G. D. Durgin. “Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems”, IEEE Microwave Magazine, vol. 15, no. 4, pp. 108–120, June 2014.

[9] D. M. Dobkin, RF in RFID: Passive UHF RFID in Practice, Elsevier, 2nd ed., 2013, pp.195–199.

[10] T. Björninen, J. Virkki, L. Sydänheimo, L. Ukkonen, “Impact of recurrent stretching on the performance of electro-textile UHF RFID tags”, In Electronics System-Integration Technology Conference (ESTC), pp.1-5, 2014 Sep 16.