An Energy-Autonomous SWIPT RFID Tag for Communication in the 2.4 GHz ISM Band

Giacomo Paolini[(1)], Abdul Quddious[(2)], David Chatzichristodoulou[(3), (4)], Diego Masotti[(1)],
Symeon Nikolaou[(3), (5)], and Alessandra Costanzo[(1), (6)]
(1) DEI "Guglielmo Marconi", University of Bologna, Bologna, Italy
(2) KIOS Research and Innovation Center of Excellence, Nicosia, Cyprus
(3) Frederick Research Center, Nicosia, Cyprus
(4) RF and Microwave Solutions LTD, Cyprus
(5) Frederick University, Dept. Electrical Computer Engineering and Informatics, Nicosia, Cyprus
(6) DEI "Guglielmo Marconi", University of Bologna, Cesena, Italy

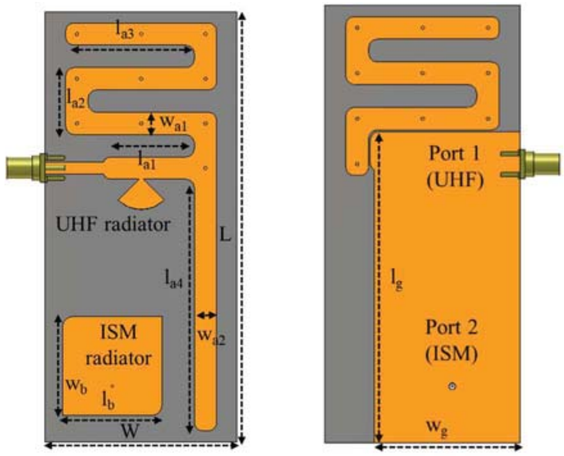
Abstract

This paper presents the design of an energy autonomous radiofrequency identification (RFID) tag for communication and/or indoor localization. It makes use of the energy harvesting (EH) technique in the 915 MHz ultra-high frequency (UHF) band for the feeding of a system-on-a-chip (SoC), working also as a radio transceiver, in order to communicate data to a reader, or a gateway, at 2.4 GHz. First, the design of a multiple-input multiple-output (MIMO) antenna is described, with the dimensions of the whole tag limited to 47 × 100 mm^2. Subsequently, the description and the performance of the UHF rectifier are reported, with its connection to the related power management unit (PMU). The PMU is then connected to a transceiver that can send information about its identification number (ID) and the received signal strength indicator (RSSI) without the need of a battery.

1. Introduction

Lately, simultaneous wireless information and power transfer (SWIPT) led to a huge amount of interest from many fields, and in particular from Industry 4.0 [1].
Specifically, wireless power transfer (WPT) and the concurrent abating of the overall integrated circuits (IC) energy requirements helped the development of techniques of powering low-power electronic devices by means of "green" energy sources, by getting rid of bulky batteries, and consequently avoiding the continuous need for their maintenance [2]. In particular, radiofrequency (RF) waves have been exploited in order to power RFID tags, or sensor nodes, with the exploitation of both near-field (NF) [3] and far-field (FF) WPT solutions [4].

In this work, an RFID tag conceiving the presence of two different radiating elements is presented: a rectifying antenna (rectenna) working at 915 MHz (UHF band) is designed for EH purposes along with a 2.4 GHz antenna



(a) (b)

Figure 1. Geometry of the proposed UHF and ISM MIMO antenna: (a) top view and (b) bottom view with the common RF ground. Dimensions (mm): L=100, W=47, l_{a1}=18.4, l_{a2}=16.5, l_{a3}=37.5, l_{a4}=62, l_b=24.5, l_g=75, w_{a1}=18.4, w_{a2}=18.4, w_b=24.5, w_g=35.

devoted to data communication serving a commercial radio transceiver which can be fully autonomous from the energy source point of view, because it uses power harvested from the UHF rectenna.

2. MIMO Antenna Design

The two-port MIMO antenna is designed with two radiating elements, one for the UHF and one for the 2.4 GHz industrial, scientific and medical (ISM) band with common RF ground plane. The UHF radiating element consists of a meandering monopole etched on both sides of the substrate which are connected through vias. The top side of the monopole is connected to the matching network consisting of an open stub and a radial stub to match the monopole radiator impedance to 50 Ω.

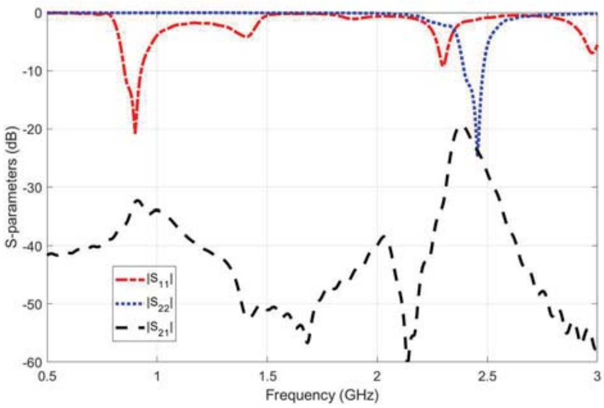


Figure 2. Simulated S-parameters of the proposed UHF and ISM MIMO antenna.

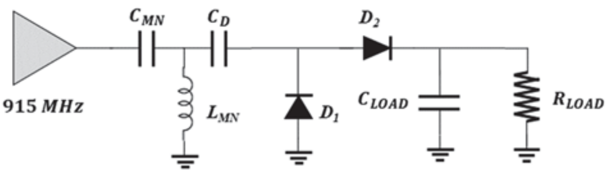


Figure 3. Schematic representation of the 915 MHz rectenna.

The feeding line of the UHF radiator is extended to the edge of the substrate where an SMA connector is connected for testing purposes. The ISM radiating element is a rectangular patch with truncated corners. The rectangular patch has a shared RF ground with the UHF radiator and is fed using a coaxial feed from the bottom of the substrate. The two-port MIMO antenna is realized by incorporating both UHF and ISM radiators on a single board of Rogers Kappa 438 substrate with a dielectric constant of 4.38, a loss tangent of 0.005 and thickness 1.524 mm. The schematic of the proposed two-port MIMO antenna is shown in Fig. 1. The overall size of the dual-port MIMO antenna is 47 × 100 mm^2. The feed point of the UHF radiator is indicated as port 1 and the one for the ISM radiator is indicated as port 2, as can be seen in Fig. 1(b). The simulated S-parameters plot of the proposed two-port MIMO antenna is depicted in Fig. 2. The –10-dB reflection coefficient bandwidth of the UHF radiator is 105 MHz, ranging from 840 to 945 MHz, covering the UHF RFID bands worldwide. The 105 MHz bandwidth covers the designated bands used in China, Europe, and the USA. The –10-dB reflection coefficient bandwidth of the ISM radiator is 80 MHz, ranging from of 2.4 to 2.48 GHz covering the 2.45 GHz ISM band. The isolation between both ports of the MIMO antenna is better than –20 dB as can be seen in Fig. 2.

3. Energy Harvesting and Communication Modules

3.1 Rectifier Design and Performances

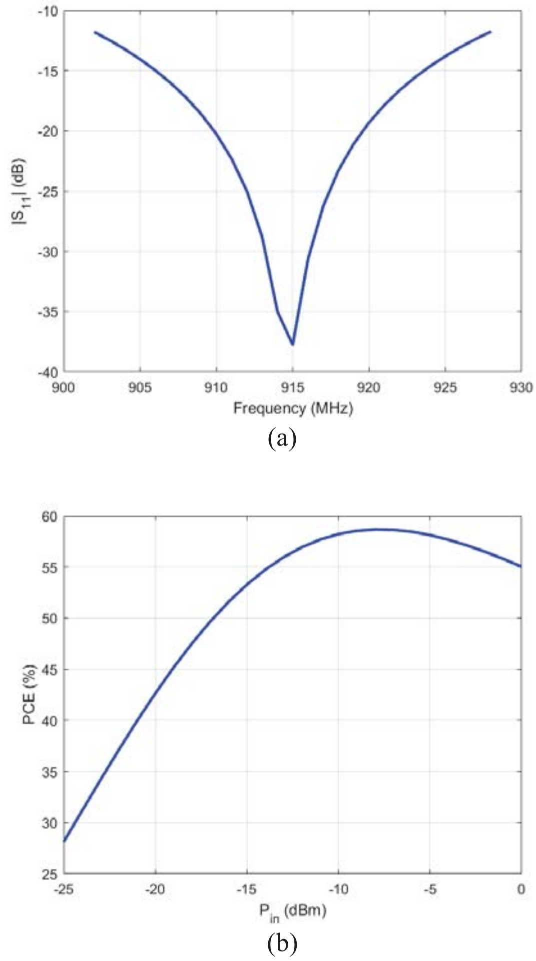


Figure 4. (a) Reflection coefficient S_{11} of the voltage-doubler rectifier vs frequency, and (b) RF-to-dc power conversion efficiency (PCE) vs RF input power P_{in}.

A UHF voltage-doubler rectifier has been designed and considered in order to convert the harvested UHF signal into exploitable dc power. The 915 MHz rectifier is connected with the abovementioned wideband UHF antenna in order to implement a rectenna.

The chosen substrate for the rectifier circuit is the same Rogers Kappa 438 (thickness: 1.524 mm, ε_r=4.38, tan(δ)=0.005), that was used for the antennas. A common microstrip feeding has been adopted to connect the UHF antenna port to the input port of the rectifier.

The topology selected for the rectifier is a voltage-doubler (schematically represented in Fig. 3), in order to achieve higher output dc voltage, since this is a critical parameter for the most common commercial PMUs' cold start (i.e., e-peas AEM30940, or Texas Instruments bq25570). It is composed of a lumped input matching network (an RF capacitor C_{MN}=0.5 pF, and a shorted RF inductor in parallel L_{MN}=23 nH), two Schottky diodes D_1 and D_2 (Skyworks SMS7630-079LF), two RF capacitors (C_D=C_{LOAD}=1 nF), and a resistor (R_{LOAD}=12.9 kΩ) acting as a load and setting the cut-off frequency of the output low-pass filter.

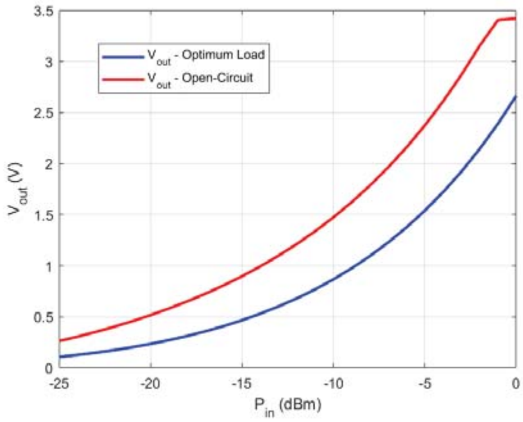


Figure 5. Rectifier (red line) open-circuit voltage and (blue line) output voltage with optimum load (R_{LOAD}) depending on the RF input power P_{in}.

In order to ensure the use of the correct values of these components, an optimization has been conducted using the Keysight ADS circuit simulator. The twofold goal was to maximize the RF-to-dc power conversion efficiency (PCE) and to enlarge the bandwidth of the rectifier in order to cover the US UHF band from 902 to 928 MHz.

The obtained results are shown in Figs. 4(a) and 4(b), showing the reflection coefficient S_{11} with respect to frequency, and the percentage PCE reached by the voltage-doubler rectifier while the input power P_{in} is varied from –25 to 0 dBm.

From Fig. 4(a), which presents the rectifier's reflection coefficient, it can be derived that, for small signal analysis (S-parameters simulation), the reflection coefficient remains better than the –10-dB matching threshold, which indicates the good matching of the non-linear rectifier circuit.

It is worth mentioning that this design is optimized for low input power levels, as can be deduced from Fig. 4(b); indeed, this is the typical power level expected to harvest from the UHF EH antenna.

3.2 Power Management Unit and Communication Module

The PMU that has been used for this prototype is the e-peas AEM30940 [5], which features a cold start from 380 mV and a maximum power point tracker (MPPT) open-circuit voltage (OCV) sampling frequency of 3 Hz.

As can be seen in Fig. 5 (red line), the simulation results indicate that it is possible to activate the cold start for an input power at the rectifier equal to –20 dBm.

Moreover, after the cold start, the boost converter integrated in this PMU can extract the available power from the source as long as the input voltage is between 50 mV and 5 V. This performance makes the rectifier operational for input power as low as –32 dBm, assuming that the cold start has been accomplished.

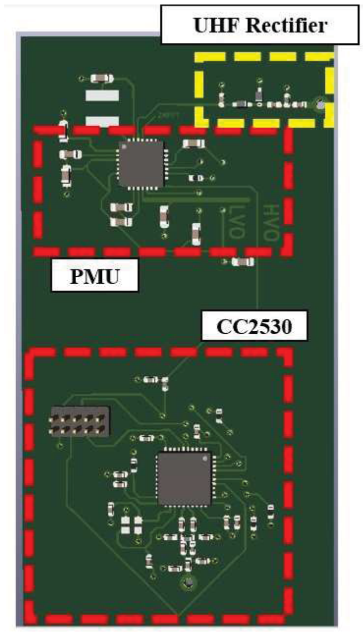


Figure 6. Layout of the board including the lumped-components rectifier at 915 MHz, the PMU, and the CC2530 transceiver (overall dimensions: 35 × 67 mm^2).

This PMU IC is able to supply low-voltages (from 1.2 to 1.8 V) typically driving low-power microcontroller units (MCU), whereas the high-voltage output (HVO) can support the energy requirements of a transceiver, with required voltage supply between 1.8 and 4.1 V.

In fact, for the communication part, a SoC from Texas Instruments (TI), namely the CC2530, has been selected for sending and receiving data to/from a reader or a gateway. Its recommended supply voltage can be anywhere between 2 and 3.6 V.

The TI CC2530 radio transceiver, integrating an Intel 8051 MCU, adopts a protocol for communication named SimpliciTI: this is a low-power RF network protocol developed by Texas Instruments allowing to exchange information, for instance, between the RFID reader and the RFID tags regarding their IDs and the corresponding instantaneous RSSI power values, as described in [6] for an indoor localization system.

Regarding the PMU energy budget, for the recommended storage capacitor of 150 µF and an output voltage (HVO mode) of 2.5 V, a stored energy of 0.47 mJ can be guaranteed. Having said that, it is possible to state that a communication cycle of transmission/reception (TX/RX) lasting for a maximum of 3.5 ms is feasible for the present configuration (current consumptions: active mode RX: 24 mA, active mode TX at 1 dBm: 29 mA).

4. Conclusion

In this work, the design of an ISM communication module using harvested power from the implemented UHF RFID antenna, has been presented. A MIMO antenna was implemented on the same board with the UHF rectifier in order to guarantee both the

communication and the wireless power reception needed to sustain the operations of the ICs.
The circuit system comprises of a rectifier at 915 MHz, a UHF antenna as the harvesting antenna, the PMU, and a commercial low-power radio transceiver working in the 2.4 GHz band.
In conclusion it can be stated that with a minimum input power at the rectifier of –20 dBm, is possible to sustain the energy requirements of a transceiver for an active state framed by TX/RX cycles.

5. Acknowledgements

This work was co-funded by the European Regional Development Fund and the Republic of Cyprus through the Research and Innovation Foundation, under the projects EXCELLENCE/1216/0376 (SWITCH) and EXCELLENCE/0918/0365 (ICARUS).

References

[1] A. Costanzo, D. Masotti, G. Paolini, and D. Schreurs, "Evolution of SWIPT for the IoT World: Near- and Far-Field Solutions for Simultaneous Wireless Information and Power Transfer," *IEEE Microwave Magazine*, **22**, 12, pp. 48-59, December 2021.

[2] S. Kim et al., "Ambient RF Energy-Harvesting Technologies for Self-Sustainable Standalone Wireless Sensor Platforms," *Proc. of the IEEE*, **102**, 11, pp. 1649-1666, November 2014.

[3] G. He, Q. Chen, X. Ren, S. Wong, and Z. Zhang, "Modeling and Design of Contactless Sliprings for Rotary Applications," *IEEE Transactions on Industrial Electronics*, **66**, 5, pp. 4130-4140, May 2019.

[4] G. Paolini, M. Guermandi, D. Masotti, M. Shanawani, F. Benassi, L. Benini, and A. Costanzo, "RF-Powered Low-Energy Sensor Nodes for Predictive Maintenance in Electromagnetically Harsh Industrial Environments," *Sensors*, **21**, 2, pp. 386-403, January 2021.

[5] E-peas AEM30940 RF Datasheet: Highly efficient, regulated dual-output, ambient energy manager for AC or DC sources with optional primary battery. Available Online: https://e-peas.com/wp-content/uploads/2021/03/e-peas-AEM30940-datasheet-RF-Vibration-energy-harvesting.pdf [accessed on 10th January 2022].

[6] G. Paolini, D. Masotti, F. Antoniazzi, T. Salmon Cinotti, and A. Costanzo, "Fall Detection and 3-D Indoor Localization by a Custom RFID Reader Embedded in a Smart e-Health Platform," *IEEE Transactions on Microwave Theory and Techniques*, **67**, 12, pp. 5329-5339, December 2019.