Battery-Free Smart Objects based on RFID backscattering

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***Abstract*—The IoT era has witnessed an explosion of smart objects. As we move towards connecting the next billion wireless devices to the internet, however, the use of batteries to power them will become unworkable, with significant repercussions on health and the environment, if improperly disposed. Hence, the need for more eco-friendly technologies.**

This article demonstrates how RFID technology, typically used to implement object identification and counting, enables the re-design of personal computing devices in a battery-free manner, representing a major leap forward in moving beyond chargers, cords and dying devices. In particular, we study the development of several battery-free devices, and identify the types of devices that can be handled today and what is future work. Testbed experiments clearly demonstrate the feasibility of devices we built, presenting performance comparable to the commercial battery-powered counterparts.

I. INTRODUCTION

The IoT era has witnessed an explosion of wireless devices — home, office, and personal devices — that created an ever-increasing demand for batteries. Each year consumers dispose billions of batteries, all containing toxic or corrosive materials, which become hazardous waste and pose threats to health and the environment if improperly disposed. Rechargeable batteries limit the problem only partially as after some time of daily recharging they become unusable. The need for more eco-friendly wireless devices is evident.

The question is: Is it possible to re-design smart objects so that they can operate without batteries? The answer is backscattering. A breakthrough in wireless communications, backscattering is being used to power sensor devices and eliminate the need to have any inbuilt batteries at all. Several low-power devices can use radio frequency (RF) signals as a power source and use them to sense, compute, and transmit data via reflecting the RF signal. Ambient [1] and RFID [2] backscattering are two techniques that enable data computation and transmission on battery-free devices.

Ambient backscattering harvests power from signals available in the environment such as TV [3], cellular [4], and Wi-Fi [5] transmissions. It has the main advantage of using existing RF signals without requiring any additional emitting device, but presents several performance drawbacks. Ambient RF energy is not always available, bringing reliability issues. In addition, current techniques for ambient backscattering have low data rate (1kbps in the best signal conditions [3][5]). Thus, they fit mainly applications involving occasional data transmission (e.g., money transfer between smart cards or revealing misplaced objects in a grocery store), but are not suitable for applications requiring continuous and real-time communication. The availability of signal is another limitation: Although TV towers broadcast signals 24 hours a day without interruptions, the ubiquity of the signal cannot be guaranteed, compromising the effectiveness of continuous and real-time data transmission. If the signal is weak, sensors cannot operate; they have to accumulate enough energy to perform the required action. Even in places where TV signals should be ubiquitous (e.g., metropolitan areas), they weaken significantly in indoor environments positioned at more than $8-10$ km from the TV tower.

RFID tags power up by harvesting power from signals emitted by an interrogator, i.e., RFID reader [2], and communicate by backscattering the incident signal. The traditional RFID technology involves a set of tags — battery-free devices — that absorb and reflect the high-power constant signal generated by the reader — a powered device — that queries them to receive their unique ID. With the advent of IoT, new applications of RFID technology have emerged: sensor-augmented RFID tags can exploit the energy harvested from the reader to run some low power sensors and transmit sensed data to realize devices such as cellphone [6], camera (WISPCam [7]), and videogame controller (JoyTag [8]).

In this paper we explore the design of Battery-Free Smart Objects (or smart devices) based on RFID technology that can be deployed in a smart home and make the following contributions:

1) Built a representative set of Moo [9] based RFID device types to illustrate the solution including devices that are real-time (e.g., a videogame controller, a microphone), periodic (e.g., a temperature sensor) and event based (detecting presence, a fire detector). Specifically, we present the development of a videogame controller, called SapyJoy, which is able to interact with several types of videogames.
2) Identified the types of devices that can be handled today and what is future work, and did extensive controlled experiments to evaluate the performance of different types of devices showing that multiple smart objects can be made battery free and what are the challenges for their coexistence in a same smart environment.
3) Showed through experiments that our newly developed devices are very fast in communicating with corresponding applications, performing even better than commercial benchmarks.

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II. Battery-Free Smart Devices

Several types of sensors — temperature, humidity, light, accelerometers, pressure buttons, analog joysticks, etc. — can be integrated with Moo tags to devise battery-free devices. The main constraint is related to tag energy consumption. Sensors should not require more than 3V and each sensor consumption should be less than 10 mW in order to allow continuous sensor activity. With more demanding sensors, up to 100mW, we have to exploit a sensor duty cycle in order to satisfy the energy constraints. As shown in [10], with deep duty cycle tuning, it is possible to power devices requiring up to 200uA at 1.8V with a 10 hertz refresh rate.

In the following we present the set of battery-free devices that we built by leveraging UMich Moo Computational RFID tags [9]. Specifically, we illustrate the solutions including devices that are periodic, event based, and real-time (performing burst sensing). Then, we present the devices that could be developed, and, finally, the devices that are already present in the literature (developed by others). Overall, this section demonstrates the wide variety of devices (with different rate requirements) that can be accommodated by our solution.

A. New developed devices

We built a representative set of Moo-based battery-free devices discussed in this subsection, including periodic, event based, and real-time devices.

a) Temperature Sensor: It is a device that periodically senses temperature and reports sampled data to the server to allow environmental monitoring.

b) Light Switch: This is an event-based device that is realized by mounting a button on the Moo Tag. When the user presses the button on the wireless and battery-less light switch, the system switches on a LED on an actuator Depending on the application, it is possible to embed multiple buttons on the same Moo tag, to control different lights deployed inside a smart building. The logical connection between the tag switch and the corresponding light is placed inside the server [11]).

c) Remote for a tea kettle: This is an event-based remote able to switch on a kettle. It is realized by mounting a button on a Moo tag — the remote — and connecting the kettle with another Moo tag — the actuator — through a relay that is activated by a reader message.

d) Video-game controller: This is a real-time device that is realized by mounting an analog joystick and two buttons on a Moo tag. The resulting wireless and battery-less videogame controller is able to interact with several types of videogames (e.g., adventure, action, puzzle, and RPG). Fig. 1 shows our videogame controller (called SapyJoy): a PCB board connects the analog joystick and the two buttons with the Moo tag, which also has an accelerometer embedded, allowing for complex game experiences. A previous version of the controller featuring only an accelerometer (no buttons and no analog joystick) was presented in [8].

e) Mouse: A platform analogous to the SapyJoy can work as a wireless and battery-less mouse by interfacing its x and y axes with the pointer on the screen. We embedded the information regarding the analog controller inside packets transmitted by the tag and realized a virtual mouse driver able to decode this information and translate it into the pointer position.

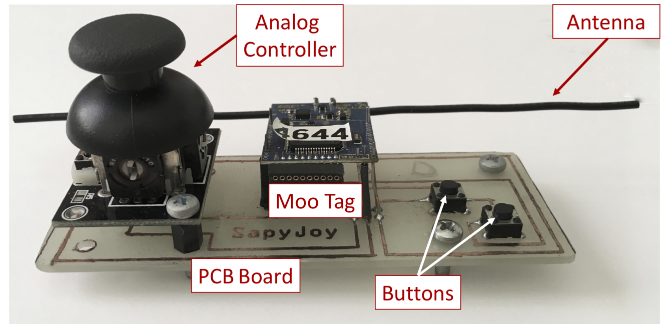

Fig. 1. SapyJoy videogame controller: A PCB board connects the analog controller and the buttons with the Moo tag.

B. Devices that can be built

By studying the technical characteristics of different sensors and actuators we identified the set of devices that can be easily developed. The following is a description of some of the devices that can be built by leveraging Moo tags. This increases the applicability of our solution for battery-less smart homes.

a) Event detector: Embedding a smoke sensor on the Moo tag it is possible to devise a fire alarm[1]. Another detectable event is presence through a motion sensor[2]. In general, any ultra low power sensor able to detect an event can be exploited to build an event detector.

b) Remote for appliances: Any appliance that can be actuated by a relay — coffee machines, shutters, doors, air fans, etc. — can be controlled by a battery-free remote, by mounting a button on a Moo tag — the remote — and connecting the appliance to another Moo tag — the actuator — through a relay.

c) Infrared Remote (IR) Commander: Embedding an ultra low power IRDA emitter [12] on the Moo tag we can create an IR remote controller for any appliance equipped with infrared interface, prolonging the lifetime of less recent and technological appliances. In this case the Moo Tag must be placed in front of the IR receiver on the controlled device. Even if the IRDA emitter consumption is quite high (170uA for transmission) we expect to have some seconds between a command and the next one, enough to recharge the accumulator.

d) Environmental sensors: Light, humidity, presence, and other sensors can be mounted on the Moo tag to allow environmental monitoring. The number of sensors that can be mounted on a Moo tag depends on the number of I/O ports that the microprocessor owns and the amount of energy available.

C. Already developed devices

There are a couple of battery free devices that have been already developed by others.

[1]https://goo.gl/jPLfva
[2]http://www.ti.com/lit/ug/tiducu5/tiducu5.pdf

a) Temperature Sensor: It is a device that periodically senses temperature and reports sampled data to the server to allow environmental monitoring.

b) Camera: As shown in [7][13][14] it's possible to implement an RFID tag with an embedded camera able to take pictures and transfer them with the power harvested by the RFID antenna.

c) Cordless Phone: As demonstrated in [6] it is possible to realize a simple phone, able to stream voice and audio from and to the reader. This device can be used as a phone, as a microphone, or a small sound diffusion system.

d) Information Display: Integrating an ultra low-power E Ink (electronic ink) display on the moo tag it is possible to realize a display for several types of information. For example, displaying the current time it is possible to realize a battery free clock. Other information that can be displayed for the current state environment, such as temperature, humidity, appliances operation, etc. The display can be useful also to show messages from authorized people outside the house. For example, in assisted living applications, remote relatives or caregivers can remind to take medication or perform some actions to people inside the home. In [17] a number of wearable displays (shoes, t-shirt, etc.) have been realized using electromagnetic induction and e-ink displays.

e) Monitoring Systems: The work in [15] shows how to create a series of sensors able to detect doors opening and monitor water usage of a drinking tap. Modifying the antenna circuit of tags, it is possible to open and close it in order to activate or deactivate the tag. The reader, depending on the tag status can understand if a door is open or closed. For example, when the door is open the tag is not activated, when it closes the tag activates. A similar approach is used in [16], where the opening and closing of the antenna circuit corresponds to the status of a button on a controller for videogames.

III. Experiments with Battery-free Smart Devices

We now evaluate the performance of our battery-less smart devices, benchmarking their performance against those of commercial battery-powered devices.

A. Testbed

We implemented prototypes for two videogame controllers, a mouse, a light switch, and a temperature sensor, using the UMich Moo Computational RFID tag [9]. To interact with our prototypes we use a USRP RFID reader equipped with two RFID antennas, and a server that interconnects the RFID reader with smart-home applications. The Moo tag receives the reader signal and uses it to harvest operating power using the RFID circuit. The harvested power runs on-board sensing, encoding of measurements data, CRC error coding, and backscatter communication to wirelessly send data back to the reader. The communication protocol between the reader and the tags is based on the EPC Gen 2 Class 1 standard [21], that has been modified to acquire data from sensors and store them in the buffer that is traditionally used to maintain the tag ID. As only a few bits (e.g, 8 bits) are sufficient to represent the tag's ID, the remaining, typically $96 - 8$ bits, can be used to send sensed data. We limited the data field to 1 byte for tag ID and 6 bytes for data samples (including 4 CRC bits). This number guarantees low packet error rate — confirmed by our experimental study — and enough space for data samples for all devices except the camera, which would require data fragmentation even in case of longer payloads.

B. Metrics

We evaluated the performance of our prototypes by measuring the following metrics:

- **Reaction time** is the time between the generation of new sensor data and the corresponding action on the recipient application. This is an application layer metric. In the case of the joystick, it measures the time between an action on the joystick (e.g., a button pressure), and the corresponding event on the videogame application. In the case of an environmental sensor, this metric measures the time between the generation of new sensor data and the corresponding reaction on the recipient actuator (e.g., a presence sensor activating a camera).
- **Packet delay** is the time between the generation of new sensor data and its delivery to the reader.
- **Throughput** is the number of bits received by the reader per unit of time.
- **Packet error rate** is the fraction of incorrectly received packets over the total number of sent packets.

While packet delay, throughput, and packet error rate can be measured at the reader side, reaction time requires a more complex procedure due to synchronization issues between sensors and actuators (e.g., the player's action and the corresponding game reaction). This time then includes not only the packet delay at the network layer, but also the time it takes for the packet to proceed up the protocol stack at the recipient. To measure reaction time we used a digital videocamera, framing the sensor and the actuator at the same time so as to have a unique clock to record events. In the joystick case the camera frames the controller and the screen at the same time to record button pressures and corresponding actions on the screen. In this way we can measure time also for commercial devices for which is impossible to act at the software level.

C. Results on single devices

We now evaluate the feasibility of devices we built.

1) Videogame controller: The first battery-free device we evaluate is our videogame controller, SapyJoy, that is compared with two commercial Bluetooth devices: a Logitech controller per console [22] and a Logitech wireless mouse [23]. The three controllers were used to play with navigating videogames — which have an update rate of 30 frames per second (fps) — as well as shooting videogames — which have an update rate of 60 fps. The three controllers were all good and we could not notice any difference in playability. To quantify this ability, and considering the difficulty in identifying a reaction to a user's action in a videogame, we implemented a simple application that represents the joystick through arrows and buttons through circles. When the player

TABLE I
COMPARISON OF REACTION TIME FOR DIFFERENT CONTROLLERS.

Device	Reaction Time (ms)	CI
SapyJoy	92.92	[82.31-102.92]
Commercial Controller	104.58	[96.31-112.85]
Commercial Mouse	110.41	[103.09-117.74]

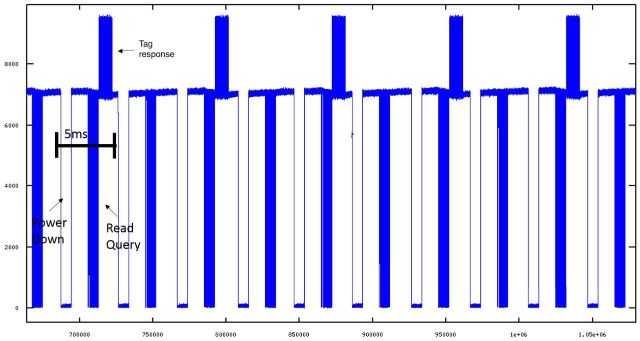

Fig. 2. Matched filter for SapyJoy.

moves the joystick, the corresponding arrow changes color on the screen (for example, if the player moves the joystick ahead, then the top arrow changes color). Analogously, when the player presses a button (i.e., the right one), the corresponding circle (i.e., the circle on the right of the screen) changes color (see Fig. 3).

Table I shows the observed reaction time (with 5% confidence interval) for the three devices, measured through a videocamera framing at the same time the controller and the screen (the update rate of the viedocamera is $60fps$). SapyJoy takes on average $92.92ms$ to see the outcome of a button pressure on the videogame, while the two commercial devices — controller and mouse — take, respectively, $104ms$ and $110ms$ to perform the same operation. These results show that SapyJoy is even faster than battery-powered devices.

Reaction time includes the packet delay at the network layer, plus the time to deliver the packet from the reader to the server, plus the time to produce the game commands corresponding to the actions performed by the user and send them to the videogame application. Thus, if we measure only the packet delay at the network layer, SapyJoy takes on average only $4.79ms$ to deliver sensed data to the reader (note that we cannot measure this metric for the commercial devices because they are not programmable).

Analyzing the matched filter for our SapyJoy we observed that although the packet delay is below $5ms$, to achieve the best performance —avoid any reader-tag collision due to any possible delay from the tag — the reader can issue a new query every $6ms$. By querying tags at this interval of time, the throughput at the reader is $6.6Kbps$ (including sensor data and protocol control bits), with less than 1% packet error rate.

2) Light switch and mouse: Now we evaluate our battery-free light switch and mouse. We use again a videocamera framing at the same time the sensor and actuator. In the case of the light switch, the sensor is the tag equipped with a pressure button while the actuator is a tag with a LED on-board. In the case of the mouse we use the same platform as for the joystick. The mouse communicates with an application showing cursor movements and button pressures through a circle that moves on the screen and changes color when a button is pressed (see Fig. 3).

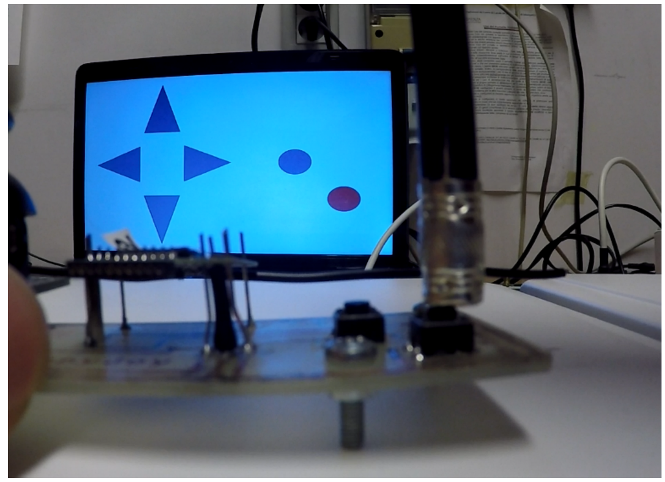

Fig. 3. Button pressure on the battery-free mouse and corresponding action on the screen.

TABLE II
REACTION TIME FOR BATTERY-FREE LIGHT SWITCH AND MOUSE.

Device	Reaction Time (ms)	CI
Light Switch	62.91	[67.41 - 73.41]
Mouse	92.92	[82.91 - 102.92]

Table II shows the reaction for the two devices. The light switch takes only $62.91ms$ to collect data from the pressed button, send it to the actuator, and switch on the LED. Although we do not have benchmarks to compare with, we believe that this time would satisfy any stringent application requirements.

Reaction time increases to $92.92ms$ in the case of the mouse, as like for the videogame, data has to reach the final application on the server, taking some time to ascend the protocol stack. However, even in this case the system is very reactive, with the user perceiving a real-time communication.

D. Results with multiple devices

We now present experimental results that evaluate multi-kind multiple battery-free devices simultaneously, so that we can evaluate their interoperability. We run experiments with three devices working at the same time: two environmental sensors — temperature and presence — and a video-game controller (our SapyJoy). The devices are queried (and hence transmit sensed data) following a TDMA approach, which provides different time slots to different devices in a cyclically repetitive frame structure. The first difference with respect to experimentation with a single device is reaction time. If a device is queried at each slot, the reaction time is clearly shorter with respect to the case in which it is queried once every multiple slots. The outcome of our experimentation is that the reaction time increases significantly (i.e., $200ms$) with respect to when it works alone (i.e., $92.92ms$). This delay would certainly increase if the number of transmitting devices increases, making interoperability a challenge as the joystick may experience too long delays.

IV. Lesson learned

Our experimentation highlights two big challenges for the design and deployment of battery free environments, like smart homes, in which there are outfitted many sensors and smart devices (e.g., cameras, presence sensors, smoke sensors, light sensors, thermostats, smart meters, etc.).

The first challenge concerns devices interoperability. Although results clearly show the feasibility of battery-free RFID-based smart objects, whose performance are comparable to that of the battery-powered counterparts, their coexistence cannot be taken for granted. When multiple devices operate simultaneously, the reaction time increases significantly with respect to the case of a device working alone. In addition, an equal assignment of channel resources would not satisfy devices needs. Multi-kind multiple battery-free devices, operating simultaneously, have widely varying communication requirements, in terms of data transmission, ON/OFF activity, and deadlines. To pick an example, a joystick may sense no changes for hours (while it is OFF), and then start sensing new data (while used for playing) at very different rates (from a few milliseconds to one or more seconds), depending on the game type and player activity. Thus, a MAC protocol for battery-free devices should schedule channel access such that devices requirements are satisfied and data is delivered in time. A first solution in this direction is given in [24].

The second big challenge regards operational limits of RFID technology: communication range is a critical barrier in the real-world implementation of this low-cost technology. The reader of our testbed has transmission power of $P_t = 0.5W$ and achieves less than one meter of distance between the antennas and the tags. With this technology it is possible to realize smart devices such as the joystick of the light switch, but not a videocamera, which requires real-time streaming. A more powerful reader (e.g., with $P_t = 1W$) allows for longer distance (up to 3 meters) between the reader's antennas and the tags, but cannot satisfy a real-time frequency. The need for technological improvement is clear. A first attempt in order to achieve better results in terms of bit rate, distance, and energy is given in [25], where a RFID device is powered from both RF harvesting and a small solar panel (3cmx3cm). In this case it was shown to reach a distance of 21 feet and a maximum bitrate of 21.7kbps. This trend is confirmed in [26], where the use of photovoltaics increases the transmission range by providing additional power to the RFID tag integrated circuit.

V. Conclusions

The last decade has witnessed an explosion of wireless devices that created an ever-increasing demand for batteries. In this paper, we show how RFID technology is a key enabler for realizing a variety of battery-free smart devices, performing real-time, periodic, and event based sensing. Most of these devices are doable now — we realized light switches, remotes for tea kettle, videogame controllers, the mouse, and studied how to realize event detectors, IF remote commanders, and remotes for general appliances — while others are more difficult to realize (e.g., videocameras). Results clearly show the feasibility of our approach, but also highlight the need for new communication protocols that can distinguish between less and more demanding devices.

We believe that our work offers a path forward for practical use of RFID technology in the development of battery free devices, motivating further work aimed at investigating techniques to support more demanding devices (videocameras) and more powerful technology (getting longer transmission ranges).

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