New Opportunities for Sustainable Interaction Using Backscatter Sensors

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Abstract
Radio frequency (RF) backscatter is a remarkably efficient wireless communications technique, most commonly used for RF identification (RFID). In recent years, systems that combine ultra low power sensors with backscatter circuitry have enabled batteryless wireless sensing and data collection. The low cost and low power requirements of such backscatter sensors have the potential to unlock a range of self-sustainable interactive applications and scenarios; several examples have already been reported in the literature.

In this paper, we briefly review the operating principles of backscatter communications, and summarise some of the existing backscatter sensing systems. In order to better understand and compare different wireless sensor designs, we present a three-element architecture. We build on this to create a basic backscatter sensor taxonomy that allows us to present a simple design space. The gaps in this space indicate approaches where we have not yet uncovered in previous work, and may therefore be fruitful directions for future work.

Author Keywords
backscatter; low power wireless sensing; RFID; sustainable interaction.

CCS Concepts

•Human-centered computing → Ubiquitous and mobile computing systems and tools; •Hardware → Sensor devices and platforms;

Introduction to Backscatter Sensing

Traditional radio frequency (RF) communication requires relatively complex and power-hungry electronics on both sides of a duplex communications channel. Backscatter communication systems such as radio frequency identification (RFID) use a different approach that breaks this symmetry. One side of the communications channel, usually called the reader or interrogator, follows a similar approach with sophisticated and power-hungry circuitry. This is paired with a vastly simpler device, the RFID tag. The tag operates at such low power levels that it can harvest all the energy necessary for operation (including communication) from the incoming RF signal. The tag communicates back to the reader by systematically changing its antenna impedance, effectively resulting in the transmission of a modulated version of the incoming signal back to the reader. This is all done without power-hungry generation or manipulation of radio frequency signals in the tag.

In this paper, we focus on systems that couple a sensor with a backscatter circuit for wireless low power sensing and data communication. Similarly to RFID, these systems leverage asymmetry to lower complexity and power consumption at the sensor by offloading RF signal manipulation to the reader. It is also possible to offload signal digitization to the reader, by transmitting analog sensor values that the reader must digitize; this further reduces complexity and power consumption on the sensor side. Such batteryless sensors lend themselves to ubiquitous deployment by providing sustainable sensing and interaction. They have the potential to be woven "into the fabric of everyday life" [14].

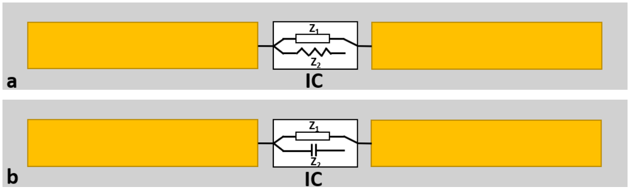

Figure 1: RAIN RFID tags with the internal load switch highlighted. (a) ASK modulation is achieved with a purely resistive Z_2; (b) PSK modulation requires a purely reactive Z_2.

In the rest of this paper we show how simple backscatter sensors can be built by modifying commercial off the shelf (COTS) RFID tags, and discuss recent work on more sophisticated custom backscatter sensing systems. We present and compare various characteristics of backscatter sensors and map out a design space that we hope will inspire the development of future backscatter sensing systems. We discuss the potential of such systems and some of their limitations, along with practical considerations we think will be important factors in potential widespread adoption. We end by briefly presenting a new custom backscatter touch sensor that we are developing. But first we briefly explain RAIN RFID, a widely used backscatter communication protocol.

RAIN RFID Communication

The RAIN RFID specification[1] is a widely used backscatter communication system that follows the GS1 UHF Gen2 RFID protocol[2], standardized by ISO/IEC as 18000-63. This protocol specifies that the reader-to-tag forward link uses

[1] https://rainrfid.org/about-rain/what-is-rain/

[2] https://www.gs1.org/sites/default/files/docs/epc/gs1-epc-gen2v2-uhf-airinterface_i21_r_2018-09-04.pdf

amplitude shift keying (ASK) modulation. The tag uses a simple envelope detector to demodulate the interrogating signal. The tag-to-reader backward link can use either ASK or phase shift keying (PSK) modulation. RFID tags implement this modulation by switching between two loads inside the tag IC. In Figure 1, Z_1 is conjugate matched to the tag's antenna impedance so that maximal incident power is absorbed by the load, which leads to a minimal power backscattered signal. For ASK modulation (Figure 1a), Z_2 is purely resistive; for PSK modulation (Figure 1b), Z_2 is purely reactive (inductive or capacitive). The tag switches between Z_1 and Z_2 according the the stored data. The communication system is completely digital.

RFID based Backscatter Sensing

RAIN RFID tags are ideal candidates for ubiquitous sensing because they are thin, passive, and inexpensive. A transducer can be added between the RFID IC and the antenna to introduce an extra load impedance $Z_{transducer}$ (Figure 2). This impedance varies with the sensing quantity and causes changes of backscatter signal amplitude. The amplitude modulated signal can then be detected by the reader and decoded to determine the sensing quantity.

A simple electrical on/off switch is an easy-to-add $Z_{transducer}$ with an impedance that switches from 0 to infinity and back. Smith et al. proposed using a mercury tilt switch between the tag IC and the antenna, such that it connects and disconnects the IC and antenna based on the tag orientation [9]. This means that the reader's ability to detect the tag is modulated by the tag orientation. Such a tag, named an α-WISP, can then be applied to an object as an orientation sensor. This approach, called ID modulation, is a special type of ASK also known as on-off keying (OOK) and is compatible with unmodified commercial RFID readers. Subsequent researchers have proposed different mecha-

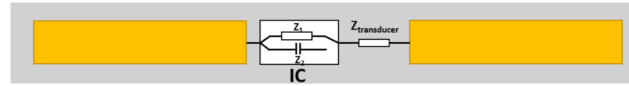

Figure 2: Principle of RFID based backscatter sensing systems.

nisms for ID modulation; for example BitID [15] proposes a short circuit based modulator to sense object status, RFIBricks [5] modulates the ID by connecting the tag IC and antenna with magnets, and TipTap [6] leverages RFID tags with separate dipole antennas to detect thumb-index finger contact positions for discreet input. To overcome the low throughput of ID modulation systems, hybrid analog-digital backscatter sensing systems have been proposed. In [10] the output voltage from a microphone added between the antenna and the tag IC is converted to load impedance using a field effect transistor (FET). The amplitude of the backscattered signal can then be directly modulated by the analog microphone output. This use of amplitude modulation (AM) increases data throughput but but can only be decoded by a customized RFID reader. AM backscatter systems are suitable for sensing tasks that need high data rates but are resilient to noise. Wang et.al [13] showed that sensors with a resistive output, such as a phototransistor or thermister, can be used in a similar manner.

The RFID based backscatter sensing systems presented above leverage RFID tag ICs to create wireless, batteryless sensors. Whilst this approach is relatively easy to implement, its flexibility and performance is limited. It only supports modulation schemes where a sensor sits between the antenna and the tag IC. Tuning the external sensor can also be hard since the antenna impedance is usually not disclosed, and the parasitic impedances introduced when adding the sensor are difficult to characterize.

Custom Backscatter Sensing

To overcome the limitations of RFID based backscatter systems, recent research has presented methods to integrate sensing more tightly with backscatter modulation, thereby achieving more flexibility and robustness. We think it's useful to think of these systems as consisting of the following three elements, also depicted in Figure 3a:

Transducer Converts the sensed parameter to an electrical output. Depending on the type of the analog sensor, the transducer output can be voltage (e.g. microphone, photo-diode), resistance (e.g. thermistor), capacitance (e.g. touch panel) or inductance (e.g. coils [4]).

Converter Converts the electrical transducer output to a signal that can be used to modulate the backscatter signal (e.g. resistance). Not always necessary because sometimes the transducer output naturally matches the modulator input.

Modulator Modulates the incident RF signal for signaling back to the reader based on the converted signal. Possible modulation schemes include amplitude (AM/ASK), frequency (FM/FSK), and phase (PM/PSK) modulation.

To make this architecture clearer, we show an example backscatter audio sensor in Figure 3b. The transducer is a microphone with a varying output voltage. The voltage signal is converted to resistance changes using a FET. The amplitude of the backscattered signal is then modulated by the changing resistance.

Existing Custom Backscatter Sensing Systems

In Table 1, we list four existing custom backscatter sensing systems reported in the literature along with the corresponding sensing tasks, modulation schemes, transducers, transducer outputs, modulating properties and receiver types. As mentioned earlier, by their very nature these systems all require a custom radio receiver/decoder rather than a COTS RFID reader. Typically a software-defined radio (SDR) such as the universal software radio peripheral (USRP) is used. On the sensor side, the tight integration between the sensing and backscatter circuits supports a wider variety of sensors and higher data throughput.

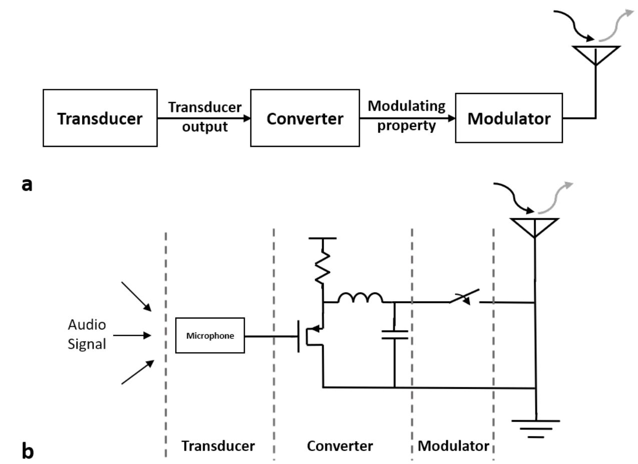

Figure 3: a) Three key components of a custom backscatter sensing system; b) An example backscatter audio sensor.

Both Battery-free Cellphone [11] and ZEUSSS [1] use a FET to convert the small voltage output from a microphone into resistance changes of a suitable magnitude to amplitude modulate the backscattered signal by changing the antenna load impedance. RF-bandaid [8] uses a low power

System	*Sensing task*	*Modulation*	*Transducer*	*Transducer output*	*Modulating property*	*Receiver*
Battery-free Cellphone [11]	Audio	AM	Microphone	Voltage	Impedance	USRP
ZEUSSS [1]	Audio	AM	Microphone	Voltage	Impedance	USRP
Battery-free Camera [7]	Video	PWM	Photo-diode	Voltage	Voltage	USRP
RF-bandaid [8]	Multi-purpose	FSK	Pressure Sensor	Resistance	Frequency	USRP

Table 1: Custom backscatter sensing systems reported in the literature.

oscillator[3] where the operating frequency is set by an external resistor to convert resistance changes into varying frequencies, which is then used for sub-carrier FSK modulation. This is more robust to noise than AM. Finally, because it is difficult to modulate the antenna load impedance when the dynamic range of the transducer output is small [2] the Battery-free Camera [7] uses a comparator to convert the small output voltage of a photodiode to signal pulse widths. An XOR gate is then used to upconvert the PWM signal with sub-carrier modulation.

A Custom Backscatter Sensor Design Space

Although other researchers have not explicitly described their custom backscatter sensors in terms of a three element architecture, namely transducer-converter-modulator, we believe this framework is a useful way to analyse how existing systems work. In particular, it allows us to frame the previous work reported above in a simple two-dimensional design space that maps out the *transducer output* vs the *modulation scheme*, see Figure 4.

The design of a low power converter from transducer output to modulation scheme is critical to the successful operation of a custom backscatter sensor system, and each *transducer output-modulation scheme* pair in our design space represents the need for a different type of converter.

[3]https://www.analog.com/media/en/technical-documentation/data-sheets/6906fc.pdf

Transducer Output vs Modulation Scheme	AM/ASK	FM/FSK	PWM
V	Battery-free cellphone[7] ZEUSSS[1]		Battery-free Camera [4]
Z		RF Bandaid[5]	

Figure 4: *Transducer Output* vs *Modulation Scheme* design space for listed literatures.

The design of a converter is easier in some cases than others, and the exact form of modulation will likely vary based on the characteristics of the transducer output and the communication requirements. For example, as pointed out in [7], it is difficult to design low-power AM converter for photodiodes since the dynamic range of the output voltage is too small (around 100mV) to create suitably large backscatter amplitude variations. This is why Naderiparizi et al. used a PWM converter implemented with a passive filter and a low-power comparator [7].

The existing systems we have presented only cover some of the potential solutions, and we think it is valuable to consider new combinations of transducer type and modulation scheme that span the complete design space.

Practical Considerations

In addition to building out systems that address new points in the design space presented above, we believe there are important practical considerations that need to be addressed by future custom backscatter sensing systems. Here we present three of these.

Compatibility with Existing Protocols

Current backscatter sensing systems require either a COTS RFID reader or an SDR to decode the modulated sensor data. However, a backscatter sensor that includes a microcontroller as part of its modulator can use a more complex modulation scheme that is compatible with an existing wireless protocol such as WiFi or Bluetooth. This would enable widely-deployed wireless receivers like WiFi routers or smartphones to be used as backscatter receivers. Such backwards-compatibility imposes significant constraints, so an alternative would be a solution that's compatible with widely-deployed hardware even if it requires custom firmware. Such backscatter sensing systems would require digital modulation though, which consumes more power than their pure analog counterparts. The total power consumption can still be much lower than low-power wireless ICs with full protocol support [3].

Sensing System Calibration

Calibration is necessary for analog sensing systems to account for manufacturing and environmental variations. One approach to this is to tune the converter on-the-fly. For example, perhaps a configurable resistor bank could be used by the RF-bandaid converter to ensure consistent pressure measurements. Such calibration circuits are necessary to enable robust and accurate sensing, even though they will consume extra power.

Multi-sensor Co-existence

One drawback for pure analog backscatter sensing systems is that the number of sensors that can communicate simultaneously is limited. Multiple backscatter sensors can be assigned with different frequency channels for concurrent communication [12]. Another method is to add digital components that enable addressability and to implement anti-collision protocols at the expense of extra power cost.

New Options for Sustainable Interaction

Our aim is to leverage the framework presented in this paper to conceive and build new custom backscatter sensing solutions that support sustainable interactive experiences. Very specifically, we think there is an opportunity to develop a new wireless and battery free touch sensor that could be used to create touch buttons, sliders and dials that are embedded into stickers. These stickers could be readily applied to make objects and environments interactive.

We are currently working towards a first prototype of the touch sensor. Like RF-Bandaid, it will be based on FSK modulation, but because the transducer has a capacitive output rather than resistive, we are working on a new converter design. We want to avoid the need for either a COTS RFID reader or an SDR; instead we would like to make the touch sensor compatible with cheap and widely deployed hardware. We are currently working on a system that is somewhat compatible with Bluetooth. The issues of calibration and co-existence are still under consideration.

Although our work on a new custom backscatter system to support sustainable touch-based interactions is still at an early stage, we would value feedback from the community.

Conclusion

In this paper, we introduced RFID and backscatter sensing, and then discussed the working principles of both RFID based and custom backscatter sensing systems. We presented a new three-element architecture that frames custom backscatter sensors, with a view to facilitate a clearer analysis of existing work and future possibilities. We then mapped out a *transducer output vs modulation scheme* 2D design space to anchor the existing systems; this highlights unexplored areas that we hope will inspire discussion in the research community and ultimately future work. We also described several aspects of backscatter sensor systems that we believe will be important practical considerations for real-world deployment. We ended by describing our ambitions to create new solutions in the backscatter sensing design space that unlock sustainable novel interactive experiences.

We believe there are many opportunities in this area and that collectively they have the potential to enable ubiquitous sensing and interaction that is more tightly woven into the fabric of everyday life than has been possible to date. We welcome a dialogue with our colleagues across the research community on these topics.

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