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This is the final peer-reviewed author’s accepted manuscript (postprint) of the following publication:

Published Version:
RF Energy Harvesting from GFSK-Modulated BLE Signals / Giacomo Paolini, Yuri Murilllo, Steven Claessens, Diego Masotti, Sofie Pollin, Alessandra Costanzo, Dominique Schreurs. - ELETTRONICO. - (2021), pp. 9413780.1-9413780.3. (Intervento presentato al convegno 2021 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNeT) tenutosi a San Diego, CA, USA nel 17-22 January 2021) [10.1109/WiSNeT51848.2021.9413780].

Availability:
This version is available at: https://hdl.handle.net/11585/794294 since: 2023-11-24

Published:
DOI: http://doi.org/10.1109/WiSNeT51848.2021.9413780

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Giacomo Paolini
DEI "Guglielmo Marconi"
University of Bologna
Bologna, Italy
giacomo.paolini4@unibo.it

Yuri Murillo
ESAT - WaveCore
KU Leuven
Leuven, Belgium
yuri.murillomange@kuleuven.be

Steven Claessens
ESAT - WaveCore
KU Leuven
Leuven, Belgium
steven.claessens@kuleuven.be

Diego Masotti
DEI "Guglielmo Marconi"
University of Bologna
Bologna, Italy
diego.masotti@unibo.it

Sofie Pollin
ESAT - WaveCore
KU Leuven
Leuven, Belgium
sofie.pollin@kuleuven.be

Alessandra Costanzo
DEI "Guglielmo Marconi"
University of Bologna
Bologna, Italy
alessandra.costanzo@unibo.it

Dominique Schreurs
ESAT - WaveCore
KU Leuven
Leuven, Belgium
dominique.schreurs@kuleuven.be

***Abstract*—This work presents a study on the feasibility of energy harvesting from modulated signals that are present normally in daily life environments, i.e. Bluetooth Low Energy. First, the design of the RF-to-DC conversion circuit is presented, considering the input excitation being a signal modulated in frequency. Next, a measurement campaign has been conducted considering as input signal both a frequency-modulated excitation given by a signal generator, and the communication packets sent by means of a commercial Bluetooth board. The experimental results show that it is possible to harvest about 1.3 nJ for every BLE packet sent with a transmitter-receiver distance up to 20 cm with 4 dBm of transmitted power.**

Keywords—SWIPT, BLE, energy harvesting, GFSK, modulation, low-power.

I. Introduction

The emerging Internet of Things (IoT) presents a paradigm shift towards densely populated networks of wirelessly connected devices. Node maintenance arises as a challenging task given both the massive size of such networks and the location of the devices, potentially spread over areas difficult to reach. Therefore, battery replacement becomes impractical, so in many applications battery-less devices are desirable or simply the only option available [1].

In the context of IoT, Bluetooth Low Energy (BLE) has become the de-facto standard given its high market penetration, low energy consumption, and adequate performance. Extensive research can be found in the state of the art on the topic of improving the efficiency of Energy Harvesting (EH), with the optimization of the RF-to-DC rectifiers [2], [3], circuits able to exploit and convert the power coming from electromagnetic waves to charge the nodes. However, not many works can be found directly targeting EH and enabling Simultaneous Wireless Information and Power Transfer (SWIPT) on BLE, as they merely focus on the design of the WPT (Wireless Power Transfer) enabled rectifier but are not optimized for GFSK (Gaussian Frequency-Shift Keying) [4], the modulation used by BLE, or simply combine WPT with other sources such as infrared [5].

In this work, a novel GFSK-optimized rectifier is designed and implemented, which is able to enable SWIPT operation on an off-the-shelf BLE board, as seen by the obtained experimental characterization results. In Section II the design of the rectifier is given, while in Section III the simulation results for the EH and SWIPT scenarios are provided. Section IV presents the measurement results of the performance of the EH operation of the BLE receiver, and finally Section V concludes this work.

II. Design of the Rectifier for FM Signals

The design of the rectenna (rectifying antenna) to be included in the battery-less sensor node previews the presence of an antenna and an RF-to-DC rectifier in order to harvest energy coming from the modulated signals. Its block diagram is fully described in Fig. 1.

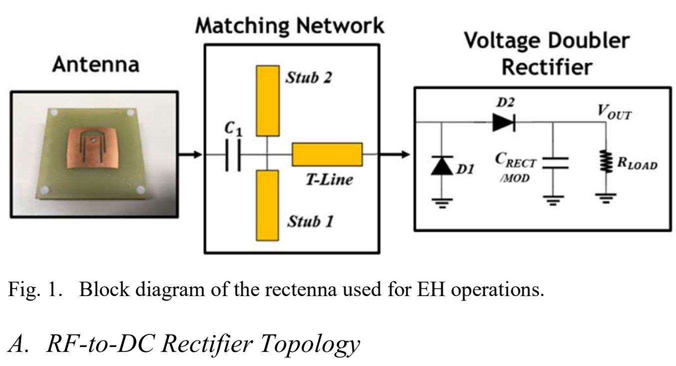

Fig. 1. Block diagram of the rectenna used for EH operations.

A. RF-to-DC Rectifier Topology

The antenna selected for EH is a multi-band patch with gain of 6 dBi in the 2.4 GHz band [6], with coaxial feeding to be connected to the RF-to-DC rectifier, which is a voltage-doubler composed of an input matching network (a 1 pF Murata RF capacitor, two 50-Ω open stubs in parallel, and a 50-Ω transmission line in series), two Schottky diodes (Skyworks SMS7630-079LF), one Murata RF capacitor ($C_{RECT/MOD}$), and a resistor (R_{LOAD}) acting as load and setting the cut-off frequency (f_{CO}) of the output low-pass filter. The final layout of the rectifier, comprising of the matching network, is represented in Fig. 2.

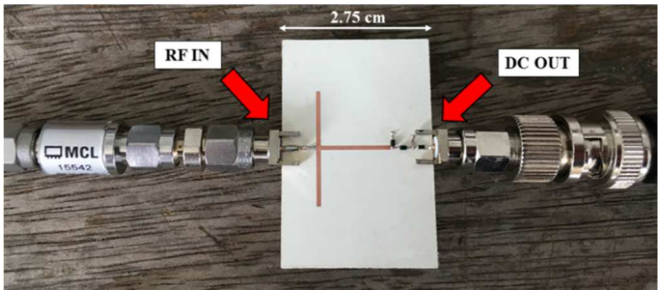

Fig. 2. Photograph of the fabricated board for BLE-harvesting purposes.

The elements that have been optimized to maximize the rectifier PCE (Power Conversion Efficiency) are C_1, the lengths of the open stubs and the transmission line, and the value of the optimum load.

B. *Generation of the 2-GFSK Signal*

Frequency-Modulated (FM) excitation, typical for BLE packets, has been considered in the simulations with the software Keysight ADS (Advanced Design System) [7]. In particular, the excitation consists of a 2-GFSK (two-level Gaussian Frequency-Shift Keying) modulation, with data rate equal to 1 Mbps and BT (bandwidth-period product) of 0.5. This means that the bandwidth (BW) of the Gaussian filter has to be 0.5 MHz.

The key elements to generate a proper 2-GFSK signal, using a Gaussian-filtered pseudo-random bit sequence, are: i) single frequency voltage source, considering an input power of -10 dBm, for this case; ii) FM modulator: RF carrier and modulating signal generating the modulated signal (sensitivity: 1 MHz); iii) voltage source, pseudo-random pulse train (bit rate: 1 Mbps); iv) voltage-controlled voltage source (Z-domain); v) Gaussian low-pass filter, with BW=0.5 MHz.

III. Simulation Results for EH and SWIPT

In this work, the main goal is to investigate the feasibility of harvesting energy from an FM source, but also to consider the possibility to demodulate the BLE signal itself at the rectifier output without the need of a local oscillator, and thus realizing SWIPT.

For this purpose, it is notable to refer to the waveforms obtained at the rectifier output (V_{OUT} in Fig. 1), whose voltage and efficiency as a function of time (30 µs simulation) are reported in Fig. 3, as well as the input voltage V_{IN}. At the output, the same circuit topology has been used to realize two low-pass filters, with f_{CO}=25 kHz for WPT, and f_{CO}=2 MHz for SWIPT of a 1-Mbps-data-rate signal, using two different output capacitances: C_{RECT}=1 nF and C_{MOD}=12 pF, respectively.

It is worth noticing that, in the SWIPT case (Fig. 3), it is possible to retrieve the stream of data corresponding to the first 17 initial values loaded into the shift register (seed) and the following 13 bits of the pseudo-random sequence as generated by ADS, with the high voltages corresponding to binary 1s, and the lower ones to 0s.

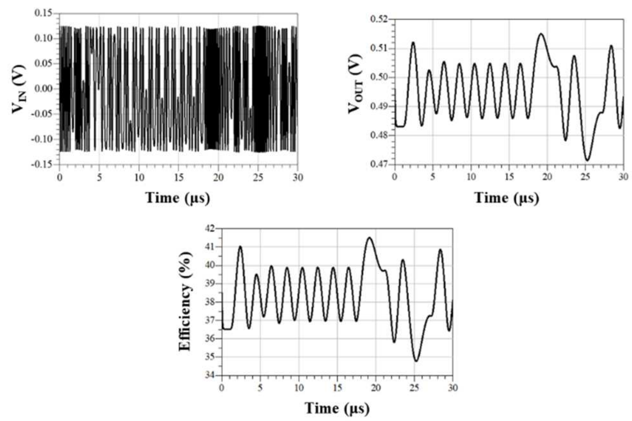

Fig. 3. Input voltage, output voltage, and efficiency for the presented rectifier, with BW of the output filter set in order to achieve SWIPT (f_{CO}=2 MHz).

IV. EH Measurement Results

As to prepare the experimental testing, the board has been tuned at 2.426 GHz (corresponding to #38 Advertising Channel of the BLE protocol) and measured in order to verify its efficiency under the effect of different types of excitations.

A. *Rectifier PCE under Different Excitations*

Fig. 4 represents the simulated and measured PCE with respectively a single tone at 2.426 GHz and applying a 2-GFSK signal (generated by an E4438C ESG vector signal generator), with a sweep of the input power from -20 to 5 dBm. In this case, it is possible to notice the quasi-total superposition between the results obtained by harvesting a single tone and an FM signal.

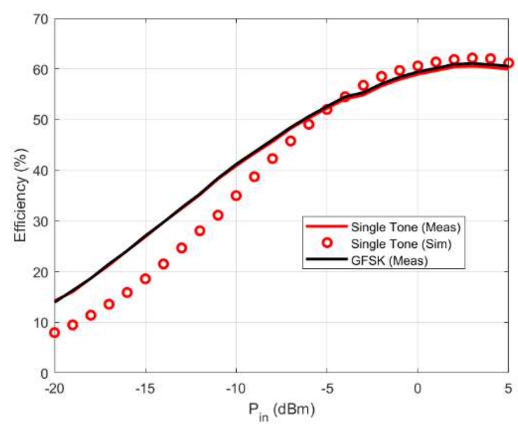

Fig. 4. Simulated and measured PCE for a single tone and a 2-GFSK excitation.

Then, three different multitone excitations have been applied in order to compare them with the previous ones. From Fig. 5, it is possible to notice that the measured PCE for the 3- and 4-tone signals are higher with respect to the GFSK, whereas in case of

5-tone excitation, the PCE results are lower for powers higher than -10 dBm, this is probably due to an earlier appearance of the diodes breakdown region.

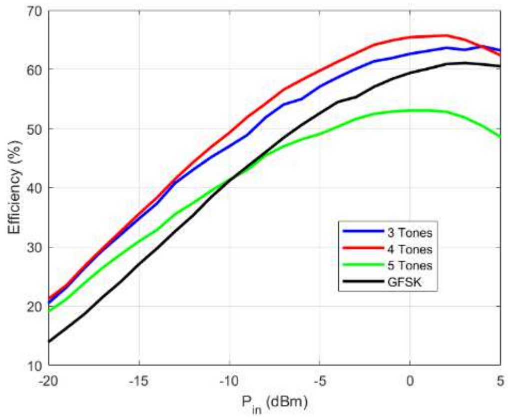

Fig. 5. Measured PCE for various multitone excitations as compared to the 2-GFSK signal.

B. Energy Harvesting Estimation from BLE Packets

The following step involved the programming of the BLE commercial board nRF52840 from Nordic Semiconductor, in order to send Bluetooth advertising packets every 10 ms. Fig. 6 represents the adopted measurement setup, with the BLE board acting as a transmitter and the rectenna as a receiver.

The goal, in this case, is to investigate the possibility to harvest RF energy directly from a real communication signal, without the need of a dedicated CW (Continuous Wave) source, as it is done in most cases for WPT.

Table 1 summarizes the distances from the BLE board to the receiving antenna, and the corresponding open circuit voltages (V_{OPEN}) at the rectifier output, with the BLE board transmitting 4 dBm.

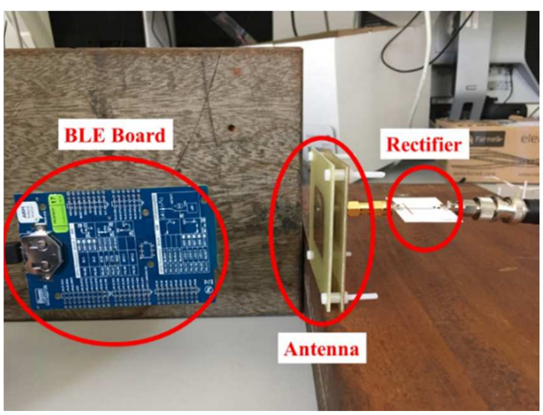

Fig. 6. Measurement setup for the experimental study of energy harvesting from BLE signals.

Finally, a tentative energy budget estimation (for one packet) has been carried out, which is reported in the third column of Table 1, assuming a packet duration of about 300 µs and adopting a 50%-efficiency for the PMU (Power Management Unit), and the actual measured rectifier efficiencies reported in Figs. 4 and 5 for the GFSK signal.

TABLE I. MEASURED OPEN CIRCUIT VOLTAGE AND ESTIMATION OF AVAILABLE ENERGY FOR DIFFERENT TRANSMITTER-RECEIVER DISTANCES

Distance	Open Circuit Voltage (V_{OPEN})	Harvested Energy
1.8 cm	3 V	54.02 nJ
4.2 cm	2 V	24.96 nJ
9.5 cm	1 V	6.18 nJ
19.4 cm	0.5 V	1.29 nJ
36.0 cm	No rectified voltage	---

V. CONCLUSIONS

In this work, the design, realization, and validation measurements of an RF-to-DC rectifier for energy harvesting from BLE-like modulated signals have been presented. In particular, the circuit performance has been tested with single tone, multitone, and GFSK excitations. Finally, BLE packets have been generated and transmitted, at variable distances from the proposed circuit, in order to draw up an estimate of the wirelessly harvested energy exploiting real communication FM signals, without the presence of a devoted CW source for WPT. Work is in progress in order to seamlessly enable concurrent EH and communication operations.

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