# Design of a Passively-Powered, Programmable Sensing Platform for UHF RFID Systems

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***Abstract*—This paper presents a wireless, battery-free, platform for sensing and computation that is powered and read by a standards compliant Ultra-High Frequency (UHF) Radio Frequency Identification (RFID) reader. The WISP (Wireless Identification and Sensing Platform) includes a fully-programmable 16 bit microcontroller with analog-to-digital converter. The microcontroller firmware implements portions of the Electronic Product Code (EPC) Class 1 Generation 1 protocol. When queried, the platform communicates arbitrary sensor data by emulating an EPC tag whose ID encodes the desired sensor data; the required 16-bit CRC is computed dynamically by the microcontroller. The RFID reader reports the received tag ID to application software which can interpret the information contained in the tag ID. The programmability of the WISP along with its implementation as a PCB allows for flexible integration of arbitrary low-power sensors. Furthermore, sensors are also exclusively powered from the RFID reader resulting in a completely battery free device. Sensors integrated into the WISP platform so far include light, temperature, and rectified voltage, and are shown experimentally to have an operating range of up to 4.5m. To the authors' knowledge, WISP is the first fully programmable computing platform that can operate using power transmitted from a long-range (UHF) RFID reader and communicate arbitrary, multi-bit data in a single response packet.**

***Index Terms*— Wireless power, RFID sensors, Passive sensors, Programmable RFID, Sensor, Transponder, UHF.**

## I. Introduction

In recent years rapid development of Radio Frequency Identification (RFID) technology has resulted in a wide variety of applications and devices used for identification and tracking purposes. RFID systems typically consist of small, low-cost, battery free devices called tags which use the radio signal from a specialized RFID reader for power and communication. When queried, each tag responds with a unique identification number by reflecting energy back to the reader though a technique called backscatter modulation. Tags are often application specific, fixed function devices that have a range of 10-50cm for inductively coupled devices and 3-10m for UHF tags. Traditionally, RFID tags have been used as a replacement for barcodes in applications such as supply chain monitoring, asset management, and building security [1].

A number of investigators, however, have proposed more ambitious applications that use conventional RFID as a sensor, inferring higher-order information from object proximity. The authors in [2] explored the use of RFID tags to create hybrid physical / digital user interfaces. Philipose *et al.* [3] proposed augmenting an environment with RFID to enhance the quality of life and independence of elderly citizens. The participants wear small RFID reader bracelets that report interaction with tagged objects. The elderly person's state can be monitored from this data and reported to care givers and family members.

More conventional RFID applications can also benefit from sensor enhanced RFID tags. Specific applications for sensor enhanced RFID tags are identified in [4] and include infrastructure and object monitoring, automatic product tamper detection, identification of harmful agents, and biomedical devices for noninvasive monitoring. A commercially available RFID tag for detecting dangerous temperatures in food products during transit is described in [4]. Products such as this one suggest the possibility that although the price of RFID tags may not decrease sufficiently for all potential tracking applications, sensor-enhanced tags may be able to provide increased functionality for the same price as conventional RFID tags.

To date there are several approaches for incorporating sensing capabilities into RFID. Active tags, a subclass of RFID tags, use batteries to power their communication circuitry, sensors, and microcontroller. Active tags benefit from relatively long wireless range (approximately 30m) and can achieve high data and sensor activity rates. However, the batteries required by active tags are disadvantageous for device cost, lifetime, weight, and volume.

In contrast, passive sensor tags receive all of their operating power from an RFID reader and are not limited by battery life. There are several examples of application-specific, non-programmable passive tags with integrated temperature and

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light sensors and an Analog to Digital Converter (ADC) [5,6]. One attractive feature of passive sensor tags is the prospect of permanently embedding them in objects for structural, medical, or product monitoring. Another is their suitability for applications in which neither batteries nor wired connections are feasible, for weight, volume, cost, or other reasons. A limitation of purely passive sensor tags is the requirement of proximity to an RFID reader. The wireless power harvesting techniques described in this paper could also be applied to wirelessly recharge a battery, super-capacitor, or pseudo-capacitor to create a hybrid sensor tag.

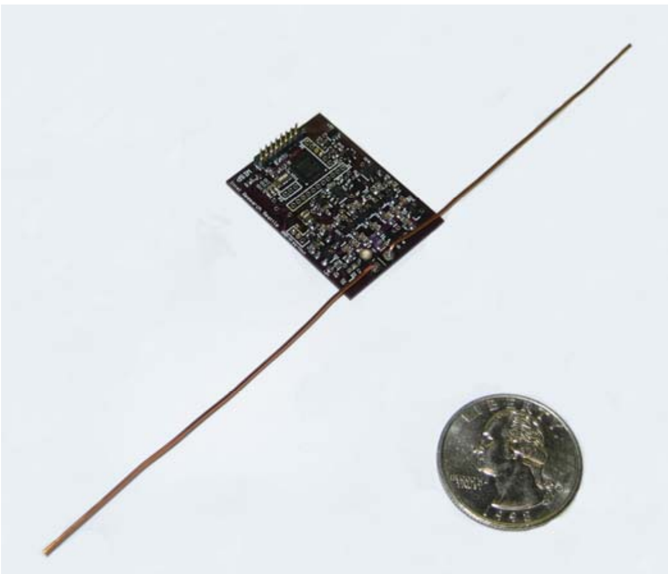

Fig. 1 A photograph of the WISP platform

A further consideration is the configurability and computational power of RFID sensor tags. Existing devices are generally fixed-function with respect to sensory inputs and lack computational capabilities. A commercially available RFID tag with some additional functionality is described in [7]: the device can transmit one bit of sensor data as well as its ID. Beyond the single bit encoding, it is limited by very short read range due to its 125 kHz operating frequency.

This paper presents the design of the Wireless Identification and Sensing Platform (WISP), a battery-free, programmable RFID sensor device (Fig. 1). Compliant with the Electronic Product Code (EPC) Class 1, Generation 1 protocol, WISP can transmit 64 bits of data per query and is fully configurable due to its ultra-low power, 16-bit, general-purpose microcontroller. Similar to conventional, passive RFID tags, WISP has no battery and is completely powered via the RF energy transmitted by an RFID reader. The architecture of WISP allows measurement of virtually any low power sensor, which are also wirelessly powered by the RFID reader. WISP is implemented as a printed circuit board (PCB), which offers a flexible platform for development and sensor integration. The present range of the platform is approximately 4.5 meters. To the authors' knowledge, WISP represents the first microcontroller to be integrated as part of a passive UHF RFID tag.

The general-purpose WISP described in this paper was preceded by several less capable devices (also called WISPs) that were described in earlier publications by our group. The α-WISP [12] used two mercury switches to mechanically toggle between two commercially produced RFID integrated circuits (IC). The π-WISP [8] used a microcontroller powered by harvested RF power to activate a GaAs RF switch, which multiplexed two commercially available RFID ICs to one tag antenna. This device could transmit at most one bit of sensor data per query, and used two separate antennae for communication and power harvesting. The significant difference between the previous work and the WISP presented in this paper is that the microcontroller is now implementing the EPC protocol and no commercial RFID ICs are used in the design. This gives the WISP the ability to control all 64 bits of the ID for data encoding versus 1 effective bit for the previous approaches based on enabling and disabling commercial tags. Furthermore, the device described in this paper uses a single antenna for power harvesting and communication, while the approach of [9] required separate antennas for these two functions. In [10], the authors discussed ubiquitous computing applications of the WISP platform, but did not present a detailed discussion of its design. Also, the harvesting and communication circuit presented in this paper is improved over the circuit on which [10] is based.

This paper presents for the first time a detailed discussion of the WISP design and power budget. The architecture and algorithms of WISP are presented in sections II and III. Next, a detailed power budget analysis shows the wireless range and sensor load capabilities of WISP. Finally, applications and real world performance are shown, in order to demonstrate the current capabilities of WISP.

## II. WISP ARCHITECTURE

The development of WISP using printed circuit board (PCB) design departs from conventional RFID design using integrated circuits (IC). There are numerous tradeoffs with this approach. The primary advantages of PCB design over IC design are fast design iteration time and low development cost. In contrast, integrated circuit implementations can include custom components, typically consume less power than discreet PCB designs, and yield a smaller form factor device. Recent research in IC-based passive sensor tags has taken incremental steps in augmenting the capabilities of RFID tags by integrating additional functional blocks; however these devices continue to be fixed in function, not programmable. For example, ADCs, specialized logic, and integrated temperature sensors have been integrated into tag ICs while maintaining the finite state machine architecture of typical RFID tags [5,6]. WISP represents an alternative design philosophy that focuses on the programmability of a full microcontroller as part of a sensor-enhanced, passive RFID device.

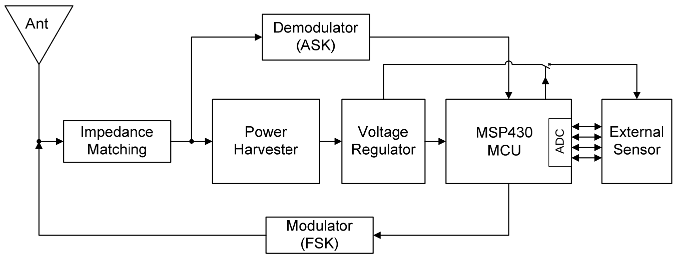

Fig. 2 Block Diagram of the WISP platform

A block diagram of the WISP is shown in Fig. 2. An antenna and impedance matching circuit precede the analog front end. The power harvester block rectifies incoming RF energy into DC voltage to power the system. The demodulator follows the envelope of the RF carrier wave to extract the Amplitude Shift Keyed (ASK) data stream. This extracted baseband waveform is read by the MSP430 microcontroller (MCU) to receive downlink data from the reader. Uplink data is sent via the modulator circuit, which functions by changing the antenna impedance. Finally, onboard sensors are powered and measured by the MCU.

The WISP platform depicted in Fig. 1is made of a two layer FR4 PCB with components limited to the top side. A dipole antenna made of 22 gauge (0.6mm diameter) copper magnet wire is visible. The WISP in its base configuration has two onboard sensors: a circuit for measuring the rectified supply voltage, a temperature sensor and an additional landing for surface mount sensors.

Small header pins expose all ports of the microcontroller for expansion to daughter boards, external sensors and peripherals. Significant reduction of the PCB area is possible and will be addressed in future designs by using a 4 layer board with components placed on both sides.

## A. Analog Front End and Tuning

A schematic of the WISP analog circuitry is shown in Fig. 3 The WISP analog front end differs slightly in purpose from that of conventional RFID tags. Due to the relatively high power consumption of WISP, the rectifier is designed to supply more current than ordinary tags. This circuit is excited by commercial, EPC Class 1 Generation 1 compliant readers operating at 902-928 MHz with an allowable transmission power of $4W_{EIRP}$ (Effective Isotropic Radiated Power).

Due to loss in signal strength over transmission distance, there is potentially very little power for the tag. Therefore, efficient conversion of the incoming RF energy to DC power for the tag is an important design consideration. A matching network provides maximum power transfer from the antenna to the rectifier, and a 5 stage voltage doubling circuit converts the incoming power to voltage. Low threshold RF Schottky diodes are used to maximize the voltage output of the rectifier. Finally, this rectified DC voltage is stored in a large capacitor and supplied to a 1.8V regulator to power the WISP.

To tune the antenna, the two dipole branches were mounted to an SMA connector that was then connected to a network analyzer, and the dipole length was optimized for the 902MHz to 928MHz band. Next, an SMA connector was attached to the WISP board in place of the antenna and the WISP was attached to the network analyzer, which was set to sweep from 902-928MHz at a power of 0dBm. The microcontroller was programmed to remain in LPM4 sleep mode to minimize its power consumption. The WISP's discreet matching network, composed of a series inductor and parallel trimmable capacitor, was tuned until the output voltage of the WISP was maximized. Note that the power harvester is a non-linear device, and its efficiency is highly load-dependent. Ultimately, the front end must be tuned to provide maximum output voltage in the presence of the desired load. Optimizing the matching network for the load of the microcontroller in its LPM4 sleep state effectively maximizes read range. To maximize read rate at close range, or power delivered at close range, one would tune the matching network differently.

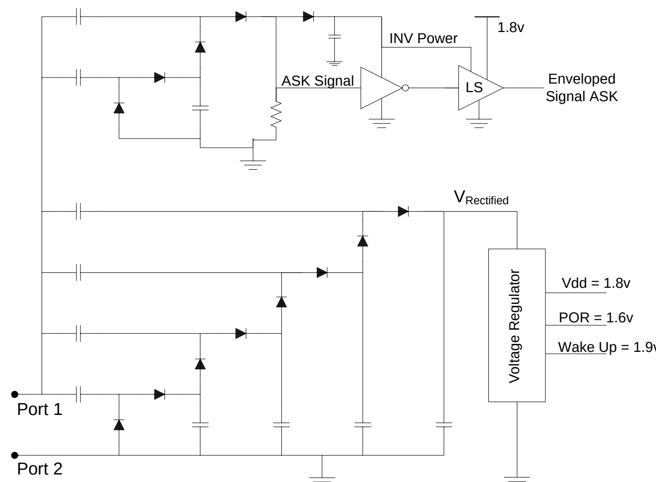

Fig. 3 Schematic of WISP power harvesting and communication circuit.

## B. Demodulation and Modulation

To encode reader-to-tag data, the reader amplitude-modulates the 915MHz RF carrier wave it emits. Normally the carrier waveform remains at a constant amplitude; when bits are transmitted, the amplitude of the carrier drops to approximately ten percent of its normal value. The duration of the low "break" indicates a logical "one" or a "zero." A short break (1.78uS) indicates a "zero," and a long break (5.34uS) indicates a "one." To decode this data, the RF signal is fed through a two stage voltage doubling rectifier in parallel with the main harvester. This "mini-harvester" appears at the top of the schematic. The final charge accumulation capacitor of the mini-harvester is much smaller than that of the main harvester, allowing it to track the dynamic range of the incoming bits. The first two voltage doubling stages of the mini-harvester, in conjunction with the resistor and capacitor, effectively demodulate the 915MHz carrier, and leave a baseband data signal on the order of 70kHz. The final "extra" diode (the top-right-most in the schematic) performs an additional rectification step, removing the 70kHz data signal and leaving a slowly varying average power level (i.e. just fast enough so that it can change on the timescale that the tag moves in space, say 10Hz) that provides a dynamic reference for bit detection.

The 70kHz data signal is fed through a Schmitt trigger inverter that thresholds this waveform to remove noise and glitches. Finally, a level shifter (labeled LS in the schematic) converts the relative magnitude of the incoming data waveform into a 1.8V logic level for the MSP430.

Note that the rails of the inverter and level shifter are connected to neither the main unregulated supply ($V_{rec}$) nor to the regulated supply, but instead are fed by the output of the final, "additional" rectification diode of the mini-harvester.

The final charge accumulation capacitor is chosen to be large enough that the components it powers (the Schmidt trigger and level shifter) continue to receive power even when the reader's output waveform is momentarily modulated down to its low state to encode reader-to-WISP bits.

To understand the benefit of the mini-harvester, note that when the carrier is off, the charge that accumulates on its accumulation capacitor leaks to ground through the resistor (in fact it leaks all the time through this path, regardless of the carrier's state). Because the data decoding is performed by a secondary harvester instead of the main harvester, the system's main accumulated power store cannot drain through this resistor. Also, because this final diode is rectifying a 70KHz signal instead of an RF signal, we were able to use an ultra-low-leakage diode for this component instead of the relatively high leakage Agilent HSMS-2852 RF diode used elsewhere.

Before moving to the mini-harvester design, leakage from the charge storage capacitor back through the demodulation resistor was a significant source of inefficiency. With a 5 stage harvester alone, and no data demodulation circuitry or microcontroller, our rectification circuit produces 3.1v from a 0dBm input signal. With the older design of [10], adding the demodulation circuit reduces the output voltage to 2.0v. Adding the new mini-harvester demodulation circuit instead reduces the output voltage to just 2.8v.

RFID tags do not actively transmit radio signals. Instead they modulate the impedance of their antenna which causes a change in the amount of energy reflected back to the reader. This modulated reflection is typically called backscatter radiation. In order to change the impedance of the antenna, a transistor is placed between the two branches of the dipole antenna. When the transistor conducts current, it short circuits the two branches of the antenna together, changing the antenna impedance; in the non-conducting state, the transistor has no effect on the antenna, and thus the power harvesting and data downlink functions occur as if it were not present. This impedance modulation is currently implemented with a 5GHz RF bipolar junction transistor which allows for effective shunting of the 915MHz carrier wave.

### C. Digital section and power conditioning

As the power available to RFID is extremely limited, careful component selection must be made to minimize current consumption. As advances in IC manufacturing now allow discreet components with less than 1uA current consumption and 1.8V operation, it is possible to construct RFID tags with discreet components.

Most importantly, the general purpose computation abilities of WISP are enabled by an ultra low power microcontroller. This 16-bit flash microcontroller, the MSP430F-1232, can run at up to 4Mhz with a 1.8V supply voltage and consumes approximately 470uA when active for this choice of frequency and voltage. (The microcontroller has a 6MHz 3V mode which consumes 1800uA, which was used in [9]; in this paper, we have extended the range over the early results in [9] by improving the microcontroller's firmware, allowing for operation at lower voltage and clock frequency, and thus longer range.) Of particular interest for low power RFID applications, the MSP430 has various low power modes, and the minimum RAM-retention supply current is only 0.5uA at 1.5 volts. The device provides over 8 KBytes of flash memory, 256 bytes of RAM and a 10 bit, 200kilo-samples-per-second Analog to Digital Converter (ADC). The low power consumption of this relatively new device is a critical factor in enabling use of a general purpose microcontroller in passive RFID systems.

Another critical design consideration is operation with uncertain power supply conditions. Because the available RF power varies greatly throughout device operation, supervisory circuitry is necessary to wake and sleep the device based on the supply voltage level. WISP uses a 1.9V supervisor and a 1.6V power-on-reset to control device state and reset the microcontroller, respectively. The supervisor provides roughly 100mV of headroom on the storage capacitor above the 1.8V regulator voltage. This serves to buffer the supply voltage from dropping below 1.8V due to the large power consumption of the microcontroller in active mode. This is discussed further in section IV.

## III. SOFTWARE

The onboard MSP430 programmable microcontroller is responsible for implementing EPC Class 1 Generation 1 communication between the WISP and an RFID reader, as well as measuring any attached sensors. Efficient programming for the device is essential in meeting the low power requirements of passive RFID tags. The WISP software can be described on three levels. At the lowest level is the communication code, which generates uplink bits and detects downlink bits. The next level, state and power management, is responsible for managing the device state, including sleep vs. active modes. The third level implements the application layer protocol for encoding sensor data in the tag ID.

## A. Packet Decoding and Encoding

The most challenging aspect of programming the MSP430 involves meeting the timing constraints of the EPC protocol while still maintaining a low clock frequency. RFID tags, with custom state machines, are designed at the hardware level to receive and send using the EPC protocol. The general-purpose MSP430 must be carefully tuned to perform EPC communication, both in the receiving and transmitting of data. In particular, a mix of C and assembly language is used, where the C code maintains ease of configurability for the firmware for different sensor applications and the assembly code allows fine grain control of the timing of the MSP430 for EPC communication.

EPC protocol employs amplitude shift keying (ASK) modulation to encode data to the tag, representing the data bits 1 and 0 with a long and short gaps in RF power, respectively. To receive data from the reader, the MSP utilizes the periodic edge of the waveform as a hardware interrupt, and then during the interrupt service routine re-samples the bit line to detect a 1 or 0 during the differentiated part of the waveform. This data is quickly shifted into memory before repeating this process. To detect the end of transmission, a timer is refreshed during each bit. When bits are no longer received, the timer expires, the packet is interpreted, and if appropriate, a response is sent to the reader.

If a valid query is received from the reader, the WISP responds with its current data packet "ID." First, the ID is copied into CPU registers to allow fast access during the transmitting period. Second, the hardware timer is configured for pulse width modulated (PWM) output. Finally, each bit of the response is read from the CPU registers and used to change the length of the PWM period, in time. Specifically, a zero is represented by a 70KHz square wave and a one is represented by a 140KHz square wave. This waveform is sent to the modulator, which creates backscatter radiation. It is important to note that although the signal to the reader is in the form of a amplitude modulated reflection of energy, the data is encoded as a "higher order" frequency modulation of the "lower order" amplitude modulation. The naming convention of describing the uplink as frequency-modulated is maintained to be consistent with the EPC Gen 1 specification.

## B. System State and Power Management Algorithm

Meeting the low power requirements of passive RFID tags requires that the MSP430 dissipate, on average, as little power as possible. With various sleep modes and fast startup time, this processor is well suited to meet the stringent power requirements. In fact, time is mostly spent in LP4 (low power mode 4) which draws only 0.5uA, and the running (active) mode current consumption is approximately 470uA at 3MHz and 1.8V.

Fig. 4 shows the operational power cycle of the microprocessor. The system is event driven by external interrupts from either the voltage supervisor signal or the bit line communication interrupt. As shown in the diagram, the microcontroller sleeps between events to conserve power.

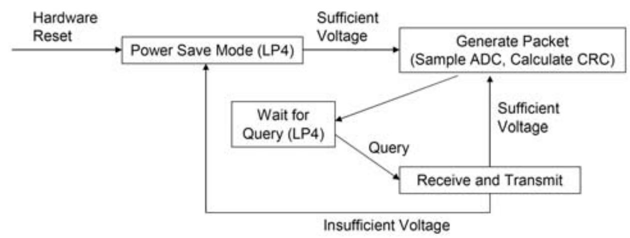


Fig. 4 Operational Power Cycle

There are three active mode blocks. The first, designated "Generate Packet," powers and samples an attached sensor and calculates the CRC to complete the EPC-compliant ID. The second block, designated "Receive," is initiated by a communication interrupt from the reader (demodulation circuit). The microcontroller receives the reader command and responds if the query is recognized. The final block, designated "Transmit," involves sending the ID to the reader. Some RFID readers must receive the same ID multiple consecutive times to correctly report the ID. While not shown in Fig. 4, the same Receive and Transmit sequence is typically repeated three times to ensure that the reader acknowledges the ID.

## C. Sensor data encoding

To communicate sensor data from WISP to a computer through an RFID reader, the data must be encoded into the tag ID. Using the first byte after the CRC to denote the type of sensor attached, the remaining seven bytes can then be used to encode sensor data. The on-board ADC measures with 10 bit accuracy, allowing a maximum of 5 measurements to be transmitted per tag ID. This data is parsed on a computer in real time to display the most recent measurements reported by WISP.

# IV. Power Budget

One of the significant challenges of incorporating microcontrollers, sensors, and peripherals into passive RFID technology is the ability to manage the large power consumption of these devices. For example, the MSP430F1232 running at 3 MHz consumes approximately 470uA at 1.8v. The resulting power consumption is significantly larger then typical passive RFID tags. Under these conditions the harvester cannot continuously supply power to the WISP during a single reader query.

One method used to overcome this challenge is to use a large storage capacitor (on the order of microfarads) to accumulate charge over multiple EPC queries. This allows for short bursts of power to activate and measure sensors and communicate at long distances where received power is minimal.

If the single query power requirements are not met, the WISP sleeps for several reader transmission cycles. This allows more time for charge accumulation. The approach of duty cycling is often used in low power applications; however this presents a challenge for RFID networks when the WISP is not necessarily able to respond to each reader query.

The next section examines the issues related to powering the WISP from two perspectives. One is the power required to turn on the device and the other is the energy required for active operation.

### A. *Turn On Power Requirement*

In order to increase the operational distance of the WISP the minimum power threshold needed for turn-on is lowered by placing the device in a sleep mode, resulting in a current consumption of 5uA (MSP430 0.5uA). Stated another way, the inactive current consumption is minimized, allowing the harvester to rectify the 1.8 volts needed for the MSP430 to activate. Given sufficient time, the storage cap will charge to the maximum output voltage of the harvester. Thus, a key parameter for maximizing the read distance of the WISP is not necessarily active current consumption but sleep current consumption. (The other key parameter determining range is the minimum voltage required for operation. The active-mode power requirement determines maximum read rate, and is less critical in determining range.) While this strategy can result in slower update rates, it is necessary for powering large sensor loads over long distances. A significant amount of engineering is needed to keep the steady state inactive current consumption under 5uA.

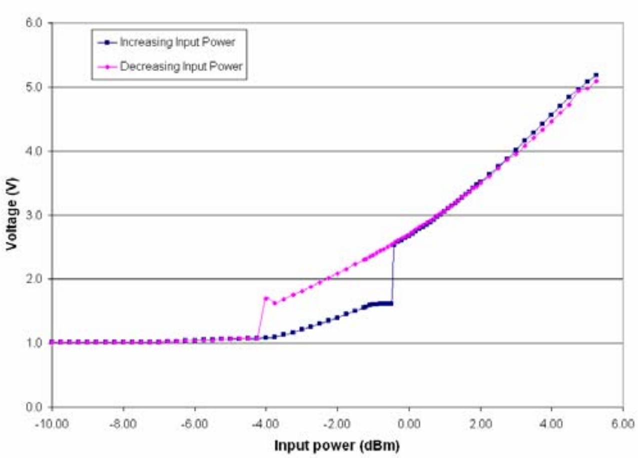


Fig. 5 Rectified voltage vs. input power measurements using a network analyzer for RF signal insertion in to the antenna ports.

Fig. 5 is a plot of rectified voltage vs. input power to the voltage multiplier. When the WISP is initially off and the input power is increased, a sudden spike in rectified voltage occurs at -0.5 dBm (1.6V). This event indicates the point at which the MSP430 boots up and enters its sleep mode, known as Low Power Mode 4 (LPM4). This shows that the current consumed during start up is larger than the current in LPM4. Hysteresis can be observed when the WISP is initially in sleep mode and the input power is decreased: the power consumed by the WISP in the 0 to -4dBm region is history dependent.

Using the best- and worst-case input power for turn-on from Fig. 5, it is possible to bracket the expected operating distance for the WISP using the Friis equation (1) for path loss.

$$P_R = P_T - 20\log\left(\frac{4\pi d}{\lambda}\right) + G_T + G_R \quad (1)$$

In this equation, $P_R$ is the received power, $P_T$ is the transmitted power, $\lambda$ is the wavelength of the RF carrier wave, $d$ is the distance from reader to WISP, and $G_T$ and $G_R$ are the gains of the reader and WISP antennas in dBi.

The transmit power of the reader $P_T$ = 1W = 30dBm. Its center frequency is 915MHz, corresponding to wavelength $\lambda$=0.33m. The transmit antenna gain $G_T$ = 6 dBi (this yields an effective isotropic radiated power of approximately $4W_{EIRP}$, the United States regulatory limit for this ISM band). The receive antenna gain $G_R$ = 2 dBi, using the standard figure for the gain of a dipole antenna. Using the operating thresholds of -4 dBm and -0.5 dBm from Fig. 5, the Friis model, which does not model multipath effects, predicts operating range thresholds of 3.3m (moving from near to far) and 2.2m (moving from far to near). Experimentally, we have observed longer ranges than predicted by the Friis model, probably enabled by additional multipath power. We have observed EPC packets received at up to 4.5 m, which is discussed further in section VI.

### B. *Active Energy Consumption*

Thus far it has been shown that a minimum power requirement needs to be met in order to rectify enough voltage to turn on the WISP. Additionally an appropriate duty cycle period is needed to allow the storage capacitor to charge to the turn-on voltage threshold. Since the rectifier cannot supply enough power for continuous operation it is important to understand the amount of energy that needs to be stored in order to power the WISP during active periods.

During one EPC Gen1 reader query, the complete WISP (not just the microcontroller) consumes on average 600µA at 1.8v. Only the WISP's active period is considered, which is measured from first bit of the received preamble to 100µs after the last bit of the response packet is transmitted, totaling 2ms. Using Coulombs Law and a storage capacitor of 8.5µF the amount of voltage head room needed to be rectified above 1.8v is 136mv, resulting in a total minimum voltage threshold of 1.93v for a complete packet transmission.

The same methodology of calculating the required stored energy can be used to when selecting sensors to be added to the WISP platform. Sensor tasks and packet generation are generally done prior to the EPC query. However, it is reasonable to assume that when performing sensor applications the WISP will exhibit similar voltage and current consumption. Inequality (2) expresses an energy feasibility condition for a particular sensor: the energy required to read the sensor must not exceed the usable stored energy. The expression can be used to calculate the voltage headroom required to operate a particular sensor, which in turn determines the range at which the sensor can be operated.

$$V_{dd}\left(I_S + I_w\right)T \le \tfrac{1}{2}C\left(V_{rec}^2 - {V_{dd}}^2\right) \quad (2)$$

The current consumption for the sensor and WISP are $I_s$ and $I_w$ respectively, $C$ is the capacitance of the storage capacitor, and $T$ is the total time of active operation. The rectified voltage is $V_{rec}$, and $V_{dd}$ is the required operating voltage. Assuming that the sensor has the same voltage supply as the WISP, $V_{dd}$ equals 1.8 volts. The left hand side of inequality (2) is a straightforward expression for energy consumed by the sensor and WISP. The right hand side represents usable stored energy. (Note that the total energy stored on the capacitor is $\tfrac{1}{2}CV_{rec}^2$, but not all of it is usable since charge stored on the capacitor at a voltage less then $V_{dd}$ cannot operate the WISP.) Inequality (2) makes it clear that the limiting factor when selecting sensors is not only the current consumption (which determines power) but also the total required execution time of the sensor and WISP (energy, rather than power). Additionally, it is important that sensors be disabled when not in use to minimize unnecessary energy expenditure.

## V. Sensors and Applications

Very low power sensors requiring less than 50uA of current are relatively easy to integrate with WISP. Examples include light, temperature, push-buttons and rectified voltage level. Reference [9] presented the results from a light sensor attached to WISP. We found the accuracy and power consumption of the on-chip MSP430 temperature sensor to be disappointing, but more accurate low power solid state temperature sensors are readily available, and we added an external temperature sensor to the WISP. Measurement of rectified voltage is easily accomplished with a voltage divider to scale the rectified voltage to the range of the 1.8V ADC. An ultra low power analog switch can be used to reduce current draw between sensor reads.

More demanding low power sensors that require up to 500uA of current are also possible to measure with WISP. Due to the relatively high current consumption of these devices, continuously powering them would severely cripple the range of WISP. To overcome these high power requirements, the sensor must only be powered for a short period of time to take a measurement. Provided that the sensor can stabilize in less than a few hundred microseconds, this allows for a wide range of sensors to be measured over RFID. WISP has successfully powered a sensor device that draws 200uA at 1.8V providing sample rates of approximately 10 samples per second. Each sample is reported to the RFID reader, and this information is then decoded in real time by a computer.

## VI. Experimental Results

Fig. 6 shows experimental results of the WISP performance, plotting harvested voltage output as a function of range from an RFID reader. The experimental set up consisted of an Alien Technologies 9RE-0001 EPC Gen 1 RFID reader driving a 6dBi circularly polarized patch antenna. The reader's antenna and WISP were placed on stands 1m above the floor. The WISP was then moved away from the reader along the center axis of the patch antenna. Measurements of the rectified voltage in LPM4 are averaged over a ten second interval using an oscilloscope. (Averaging over this long window is necessary because several times per second, the reader pseudo-randomly changes its output power and frequency within the 902-928MHz band.)

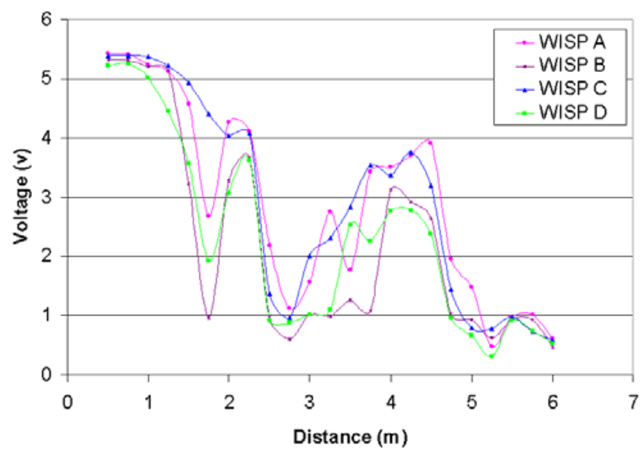


Fig. 6 Rectified voltage in sleep mode vs. distance for an RFID reader

This data shows the average voltage that four individual WISPs each produce in sleep mode as a function of distance. This plot shows that the operational range of the WISP can be somewhat greater than the range naively predicted by the Friis equation. At a distance of 2 meters the average rectified voltage in sleep mode is over 3 volts, allowing the WISP to turn on. Rectified voltage increases with input power. Thus one expects the duty cycle at 1m (where the voltage is high) to be greater than the duty cycle at 4m (where the voltage is lower), and indeed experimental observation is consistent with this expectation.

It is important to note the drop in rectified voltage at 2.7m. In this region the WISP generally does not function except for a few sporadic reads. We cannot yet fully explain this phenomenon, but we are convinced that it is an RF propagation effect (possibly multipath scattering off the floor), and not anomalous behavior of the WISP power harvester. Fig. 3 of [11] shows a similar effect, namely RFID read rates that are non-monotonic with distance, using the same RFID reader, antenna, and floor as in this paper, but with commercial RFID tags. Furthermore, one of this paper's authors has also observed the same effect using commercial tags (and the same antennas, readers, and floor), as shown in Fig. 2 of [12].

Based on the ranges predicted by the Friis equation, it may be that the increase in voltage observed beyond 2.7m is due to an increase in incident power caused by reflections off the floor. At the range near 2.7m, the most strongly reflected "rays" may be from outside the primary lobe of the antenna. At a longer range (say 4m), the outer edge of the antenna's main lobe might begin to have a strong reflection path. Of course coherent interference effects may also play a significant role, and it may be necessary to consider such effects to fully explain the details of the voltages and read rates observed in this and other [11,12] papers.

## VII. Conclusion

This paper presents a programmable passive RFID device capable of being reconfigured for new tasks and easily accommodating the integration of low power sensors. The WISP architecture is based on conventional RFID design strategies which use multi-stage voltage multipliers to rectify DC voltage for operation. An envelope detector and an uplink transistor are used by the 16 bit microcontroller to implement the EPC protocol. Additionally WISP has shown the capability to communicate multi-bit sensor data over distances of up to 4.5 m using a standard RFID reader.

WISP has proven the feasibility of powering a 16 bit microcontroller and arbitrary low power sensors using only the RF energy from a standards-compliant RFID reader. Furthermore, WISP has demonstrated the communication of sensor data using the EPC Class 1 Generation 1 protocol. The authors believe that WISP is the first of a new class of battery-free, wireless sensing and computational devices.

## VIII. Future Work

A detailed explanation and model of the measured voltages of Fig. 6 is one topic for future work. Future design efforts will focus on continued refinement the WISP platform. Improvements in antenna design, including PCB-integrated antennas, as well as improved board layout, can yield smaller size and enhanced wireless range. Also, more effective power management and rectification techniques can increase the range of the WISP. Development of new applications using low power sensors such as thermal, acoustic, pressure, and strain sensors will be investigated. Exploring applications of the on-board computational power, for compression and other embedded sensor data processing functions, is another area for future research. The techniques and lessons learned from the PCB implementation will be transferred to an integrated circuit implementation. This will provide lower power consumption and high customization of design. Finally, new protocols optimized for RFID sensing are an additional area of research suggested by this work.

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