

# Hybrid Analog-Digital Backscatter Platform for High Data Rate, Battery-Free Sensing

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**Abstract**—This paper presents a hybrid analog-digital backscatter platform for high data rate battery free wireless sensing. A digital RFID platform (WISP) has been integrated with an analog sensor (microphone) to develop a digitally addressable RFID tag which uses analog backscatter for high data rate transmission of sensor data (audio). The hybrid WISP operates in two modes: digital mode (default mode) to transmit and receive digital data (as per EPC Gen 2 RFID protocol) and analog mode (activated by Gen 2 *READ* command) to backscatter audio sensor data. We report an operating range of more than 4 meters for the digitally addressable, battery free wireless audio sensor.

## I. INTRODUCTION

Pervasive computing aims to seamlessly integrate computing with everyday objects to create an interactive and context aware environment. A key enabler for pervasive computing is a mobile platform that provides computing, sensing, and high data rate communication. The conventional approach to building pervasive computing systems uses wired sensors or battery-powered, wireless sensor nodes. However, the need for wires or frequent battery replacement limits the viability of these approaches for many applications. An emerging solution for wireless sensing is the use of sensor-equipped Radio Frequency and Identification (RFID) tags or RF-powered platforms such as the Intel/UW WISP [1]. Because these platforms harvest their operating energy from RF signals, they can be small, long-lived, and embedded virtually anywhere [2].

In RF-powered systems, power and data are transmitted by readers to tags using electromagnetic waves. Tags harvest energy from incident RF signals, and use it to power on-board computation and sensing. Tags transmit data to readers by modulating the reflectivity of their antenna (i.e., backscattering), and readers receive data by detecting these changes in the reflected signal. Conventional backscatter systems use *digital backscatter*, where the impedance of the tag’s antenna switches between two states to transmit binary data. Tags sample sensors using an ADC, and sensor values are packetized and transmitted to the reader, e.g., using the EPC Gen 2 RFID protocol. This approach has the benefits of digital communication such as noise immunity and channel sharing.

However, use of digital backscatter to communicate sensor data suffers from power and protocol limitations. ADCs are power-hungry components, and sampling at

even a few Hertz can consume more energy than can be harvested if the tag is far from a reader. Moreover, the protocol overhead and low bitrate of existing protocols limits the maximum uplink rate to tens of packets per second [2].

An alternate but less explored approach for low-power sensing is *analog backscatter*, where the sensed phenomena directly modifies some characteristic (e.g., frequency response or quality factor) of the resonant structure or antenna. For example, the capacitive membrane of Theremin’s cavity resonator (famously used in the Great Seal bug [3], [4]) changes shape and capacitance when struck by sound waves, and more recent work coats tags with a humidity-sensitive chemical that changes the frequency response of the antenna [5]. The benefits of analog backscatter include low/zero power consumption and high rate (i.e., continuous) sensing. However, it can only support a few devices in a given area, is prone to noise, and fraught with calibration issues. Moreover, the use of special antennas/resonant structures makes this technique incompatible with digital backscatter.

In this work, we propose a hybrid analog-digital backscatter platform with a single antenna to integrate digitally addressable, RF-powered digital platforms with selectable sensors that use analog backscatter to transmit high data rate sensor data. The hybrid platform can operate in both digital mode, where it receives and transmits digital data, and analog mode where a sensor is turned on and begins analog backscattering data. Since analog backscatter suffers from noise issues, we are targeting sensing applications which require high data rate but can tolerate noise. We demonstrate our approach by integrating the WISP RF-powered platform with a microphone for digitally-addressable, battery-free audio sensor.

## II. HYBRID ANALOG-DIGITAL BACKSCATTER

In typical RFID systems, readers transmit electromagnetic waves to transfer both data and power to tags. A fraction of this RF power is absorbed by the tag, and the rest is backscattered. The amount of reflected power received by the reader is given by

$$P_{backscatter} = P_a \frac{4R_a^2}{|Z_a + Z_L|^2} G = F(Z_L) \quad (1)$$

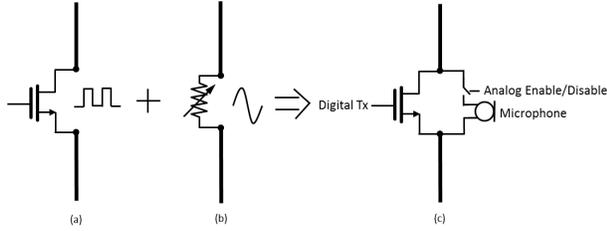


Fig. 1. (a) Digital backscatter (b) Analog backscatter (c) Integrated analog-digital hybrid backscatter platform (hybrid WISP)

where  $Z_a$  and  $Z_L$  represent the tag antenna impedance and load impedance respectively,  $R_a$  is the resistive component of the tag antenna impedance,  $G$  is the gain of the tag antenna and  $P_a$  is the power received at the tag. In digital backscatter systems (refer to Fig. 1(a)), a MOSFET is the load impedance connected across the antenna. To transmit data, tags switch the MOSFET between the low impedance and high impedance states to provide a high contrast in the backscattered power, and the reader detects these changes to decode the digital data. Our approach to analog backscatter generalizes this concept to the analog domain, as illustrated in Fig. 1(b). Instead of switching the load impedance between two distinct states, we propose a continuous variation in the load impedance resulting in a continuous (analog) modulation of the RF power backscattered to the reader. For sensing applications, we chose a sensor whose impedance changes as a function of the sensed quantity. An RF switch is used to connect the sensor across the antenna such that the sensor is the load. As the impedance of the load (i.e. sensor) ( $Z_L$ ) varies as a function of the sensing quantity, the power backscattered by the tag varies accordingly.

$$P_{backscatter} = F(Z_L) = F(f(\text{sense})) = F'(\text{sense}) \quad (2)$$

In contrast to digital backscatter, where the sample rate is limited by the energy budget of the tag and protocol bottlenecks, analog backscatter can support much higher sensing rates as the data rate is limited only by the RF front end of the reader. In contrast to previous analog backscatter techniques, our approach can be applied to a range of sensors, devices can be outfitted with multiple sensors, and sensors can be densely deployed as they are addressable and can be turned on/off.

### III. SYSTEM DESIGN AND EXPERIMENTAL SETUP

We prototype our approach by integrating a microphone with the Intel/UW Wireless Identification and Sensing Platform (WISP)[1]. The WISP is a flexible RF-powered platform featuring a fully programmable 16-bit microcontroller and an array of sensors, that communicates with commercial RFID readers at 915 MHz using the EPC global Class-1 Generation-2 (Gen 2) protocol [6]. Microphone was chosen as the analog sensor because audio

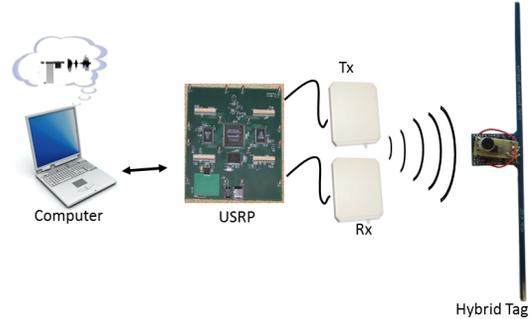


Fig. 2. Experimental Setup

transmission requires high data rate communication which cannot be supported by digital backscatter platforms. The hybrid platform (hybrid WISP) is read using a custom software defined RFID reader [7] and the experimental setup is shown in Fig. 2.

#### A. Hybrid WISP Design

As shown in Fig. 1(c), the RF front end of the hybrid WISP consists of a dipole antenna connected to an RF MOSFET in parallel to a microphone. The microphone is switched in and out of the backscatter network using an RF switch. The microphone (Panasonic WM-61A) has no additional biasing circuitry and the internal JFET is self-biased in the triode region (hence consumes no additional power). The RF switch (ADG902) and the digital RF MOSFET (BF1212WR) are both controlled by the output ports of the WISP micro controller. The WISP implements the Gen 2 protocol completely in firmware, and we modified this state-machine so that it transitions to analog backscatter mode when it receives a Gen 2 *READ* command that is addressed to it. After a configurable amount of time, the firmware switches the microphone out of the network and returns to digital mode.

#### B. Custom RFID Reader Design

To experiment with our hybrid approach on the reader side, we extended a software-radio based Gen 2 reader we developed previously using the Universal Software Radio Peripheral and GNU Radio [7]. The RFID reader and the hybrid WISPs operate by default in digital mode, where the reader continuously queries for WISPs that are present. During a query round, the reader can transition a given WISP to analog mode by transmitting Gen 2 *READ* command addressed to that WISP. Once in analog mode, the WISP backscatters sensor (audio) data for a predetermined period of time and the RFID reader logs the data. At end of this time, the WISP transitions back to digital mode and the reader continues to query for other WISPs. To recover the audio signal, the logged data is band pass filtered (300 Hz - 3.4 kHz) using GNU Radio signal processing blocks. No additional signal processing is required.

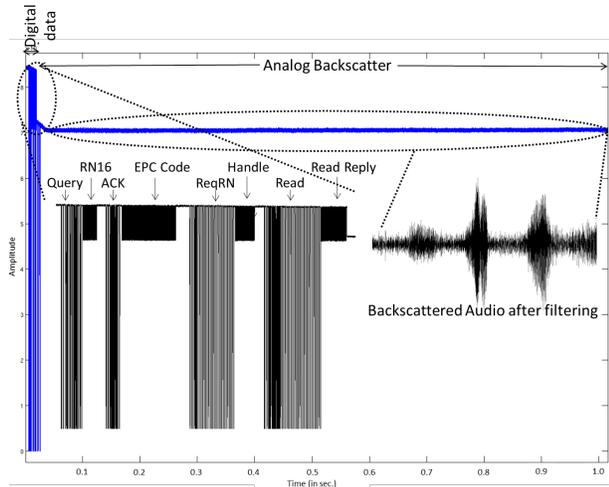


Fig. 3. Communication between the USRP RFID Reader and Hybrid WISP

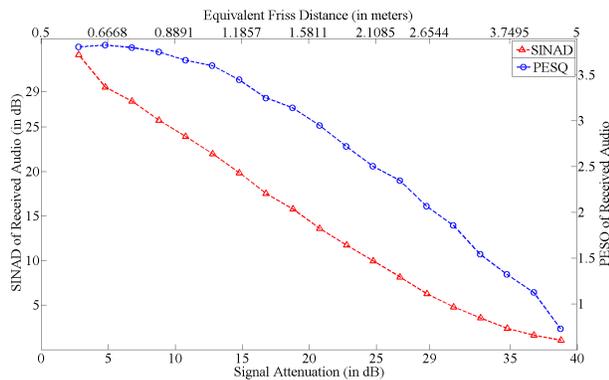


Fig. 4. Variation of quality of backscattered audio with distance

#### IV. RESULTS

Fig. 3 shows the time multiplexed analog-digital communication between the USRP RFID reader and the hybrid WISP. The reader initiates a query round, receives the WISPs ID, and then transmits a *READ* command to transition the WISP to analog mode. The left inset in the figure shows the amplitude modulated reader commands, and the WISP’s digitally backscattered responses. The inset to the right shows a close-up of the filtered analog backscattered audio data.

Fig. 4 shows the audio quality for the analog backscatter microphone as a function of RF signal strength and distance. The quality of the audio is quantified in terms of the signal to noise and distortion ratio (*SINAD*) and the Perpetual Evaluation of Sound Quality (*PESQ*) score [8]. The experimental setup consisted of the reader antennas and the hybrid WISP placed 0.5 m apart and 1 m above the ground to minimize multi path effects. The reader transmits 26.7 dBm (477 mW), and we model the path loss using variable attenuators on both the forward and reverse path.

A reference sound clip was played at 90 decibels as input to the microphone. We found that according to Friis path loss equation [9], the *SINAD* of the audio signal decreases linearly as the attenuation is increased. Since the quality of speech varies as the function of the distance, the operating range of analog backscatter microphone is determined by the minimum acceptable quality of sound (defined in terms of *PESQ* scores). As an example,  $PESQ \geq 1$  is decipherable speech, and the expected operational range (based on the Friis equation) in this scenario is 4.5 meters.

#### V. CONCLUSION AND FUTURE WORK

We have demonstrated a hybrid analog-digital backscatter platform to achieve high data rate, battery-free sensing. This approach combines the benefits of digital backscatter systems, such as device addressability, and the high data rate sensing of analog backscatter. We demonstrate our approach by integrating a microphone with the Intel/UW RF-powered platform, and show that our hybrid platform can stream good quality audio at a range of more than 4 meters. Such wirelessly-powered microphones can provide battery-free audio communication and audio-based localization for pervasive computing.

Moving forward, we are investigating alternate microphones (higher sensitivity) and reader side optimizations such as increased transmit power to extend the operating range of the analog backscatter microphone. We are also exploring other sensors, such as piezoelectric and piezo resistive components, and developing techniques whereby the digital-mode can be leveraged to calibrate the analog sensors. We believe our approach can lead to a versatile, high data rate, battery-free sensing platform.

#### VI. ACKNOWLEDGMENT

This work was funded by the Intel Science and Technology Center for Pervasive Computing (ISTC-PC) at the University of Washington.

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