Low-Cost Energy-Autonomous Sensor Nodes Through RF Energy Harvesting and Printed Technology

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***Abstract*—The irruption of Internet of Things and 5G in our society comes along with several technological challenges to overcome. From an overall perspective, the low-cost and environmental friendliness of these technologies need to be ensured for their universal deployment in different areas, starting with the sensors and finishing with the power sources. To address these challenges, the production and maintenance of a great number of sensor nodes incur costs, which include manufacturing and integration in mass of elements and sub-blocks, changing or recharging of batteries, as well as management of natural resources and waste. In this article, we demonstrate how Radio Frequency Energy Harvesting (RFEH) and printed flexible technology (a growing technology for sensors) can solve these concerns through cost-effective mass-production and utilization of energy harvesting for the development of energy-autonomous nodes, as part of a wireless sensor network. We present as illustration a sprayed flexible relative humidity sensor powered with RFEH under the store-and-use principle.**

***Keywords*–Radio frequency energy harvesting; printed flexible sensors; IoT; sprayed flexible technology; store-and-use principle.**

I. Introduction

The concept of Internet of Things (IoT) is merging everyday objects, vehicles, buildings, etc., with electronics as part of a Wireless Sensor Network (WSN), giving new perspectives to a broad range of areas traditionally out of the innovation scope. In the following years, while it deploys, a lot of effort will focus on the expenses, security and energy sources of the WSN-nodes, as they occur to be the most critical issues. Under these circumstances, Energy Harvesting (EH) methods and low-cost hardware techniques such as *Radio Frequency Energy Harvesting (RFEH)* and *printed technology*, respectively, appear to be innovations to overcome successfully these matters and that aim at the same time at the series production and distribution.

Depending on the application, the energetic demands of the deployed nodes differ vastly. While the tendency in the low-power cases is the use of non-rechargeable chemical (lithium) batteries [1], in several situations is not an option due to:

- Longevity of a minimum time frame of months or years without compromising the quality of service.
- Large-scale deployment of nodes, materialized in impractical maintenance.
- Hard access to the devices (high structures, wild animals, etc.).
- Cost of the batteries during the whole product life.

Besides, the massive employment and disposal of batteries cost a big price to the environment in the shape of resources over-exploitation and wastes [2], [3].

On the other hand, EH takes advantage of the existing ambient energy such as thermal, solar, vibrational or electromagnetic waves among others; providing energy-autonomous systems that do not need batteries for their operation. Specifically, RFEH exploits the far field region of ambient radiation whose frequencies range between some kilohertzs and hundreds of gigahertzs [4].

Likewise, the usage of printed sensors solves a number of problems that often head towards an increase of the costs in manufacturing, integration and assembly. In contrast to traditional integrated sensors, printed ones can integrate at the same instance a broad combination of variables like environmental gas concentrations, temperature, human heartbeat, relative humidity or biopotentials, among others. Large-scale and multipurpose fabrication techniques allow as well their manufacture in a cost-effective way. Additionally, their flexible capabilities open the doors to use-cases as wearables whose manufacturing costs decrease, facilitating their broad utilization.

Having these two technologies together brings low costs in production (cheap printed materials and integration) and maintenance (no batteries), along with respect for the environment. Moreover, printed sensors present ultra-low power requirements, fitting perfectly with RFEH which stays in that energetic range in most of the scenarios.

This paper is organized as follows: Section II explains the general concepts of RFEH and flexible electronics technology, keeping a perspective under the common linker of IoT. Section III introduces and analyzes their integration and describes the proposed solutions in terms of hardware and working principle. Finally, Section IV presents the conclusions.

II. Background

A. RF Energy Harvesting

An IoT energy harvester is a system that captures energy from ambient sources and converts it into electricity for further use. Normally, the goal will be powering wireless autonomous devices like nodes part of a WSN.

The selection of the source depends only on the ambient conditions around and on the application requirements, i.e., amount of energy needed, update period, part of the day of

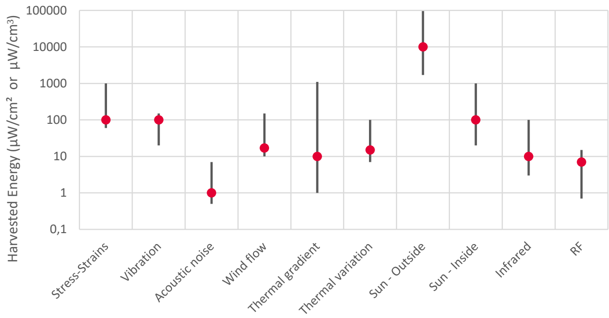

Figure 1. Comparison of different energy harvesting sources [4].

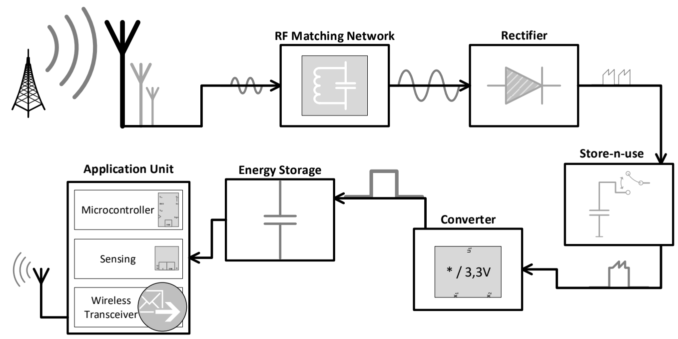

Figure 2. Block diagram of a basic RFEH complete system (with store-and-use principle).

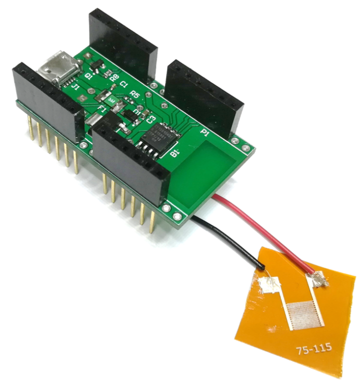

Figure 3. Example of hybrid prototype between flexible electronics (flexible Kapton printed sensor) and rigid (microcontroller).

operation, among others. Figure 1 compares the most common EH methods in terms of energy harvested.

RFEH grants clear advantages in contrast with the rest of techniques or wired options [2], [5]:

- Everywhere and every-time availability (unlike solar or thermal).
- Predictability and stability over time (unlike wind flow or vibrational).
- Wireless nature (unlike the common USB-powered option).
- Low-cost implementation (an antenna and a simple rectification circuit suffice).
- Small form-factor (within the interest frequency range).

However, as seen in the previous figure, the available power presents the mayor challenge, since extremely high efficiencies in the circuits are needed for its usage. Friis equation determines the inverse square relation with the distance to the signal source and with the efficiency of the rectifying and converting circuits [6]. Moreover, often the availability of the signal is permanent but not constant, e.g., Wi-Fi router duty-cycle or mobile phone random use [3], [7].

RFEH is usually categorized as “ultra-low power” (barely tens of microwatts), although it can be also employed as a wireless energy transfer technique. Using a dedicated signal emitter unlocks a broader range of applications more power consuming, reaching hundreds of microwatts. The advantage against the well-known inductive coupling (including resonant inductive) is the effective distance reached (it presents 20 dB attenuation per decade versus 60 dB [5]), although it has much lower source-to-load energy efficiency. That turns the maximum separation of a few centimeters into several kilometers.

The basic operation of a RFEH harvester (see Figure 2) starts with an antenna (or antennas) capturing the signal carrier of interest. A rectifier follows, which converts the microwave energy into dc, consisting of Schottky diodes or CMOS structures in diode configuration in nearly all the literature. For the best power transfer between these two stages, a matching network tuned at the target frequency is needed.

In order to obtain an appropriate and constant voltage level, a voltage regulation stage is essential, generally in form of a boost converter or a charge pump. Once at the desired level, the energy is stored in a capacitor, dimensioned according to the application needs.

B. Flexible Electronics Technology

Together with the EH technology, flexible electronics has attracted significant attention in the field of WSNs. Recent advances show promising future prospects in diverse areas, such as wearables, electronic skin (e-skin) and even implantable devices [8], [9], which satisfy requirements that were not affordable with the current rigid silicon-based solutions.

In addition to its inherent properties (flexibility, lightness, transparency, etc.), the interest in flexible electronics relies on the possibility to reduce the manufacturing cost of large-area devices, since its associated fabrication processes are usually compatible with roll-to-roll techniques [10].

Over the years, diverse methods and materials have been presented for the manufacturing of flexible electronics, such as screen- and inkjet-printing of conductive pastes, or spray deposition and laser processing of nanomaterials [11]–[13]. However, the development of fully flexible IoT devices is still in early stages, and precisely because of that, most proof-of-concept designs are based on hybrid technologies in which the flexible part is limited to the sensors or antennas [14]–[16] and, more recently, to the energy storage devices [17], [18] (see Figure 3).

III. Energy-Autonomous and Low-Cost IoT Nodes

Within the IoT and WSN world exist several scenarios where the application requirements are not too demanding towards the update period or transmission range. With the

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inclusion of printed ultra-low power sensors and if the surrounding environment enhances its usage, RFEH appears as a singular method for powering the nodes, becoming an excellent composite for both technologies.

The complete IoT node consists of: i) printed sensor, a capacitive structure in this case for measuring the Relative Humidity (RH) of the air; ii) a microcontroller (µC) plus transceiver chip, the logic and communicator of the circuit (also able to be manufactured in bendable technology); iii) different antennas, for communication ($868\,\mathrm{MHz}$) and harvesting from Global System for Mobile communications (GSM) ($949\,\mathrm{MHz}$); iv) RFEH block, outputting directly regulated dc voltage to a v) storage capacitor.

In this manner, we achieve energy-autonomous and low-cost nodes, since we avoid the use of any sort of battery and the production, integration and maintenance phases are remarkably cheaper.

A. Working Principle

The working principle attends to the one described in Figure 4, commonly known as duty-cycled operation. In this manner, after a measurement and transmission cycle, the system will be most of its time in sleep mode (ultra-low power consumption or even disconnected), while the harvesting electronics charge the capacitors for a new measurement.

The wake-up process can be triggered in different ways:

- With a fixed period determined by the application, although within a certain time range where the capacitors are assured to be charged (Radio Frequency (RF) energy available is stable and predictable).
- With an extra wake-up radio that triggers the active mode [4].
- Or every time a certain voltage level is reached while charging.

In any case, the *minimum period* will depend only on the RF spectrum, i.e., how much energy is available around the node, and of course, on the application needs.

Once a measurement is carried out and sent, the gateway -or objective node depending on the communication topology- will forward the message to the cloud and answer the node in case of need. These points are assumed to not work with energy harvesting.

B. Harvested Energy

The power levels in city open-spaces nowadays go up to $-30\,\mathrm{dBm}$ and even $-20\,\mathrm{dBm}$ at bands of high usage such as GSM, tv broadcasting, license-free bands or wireless local networks [19]–[21]. Furthermore, with active emitting, the levels can reach in average more than $-3\,\mathrm{dBm}$ [5].

The losses, from the source emission until the load, can be split in two parts. The first and largest are the propagation losses along the path, defined by the Friis transmission equation, and increased by presumable obstacles and misalignment of the antennas. The second part is related to the efficiency at the rectifier-converter-storage chain. Slight drops in this efficiency will stop the system from working, since the voltage levels are close to the thresholds of the actual silicon electronics.

The current state of the art in rectification and storage for the power levels mentioned satisfies the energy needs

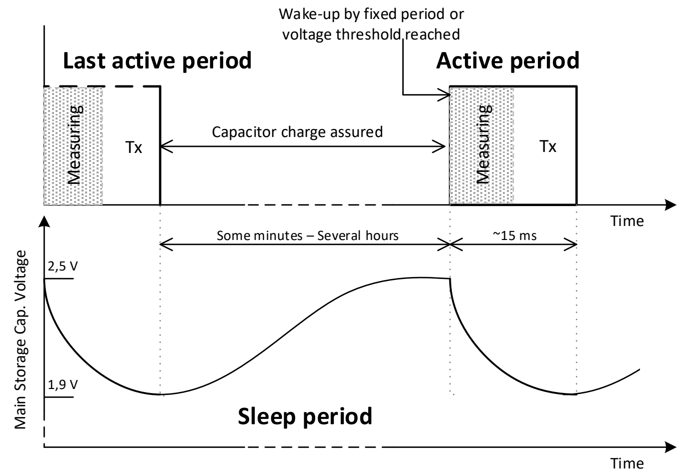

Figure 4. Working principle of an ultra-low power IoT node with duty-cycled operation and EH.

for several IoT use-cases, although the conversion stage gets harder to deal with due to the low levels of power and/or voltage. Most of the off-the-shelf converters are considered "low-power" (range of milliwatts) and are able to operate either with extremely low levels of voltage or power, but not with both together. This results in a harder employment of EH techniques, as the converter stage must be custom designed or, alternatively, this task is taken over by the rectifier, being then only valid under certain energy conditions.

Nevertheless, making use of the store-and-use principle as an intermediate stage [22], more energetic bursts in periods can be output to the converter. In this way, and with a favorable environment as the mentioned before, the power harvested from some microwatts to hundreds of them, can be stored in the desired voltage level for its use by the application unit in a duty-cycled fashion.

In this direction, we have developed a battery-less harvesting block capable of capturing RF energy while using commercial low-power dc/dc converters (see Figure 5). Making use of an innovative autonomous switched capacitor design, we implemented the store-and-use principle, functioning not only as an energy adaption phase, but also as an impedance matching.

C. Flexible Relative Humidity Sensor

The developed IoT node integrates a flexible sensor intended for the monitoring of the ambient RH. The operation of this sensor, shown in Figure 6-a, is based on the outstanding sensitivity to humidity changes of the dielectric constant of Graphene Oxide (GO) [23], [24]. For that, a flexible PolyEthylene Terephthalate (PET) substrate was coated with a thin-layer of GO, which was prepared at a concentration of $0.4\,\mathrm{wt\%}$ following a modified version of the Hummers and Offeman's method, as described in [25]. The spray-coating of the substrate ($38.5\,\mathrm{\mu L/cm^2}$) was done using a manual airbrush similar to the presented in [26], [27]. Finally, once the GO layer was completely dried, a capacitive structure consisting of 16 InterDigitally arranged Electrodes (IDE) was screen-printed on its surface using a silver-based conductive ink (LOCTITE® ECI 1010 E&C from Henkel AG, Düsseldorf, Germany), as

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Figure 5. Picture of developed RFEH block.

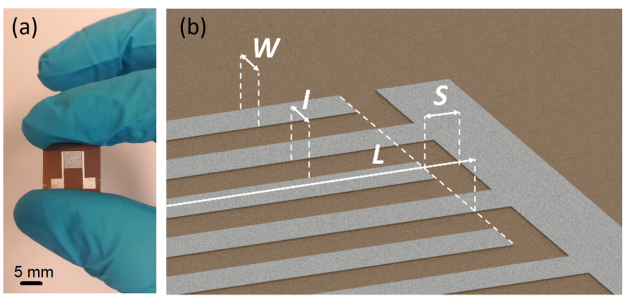

Figure 6. a) Flexible GO-based humidity sensor. b) Dimensions of the screen-printed pattern (W: width 150 µm, S: spacing, 225 µm, I: interspacing 225 µm, L: length 5 mm).

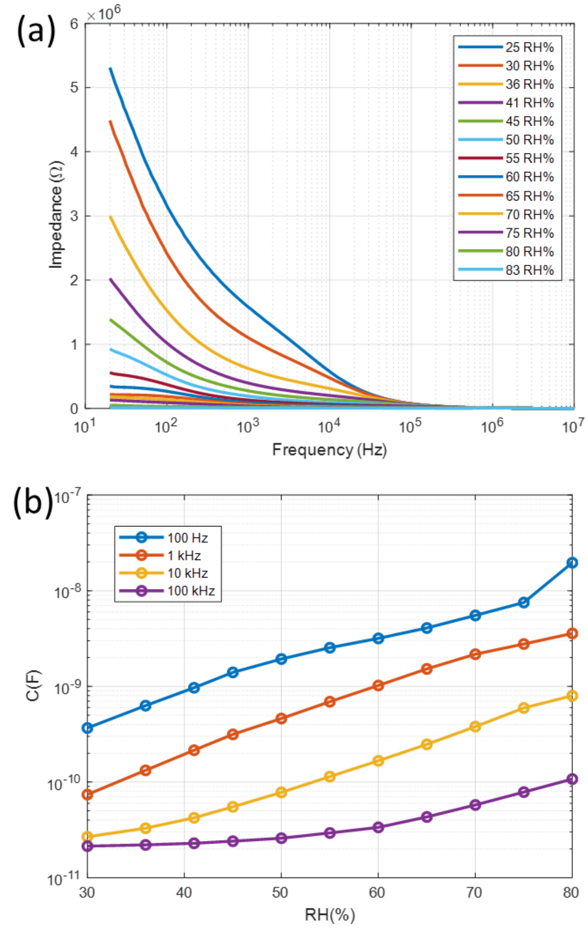

Figure 7. Impedance response of the sensor a) and extracted equivalent parallel capacitance b) as a function of the RH and frequency.

depicted in Figure 6-b. We opted for this configuration for two main reasons. Firstly, to have a more uniform layer on which the GO can be deposited with a better control of the thickness and, secondly, to minimize the impact of the substrate on the performance of the sensors. Electrical connections were glued to the electrodes using silver conductive paint (186-3600 RS Pro, RS Components, Corby, UK), following the manufacturer recommendations, which did not affect the thermal reduction of the GO.

The calibration curves obtained for this humidity sensor are shown in Figure 7. The experiments were performed using the climate chamber VCL4006 (from Vötsch Industrietechnik GmbH, Balingen, Germany) at a constant temperature of 40 °C to use the whole humidity range of the chamber. The results show that the impedance decreases with both increasing humidity and frequency values (see Figure 7-a). These impedance values were used to extract the equivalent parallel capacitance as a function of the RH at four different frequencies (100 Hz, 1 kHz, 10 kHz and 100 kHz) as shown in Figure 7-b. The sensitivity offered by this sensor depends on the frequency of the excitation signal, being 385.53 pF at 100 Hz, 70.07 pF at 1 kHz, 15.44 pF at 10 kHz and 1.72 pF at 100 kHz.

IV. Conclusion

In this article, we introduced a solution for the use of RFEH in conjunction with flexible printed sensors as a form of decreasing the costs of WSNs deployment. Besides the general cost reduction due to the omission of battery-recharge or substitution and wiring; the employment of innovative low-cost printed sensors provides an extra boost in manufacturing and integration savings.

The presented sprayed GO-based sensor is an example of how this technology can achieve satisfactory measurement results in an extremely cost-effective manner and with ultra-low power requirements. On the other end of the system, the store-and-use principle applied to RFEH provides lower levels from where the energy can be harvested, through energy accumulation and impedance matching between the rectifier and converter stages.

The future work encompasses the optimization of the energetic sub-blocks in order to reach lower levels, as well as the improvement of the sensor accuracy.

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