RAMSES: RFID Augmented Module for Smart Environmental Sensing

Danilo De Donno, Luca Catarinucci, and Luciano Tarricone

Abstract—This paper presents an RFID Augmented Module for Smart Environmental Sensing (RAMSES), which is a fully-passive device with sensing and computation capabilities conceived to explore novel and unconventional radio frequency identification (RFID) applications. RAMSES implements an RF energy-harvesting circuit enhanced by a DC-DC voltage booster in silicon-on-insulator (SOI) technology, an ultra-low-power microcontroller, temperature, light, and acceleration sensors, and a new-generation 1°C-RFID chip to wirelessly deliver sensor data to standard RFID EPCglobal Class-1 Generation-2 readers. A preliminary RAMSES prototype, fabricated on a printed circuit board using low-cost off-the-shelf discrete components, has been extensively tested through experiments conducted both in lab and real-world application scenarios. The achieved results have demonstrated the ability of RAMSES to harvest the RF energy emitted by an interrogator placed up to 10 m of distance and autonomously perform sensing, computation, and data communication. To the authors’ knowledge, this is the longest range ever reported for fully-passive RFID sensors. Furthermore, for applications requiring larger operating distances, RAMSES provides also a battery-assisted passive mode yielding up to 22-m communication range.

Index Terms—Radio frequency identification, RF energy harvesting, wireless sensor networks, computational RFID, smart environment.

I. INTRODUCTION

The evolution of radio frequency identification (RFID) technologies over the years is spurring the advent of new and fascinating applications beyond the simple object identification and tracking in supply chains. For example, as envisioned in [1], the small form factor and perpetual self-powered operation of passive RFID tags are expected to be key aspects of the approaching Internet of Things (IoT), where everyday networked objects with sensing and computation capabilities will interact with each other to create smart environments.

To date, the integration of communication, computation, sensing, actuation, and storage functionalities in passive ultra-high-frequency (UHF) RFID tags has raised a broad interest from both academia and industry. The pioneers in developing augmented UHF RFID tags were Smith et al. in 2005 with their wireless identification and sensing platform (WISP) implementing the ID-modulation mechanism for sensor data transmission [2]. In 2008, the same authors improved the WISP functionalities [3] by developing the first battery-free programmable UHF RFID tag with sensors. A low-cost general-purpose alternative to the WISP is the sensor-tag (S-Tag) [4]. Based on a multi-ID approach, the S-Tag can be connected to generic sensors and, when interrogated by a standard EPCglobal Class-1 Generation-2 (Gen2 for short hereafter) reader, it transmits a proper combination of electronic product codes (EPCs) that univocally encodes the sensor value. In [5], an augmented UHF RFID tag, not compliant with any existing RFID standard and equipped with microcontroller unit (MCU) and sensors, is prototyped on a flexible organic substrate using inkjet-printing technology. Moreover, the authors address the integration of carbon-nanotubes on paper substrates for the fabrication of ultra-sensitive gas sensors and present benchmarking results for different scavenging approaches involving solar and charge-transfer-based mechanisms. A passive multistandard RFID tag enhanced with sensing and localization functionalities and implemented in a 0.13μm bulk CMOS process is presented in [6]. An interesting design strategy for fully-passive RFID sensors is proposed in [7]-[10]. It relies on detecting variations in gain, input impedance, and differential radar cross-section of the tag’s antenna caused by environmental changes (e.g. temperature [7] and humidity [8]) or mechanical stresses (e.g. strain [9] and motion [10]). This sensing mechanism, besides being extremely susceptible to radio propagation phenomena, is not compatible with existing RFID infrastructures since it requires expensive equipments, such as vector network analyzers or customized receivers, to reliably extract sensor-dependent characteristics from backscattered radio signals.

In addition to the academic research, RFID manufacturers are starting to commercialize Gen2 tags that incorporate sensing, computation, and data-logging capabilities for unconventional RFID applications. Among them, it is worth mentioning the SL900A sensory tag by Austria Micro Systems (AMS) [11], the Easy2Log tag by CAEN RFID [12], and the SensTAG by Phase IV [13]. Nevertheless, none of the aforementioned solutions [2]-[13] comprises all the primary characteristics required by future RFID-based sensing applications, e.g. the full compliance with RFID standards and regulations (most devices need specific settings for the reader), a satisfactory operating range (comparable to that of conventional UHF passive tags), a variety of on-board sensors, high expansibility and programmability.

This work presents the design and performance evaluation of a long-range, self-powered, Gen2-compliant, and programmable RFID Augmented Module for Smart Environmental Sensing (RAMSES). RAMSES exploits a new-generation RFID chip with dual communication interface: a wired I²C interface managed by a microcontroller and a wireless UHF interface for communication with standard RFID Gen2 read-

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ers. RAMSES is fabricated using commercial off-the-shelf (COTS) low-cost discrete components on an FR4 substrate (see Fig. 1), operates both in fully-passive and battery-assisted-passive (BAP) modes, and is equipped with temperature, light, and acceleration sensors. In fully-passive mode, RAMSES employs an RF-DC rectifier enhanced by a DC-DC charge pump in silicon-on-insulator (SOI) technology to harvest energy from the RFID signal emitted by the interrogating reader. In addition, the harvester implements a supervisory mechanism that wakes up the RAMSES MCU only when the available on-board energy is sufficient to perform sensing and I\(^2\)C-RFID communication tasks. Compared to the aforementioned devices [2]-[13], RAMSES exhibits superior performance in terms of maximum communication distance with the reader, sensing capabilities, and configurability. Moreover, differently from application-specific integrated circuit (ASIC) products, the printed-circuit-board (PCB) design offers flexibility to integrate new sensors/actuators and to embed RAMSES into electronic devices for further expanding the range of applications, e.g. towards heterogeneous wireless sensor networks (WSN) [14].

This paper is organized as follows. RAMSES architecture, components, and design strategies are discussed in §II. Next, a series of experiments aimed at evaluating RAMSES performance and functionalities are presented in §III. Finally, conclusions are drawn in §IV.

II. RAMSES DESIGN AND PERFORMANCE

A block diagram of RAMSES architecture is depicted in Fig. 2. A conventional UHF RFID tag, composed of a dipole-like antenna and a Gen2 chip, makes up the RFID section. The main feature of the adopted RFID chip is the capability of its memory to be accessed via the wired \(I^2C\) interface (in addition to the standard Gen2 air interface). Consequently, sensor data transferred over the \(I^2C\) bus by means of an MCU are directly accessible to standard RFID Gen2 readers. The power needed to operate RAMSES could be definitely retrieved by a battery (BAP mode), but also harvested from the RFID interrogation signal emitted by the reader. To this end, RAMSES is equipped with an RF power harvesting and management section comprising a 50-\(\Omega\) antenna matched to an RF-DC rectifier. A DC-DC charge pump with integrated supervisory mechanism stores and efficiently releases the rectified voltage to power the digital (MCU and temperature/light/acceleration sensors) and RFID sections.

The system architecture depicted in Fig. 2 is extensively described in the following subsections while a number of experiments aimed at assessing RAMSES performance and functionalities are presented in §III.

A. RF power harvesting and management section

As anticipated, RAMSES provides both BAP and fully-passive operating modes. In the fully-passive case, a single-stage full-wave rectifier is used to convert the UHF RFID energy transmitted by the reader during the interrogation process to DC power. The rectifier is connected to a 50-\(\Omega\) whip antenna specifically designed for compact devices operating in the 824-960 MHz frequency band. A high-Q RF inductor and a high-Q ceramic trimmer capacitor compose the LC impedance-matching network. The Skyworks SMS7630 zerobias Schottky diodes have been chosen as rectifying devices because of their high-detection sensitivity at UHF frequencies. Then, the Seiko Instruments S-882Z24 charge pump IC [15] is adopted to step-up the rectified voltage \(V_{\text{dc}}\). Such a DC-DC converter implements fully-depleted SOI technology to enable ultra-low-voltage operation. In fact, when \(V_{\text{dc}}\) is 0.35 V or higher the oscillation circuit starts operating and the stepped-up electric power is accumulated in a storage capacitor (see Fig. 2). When the capacitor reaches \(V_{\text{out}} = V_{\text{dc}} = 2.4\) V, the integrated supervisory circuit of the S-882Z24 automatically
releases the stored energy to a 1.8-V low-dropout (LDO) voltage regulator to power up the digital section. When $V_{\text{dc}}$ decreases to approximately $V_{\text{dc},\text{lo}}=1.85$ V as a result of the storage capacitor discharge, the S-8822Z24 disconnects its output and starts a new charging process.

In the BAP case, the RF energy-harvesting module is bypassed since the 3-V lithium cell provides entirely the power needed to operate RAMSES (note that the communication with the reader still occurs via backscattering). As reported later in the paper, the BAP mode allows to significantly enhance RAMSES performance, primarily in terms of read range.

B. Digital section (sensing and computation)

This section is woken by the intrinsic supervisory behavior of the charge-pump IC used in the RF energy-harvesting circuit. In fact, as previously described, when the voltage accumulated in the storage capacitor reaches the 2.4-V threshold, the DC-DC charge pump automatically releases the stored energy to the 1.8-V voltage regulator which is connected, in turn, to a 16-bit MSP430F5132 MCU. This ultra-low-power MCU can run up to 12 MHz with 1.8-V supply voltage (180-μA/MHz supply current) and provides 8 kB of flash memory, 1 kB of SRAM, and eight 10-bit 200-ksp/s Analog-to-Digital Converter (ADC) channels.

The MCU is programmed with an energy-efficient firmware running at 1 MHz and implementing I2C read/write and ADC sampling routines. The 10-bit ADC samples a TI LM94021 analog temperature sensor consuming down to 9 μA. Then, readings from an ADXL346 accelerometer and a MAX44009 ambient light sensor are taken via the I2C interface. The ADXL346 is an ultra-low power (90-μA current consumption) 3-axis accelerometer with high-resolution measurements (13 bits/axis) up to ±16g. The MAX44009, instead, is the industry’s lowest-power ambient light sensor (1-μA current consumption) with 16-bit resolution. The sensor readings are organized and written (via I2C) into the EPC memory banks of the RFID Gen2 chip as sketched in Fig. 3. Once interrogated, the EPC frames are delivered to the reader using zero-power backscatter modulation.

In future EPCglobal-compliant applications, the sensor data could be stored into the password-protected user memory of the chip and wirelessly accessed by the reader through the Gen2 Read/Write commands, thus leaving the 96-bit EPC totally reserved for product identification.

C. RFID section

A compact dipole-like RFID antenna has been designed and patterned directly on the PCB (see Fig. 1). The input impedance of the antenna has been tuned to achieve a complex conjugate matching with an Impinj Monza X-2K RFID chip [16] ($Z_{\text{chip}}=R_{\text{chip}}+jX_{\text{chip}}=20.83-j181.39 \, \Omega$) at 866.5 MHz, i.e. the center frequency of the European UHF RFID band. The
Monza X-2K is an UHF RFID Gen2 IC with 2176 bits of non-volatile memory (NVM) and an I²C interface. As an I²C device, Monza X-2K operates as a standard EEPROM whose contents can also be accessed wirelessly via the Gen2 protocol. As previously described, the MCU in the digital section is programmed to sample temperature, light, and acceleration sensors, and organize the data into the EPC memory banks of the Monza X-2K as sketched in Fig. 3.

The antenna design takes cue from the commercial ALN-9660 RFID tag inlay which uses meander lines to achieve a very compact form factor (7.5x1.7 cm²). As shown in Fig. 4(a), detailed simulations taking into account the effect of the DC metal traces have been conducted in order to maximize the performance and optimize the design of the final RAMSES prototype. Three main elements define the antenna structure: the central loop, which primarily impacts the tuning of the real part of the input impedance and prevents potential high-voltage discharge, the meander lines on the tuning of the real part of the input impedance and antenna structure: the central loop, which primarily impacts the tuning of the real part of the input impedance and by adding a capacitive lumped element with reactance Xchip. In this way, the problem is led back to the design of classic antennas with real impedance. Finally, the antenna design has been optimized by setting the minimization of the reflection coefficient at the desired frequency as the fitness function and by adopting a gradient-based interpolated quasi-newton optimizer. It is worth mentioning that the complex conjugate impedance matching between antenna and RFID chip and the excellent sensitivity exhibited by conventional RFID readers (below -90 dBm) provide best performance, mainly in terms of read range, when RAMSES operates in fully-passive mode. On the contrary, in the battery-assisted passive RAMSES, the performance limitation is the reader sensitivity itself. In this case, an optimum antenna impedance should be found in order to maximize the backscattered power and, consequently, to further improve the communication range [17].

The E-plane polar diagram in Fig. 4(b) depicts the typical dipole radiation pattern (1.8 dBi is the realized gain) achieved for the antenna while the good impedance matching around the frequency of interest (-18-dB reflection coefficient at 866.5 MHz) is highlighted in Fig. 4(c). Note that, depending on the application and the harshness of the environment, a directive patch antenna instead of an omnidirection dipole could be used to maximize performance (e.g. a longer read range) and platform tolerance [18]-[20].

III. EXPERIMENTAL RESULTS

The RAMSES prototype in Fig. 1 has been fabricated in our labs by using a photolithography process on FR4 substrate and handy soldering off-the-shelf discrete components. The RFID antenna is patterned directly on the PCB while an SMA connector allows to connect generic 50-Ω UHF antennas to the harvester. A small female header exposes the I²C bus and other MCU ports for future expansions to external sensors and devices. The estimated total cost of the prototype, including components, substrate, and fabrication materials, is below $20. In future versions of the device, the overall PCB size could be significantly reduced by designing a more complex layout with components on both sides of the board.

In order to analyze the RAMSES behavior and evaluate its performance and sensing capabilities in real operating conditions, a series of experiments was carried out. The achieved results are presented and discussed below.

A. RF energy-harvesting performance

As a first experiment, the sensitivity of the RF energy-harvesting circuit was measured by injecting, via the Vector Network Analyzer (VNA), an 866.5-MHz continuous wave (CW) into the RAMSES SMA connector. The VNA power was iteratively changed and, at each power level, the LC matching network tuned accordingly to achieve the maximum power transfer to the rectifier. The minimum power necessary to activate the DC-DC charge pump, i.e. to charge the storage capacitor, was found to be approximately -17 dBm. The red-line graph in Fig. 5 shows the good impedance matching and frequency tuning achieved when the VNA output power is set to -17 dBm. Note that performing the impedance matching at the minimum input power needed for charging the storage capacitor ensures the maximum RF energy-harvesting range.

In order to corroborate such a result and rapidly perform sensitivity measurements at different frequencies, an over-the-air analysis in an anechoic chamber was carried out. A software-defined radio (SDR) equipment [21]-[24] was connected to a circularly polarized antenna with gain G antenna=5.5 dBi and placed at 1 m of distance from RAMSES. Both RAMSES and the instrument’s antenna were oriented in the maximum-gain direction. A CW was generated and the minimum transmit power Ptx on needed to charge the storage capacitor up to V out=2.4 V was recorded at different frequencies in the 830-930 MHz band. The sensitivity value was calculated according to the following equation based on the free-space Friis propagation model:

\[ S = EIRP_{\text{on}} G_{\text{tx}} \left( \frac{\lambda}{4\pi d} \right)^2 \eta_{\text{pl}} \text{ (Watt)} \]  

where \( EIRP_{\text{on}} = P_{\text{on}} G_{\text{tx}} \) is the minimum equivalent isotropically radiated power (EIRP) required to operate RAMSES,
TABLE I
CURRENT CONSUMPTION OF RAMSES COMPONENTS

<table>
<thead>
<tr>
<th>Component type</th>
<th>Part number</th>
<th>Supply current (μA)</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear voltage regulator</td>
<td>ON Semi NCP583</td>
<td>4</td>
<td>LDO, 1.8-V output voltage</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>TI MSP430F5132</td>
<td>180</td>
<td>Active current (1.8-V supply voltage, 1-MHz clock)</td>
</tr>
<tr>
<td>RFID chip</td>
<td>Impin Monza X-2K</td>
<td>100</td>
<td>During an I²C write operation</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>TI LM94021</td>
<td>9</td>
<td>During the sampling phase of the MCU ADC</td>
</tr>
<tr>
<td>Ambient light sensor</td>
<td>MAX44009</td>
<td>1</td>
<td>Measurement mode (16-bit resolution)</td>
</tr>
<tr>
<td>3-axis accelerometer</td>
<td>ADXL1346</td>
<td>90</td>
<td>Measurement mode (13-bit/axis resolution, 400-Hz output data rate)</td>
</tr>
</tbody>
</table>

Fig. 6. Measured efficiencies of the rectifier, the DC-DC charge pump, and the overall system at different power levels. The test signal is a CW at 866.5 MHz injected by the VNA directly into the RAMSES SMA port.

The measured efficiencies are defined as follows:

\[
\text{Rectifier efficiency} = \frac{P_{dc}}{P_{in}}
\]

(2)

\[
\text{Charge-pump efficiency} = \frac{P_{dc}}{P_{in}}
\]

(3)

\[
\text{System efficiency} = \frac{P_{dc}}{P_{in}},
\]

(4)

where \(P_{dc}\) is the RF power of the 866.5-MHz CW injected by the VNA into the RAMSES SMA port, \(P_{in}\) is the DC output power from the rectifier (i.e., the DC input power to the charge-pump IC), and \(P_{dc}\) is the DC output power from the charge-pump IC. As shown in Fig. 6, the total system efficiency reaches approximately 20% when the input power is -9 dBm. The considerable supply power required by the charge-pump IC to build up the output voltage kills, in fact, the 80% efficiency achieved by the rectifier. On the other hand, the DC-DC charge pump allows to trade off efficiency against sensitivity, thus enhancing the maximum operating distance. This phenomenon has been demonstrated in [25], where the performance of RF energy-harvesting circuits, with and without the DC-DC charge-pump, has been compared.

B. Overall performance: duty cycle and read range

The power absorbed by MCU, sensors, and I²C-RFID chip causes the storage capacitor to discharge. More specifically, when \(V_{dc}\) declines approximately to \(V_{dc,lo}=1.85\) V the charge-pump IC automatically stops the discharge process by disconnecting its output. The idle time between MCU operations, i.e., the duty cycle of the overall system, is determined by the amount of input power to the charge-pump IC and by the size of the storage capacitor. In fact, since for a given task the MCU execution time \(T_{on}\) is fixed, RAMSES duty cycle:

\[
\text{Duty cycle} = \frac{T_{on}}{T_{on} + T_{charge}}
\]

(5)
can be maximized by minimizing the time \(T_{charge}\) needed by the harvester to charge the storage capacitor. Regardless of the harvested RF power, the best performance is achieved with the minimum size of the storage capacitor calculated by the following equation [3]:

\[
C \geq \frac{2V_{cc}I_{s}T}{\left(\frac{V_{dc,hi}}{V_{out}}\right)^{2} - \left(\frac{V_{dc,lo}}{V_{out}}\right)^{2}}
\]

(6)

stating that the energy required to run the MCU firmware must not exceed the stored energy. An approximate minimum capacitance \(C=90\, \mu F\) is obtained by considering \(I_{s}=230\, \mu A\) as the measured average current consumption of RAMSES, \(V_{cc}=1.8\) V as the MCU operating voltage supplied by the LDO.

\(G_{N}=0.5\) dBi is the gain (measured experimentally) of the 50-Ω whip antenna used for RF energy-harvesting, \(\lambda\) is the wavelength, \(\eta_{pl}=0.5\) is the polarization loss factor due to the circularly polarized transmit antenna, and \(d=1\) m is the distance between the RF source and RAMSES. The achieved results are plotted in Fig. 5 (black-line graph, secondary y-axis) where the proper impedance matching and tuning of the harvester are demonstrated by the better sensitivity values achieved around 866.5 MHz. Furthermore, the peak sensitivity at -17 dBm confirms the previous outcomes from the VNA.

Compared with the sensitivity attained by our earlier RF energy-harvesting modules [25], [26], RAMSES exhibits an approximate 3-dB improvement. This is primarily due to the single-stage RF-DC converter adopted in RAMSES against the 5-stage Cockcroft-Walton voltage multiplier [27] used in our prior work. In fact, since the DC-DC charge pump starts to operate at extremely low input voltages (as low as 0.35 V), voltage multiplication during the initial RF-DC conversion phase is not required at all. Furthermore, reducing the number of rectifier stages and, consequently, the power dissipated in each diode allows to maximize the current supplied to the DC-DC charge pump IC whose energy consumption is considerable (≈ 100μA at 0.35-V input voltage).

The efficiencies of rectifier, charge-pump IC, and overall system at different power levels (injected by the VNA) were measured and the results at 866.5 MHz plotted in Fig. 6. The
Fig. 7. Measured average time needed for the harvester to charge 10 $\mu$F (allowing RAMSES to perform only temperature measurements) and 100 $\mu$F (full RAMSES functionalities) storage ceramic capacitors (primary y axis) and achieved duty cycle (secondary y axis) when varying the distance of RAMSES from the interrogating reader.

regulator, and $T=250$ ms as the measured time needed for the MCU to complete its tasks (i.e., to take measurements from three sensors and communicate with the RFID chip via the I$^{2}$C interface). The current consumption of RAMSES components down-line the RF energy-harvesting circuit is summarized in Table I.

In order to evaluate RAMSES performance in terms of storage capacitor charge time and duty cycle, we used a commercial RFID Gen2 reader set with the maximum allowable transmit power for the European regulations, i.e., 3.2-W EIRP in the 865-868 MHz frequency band, to energize and interrogate RAMSES at different distances. The experiments were conducted in a large lecture room with reader antenna and RAMSES placed in the line of sight (LOS) 1.5 m above the floor, both oriented in the maximum-gain direction. As shown in Fig. 7, RAMSES is able to autonomously operate (fully-passive mode) up to approximately 10 m of distance from the reader. Since the rapidity of the DC-DC charge pump to build up the output voltage depends on the amount of RF energy incident on the harvesting antenna, the time needed to charge the storage capacitor increases with the distance. Obviously, a smaller capacitor takes less time to be charged at the cost of a reduced number of tasks and functionalities runnable by the MCU. It was found experimentally that a 10 $\mu$F capacitor is sufficient to perform only temperature measurements while the full RAMSES functionalities (temperature, light, and acceleration measurements) are feasible with a 100 $\mu$F capacitor, thus confirming the theoretical result achieved by (6).

RAMSES characteristics compared with similar RFID Gen2-compliant devices are summarized in Table II. To the authors’ knowledge, RAMSES is the longest-range fully-passive Gen2 tag integrating MCU and up to three sensors. Moreover, the capability of the Monza X-2K I$^{2}$C-RFID chip to boost its sensitivity (from -17 dBm up to -24 dBm) when connected to a DC source allows RAMSES to operate in BAP mode up to 22 m of distance from the reader. Similar simulated performance are exhibited only by the WISP [3].

### Table II

<table>
<thead>
<tr>
<th>Reference</th>
<th>Read range (m)</th>
<th>On-board sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAMSES</td>
<td>10</td>
<td>22</td>
</tr>
<tr>
<td>WISP [3]</td>
<td>4</td>
<td>24 (simulated)</td>
</tr>
<tr>
<td>Multistandard tag [6]</td>
<td>8</td>
<td>not supported</td>
</tr>
<tr>
<td>Easy2Log [12]</td>
<td>not supported</td>
<td>10</td>
</tr>
<tr>
<td>SensTag [13]</td>
<td>4.5</td>
<td>1 (specified by the user)</td>
</tr>
</tbody>
</table>

Fig. 8. 24-hour temperature and ambient light monitoring performed by RAMSES in an indoor scenario.

### C. Sensing applications

A series of tests aimed at verifying RAMSES capabilities to perform environmental sensing has been conducted in real-world application scenarios. In a first experiment, we placed RAMSES near the window of a standard office room to monitor indoor temperature and light conditions over the course of a day. A reader antenna mounted on the ceiling was used to interrogate RAMSES (placed at about 5-m LOS distance and configured in fully-passive mode) and to collect the sensor data at the host PC. The results reported in Fig. 8 show how the sensor measurements performed by RAMSES are consistent with events occurred over the 24-hour observation period. For example, when the window was opened at about 6 a.m. the temperature decreased because of the fresh air entering from outside. Similarly, the temperature increased when the window was closed in late afternoon. Light and temperature drops around 5 p.m. were due to the approaching sunset.

In a second experiment, we placed RAMSES at 10 m of distance from the reader and used it to log acceleration data from the on-board 3-axis accelerometer every 5 seconds. RAMSES was configured in BAP mode and attached to an internal face of a parcel whose position with respect to the ground was periodically changed to simulate abusive handling during a shipment of fragile items. As previously outlined, the BAP mode boosts the Monza X-2K IC sensitivity thus minimizing the performance degradation due to the RAMSES orientation change and, to a lesser extent, the attachment to the parcel surface. As shown in Fig. 9, RAMSES is able to...
detect orientation changes by measuring the effect of gravity on the accelerometer axes for all the six positions experienced during the test. Interestingly, the BAP mode provides data-logging functionalities which enable RAMSES to monitor the shipment status constantly, even outside the reader coverage area.

IV. CONCLUSION AND ON-GOING WORK

In this paper, the design, prototyping, and experimental validation of a self-powered wireless sensor module (RAMSES) compliant with the UHF RFID Gen2 standard have been presented. RAMSES features an RF-DC rectifier boosted by a DC-DC charge pump IC in SOI technology to harvest RF energy. When the RF power level received from the interrogating reader is -17 dBm or higher, RAMSES starts to operate. An ultra-low-power microcontroller samples an analog temperature sensor, a digital ambient light sensor, and a digital 3-axis accelerometer. Data are transferred to a new-generation IFC-RFID chip whose EPC code is dynamically updated with actual sensor measurements. Two real-world experiments illustrative of RAMSES capabilities and potential applications have been presented. In the former, RAMSES has been used to monitor ambient temperature and light conditions over a 24-hour observation period. In the latter, static acceleration measurements on a parcel have been logged by RAMSES in BAP mode in order to verify its ability to catch abusive handling events during a shipment. The preliminary RAMSES prototype, fabricated on an FR4 substrate using low-cost discrete components, is able to perform RFID-based sensor data transmissions up to approximately 10 m and 22 m of distance from the interrogator in full-passive and BAP modes respectively. To the best of the authors’ knowledge, these represent the longest communication distances ever reported for similar sensor-enhanced RFID devices.

In the progress of this work, we are planning to explore alternatives to the EEPROM-based Monza X-2K RFID chip, e.g. the Ramtron WM71016 and Fujitsu MB97R804, both implementing Ferromagnetic-RAM (F-RAM) technology, to improve memory endurance and power consumption. Moreover, we are planning to apply our knowledge and experience from this preliminary project to a system-on-chip RAMSES solution. In fact, the implementation here proposed as a PCB design using commercial off-the-shelf (COTS) components has a number of drawbacks compared to an IC implementation [28], mainly in terms of cost and power consumption.

REFERENCES


